Surface Roughness of Heat Treated and Untreated Beech (*Fagus sylvatica* L.) Wood after Sanding

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The effect of sanding, as the last operation before finishing, on the quality of heat treated wood surfaces has been insufficiently explored and explained. This paper compared the effects of sanding with three commonly used sanding grit sizes P60, P100, and P150 on the surface roughness values of beech (*Fagus sylvatica* L.) wood. The wood samples were treated by the ThermoWood process at 200 °C for 2.5 h. A large range of standard roughness parameters (R_a, R_q, R_v, R_t, R_{Sm}, R_{sk}, R_k, R_{pk}, and R_{vk}) and two waviness parameters (W_a, and W_t) were included in the analysis, as well as environmental scanning electron microscope (ESEM) images of the sanded surfaces. The results showed that the heat treatment slightly increased the surface roughness and decreased the wood surface waviness after sanding. All roughness and waviness parameters increased with increasing sanding mean grit diameters by following a strong linear correlation. The processing roughness was closely approximated by the parameter R_k. For both, treated and untreated beech, sanding had a tendency to obscure (in magnitude and number) wood anatomical details in the measured data. However, the influence of wood anatomy in the valleys domain increased as the grit size became finer.

Keywords: Surface roughness; Heat treated beech; Sanding quality; Roughness parameters; Microscopic images

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INTRODUCTION

Heat treatment of wood can considerably improve some wood properties (Tjeerdsma and Militz 2005). Many aspects of heat treatment have been studied including: dimensional stability, wood durability, mechanical properties, equilibrium moisture content, mass loss, wettability, colour change, and chemical modification (Esteves and Pereira 2009). Some studies have examined the impact of heat treatment on machinability and the resulting wood surface quality (de Moura and Brito 2008; Skaljić *et al.* 2009; Budakci *et al*. 2011; Tu *et al*. 2014; Gaff *et al*. 2015; Kminiak *et al*. 2015; Kvietková *et al*. 2015a, Kvietková *et al*. 2015b; Ispas *et al.* 2016; Pinkowski *et al*. 2016; Gurau *et al*. 2017). Machining of a wood surface is characterized by the surface quality, which is generally analyzed by the surface roughness measurements, resulting from the interaction between the cutting tool and the wood surface.

Surface quality can be measured with either optical, non-contact measuring instruments such as a laser, or by means of a stylus contact method. The latter was found to give more repeatable results and seems more reliable for wood (Gurau *et al*. 2005) because the laser appears to distort the surface data (Sandak and Tanaka 2003). Accurate measurement of wood surface roughness requires the correct selection of the evaluation length as well as the lateral resolution (Gurau and Irle 2017). The measured surface or surface-profile is filtered in order to leave only the high frequency irregularities that characterize the roughness values. The selection of filter is crucial, because wood roughness is known to be distorted by common Gaussian filters (Krisch and Csiha 1999; Molnar *et al*. 2017). A robust Gaussian filter applied iteratively to a data set was tested and found useful for wood surfaces because it does not introduce any bias, which can occur around certain anatomical features (Fujiwara *et al*. 2004; Gurau *et al*. 2006). The need for a robust filter for analysis of wood surfaces was confirmed and tested by the more recent studies of Piratelli-Filho *et al*. (2012) and Tan *et al*. (2012). However, no previous research on the surface roughness of heat-treated wood has used a robust filter. All previous researchers have applied simple Gaussian filters inherent in most measuring instruments on the market. After filtering, roughness parameters can be calculated and these are the basis for comparisons between the quality of processed surfaces or/and wood treatment.

Due to the chemical changes that wood undergoes during a heat treatment, its density decreases, most mechanical properties are degraded, and its brittleness increases with the deterioration of fracture properties (Esteves and Pereira 2009; Bakar *et al*. 2013; Schneid *et al*. 2014; Sandak *et al*. 2017). Thus, the heat-treated wood is more susceptible to mechanical damage during machining and it sometimes requires an adaptation of the processing parameters.

Studies on the influence of grit size on the surface roughness values of solid wood are numerous (de Moura and Hernandez 2006; Kilic *et al*. 2006; Ratnasingam 2006; Marthy and Cismaru 2009; Sulaiman *et al*. 2009; Salca and Hiziroglu 2012; Varasquim *et al*. 2012; Vitosyte *et al*. 2012; de Moura Palermo *et al*. 2014; Miao and Li 2014). Even though a trend of decreasing roughness with increasing grit number is unanimously reported, there has not been a thorough analysis by means of several roughness parameters. Furthermore, only few studies in the literature compared the surface roughness of untreated and heat-treated wood after sanding. De Moura Palermo *et al*. (2014) found an increase in surface roughness of heat-treated *Eucalyptus grandis* compared with untreated wood after sanding with P80 and P100 grit sizes. In that study, after high temperature treatment (190 °C for 6.5 h), the abrasive grits penetrate the wood more deeply than the untreated wood because of the reduced mechanical strength of the former. A number of studies have shown that heat treatment affects the mechanical properties of wood (Bekhta and Niemz 2003; Boonstra *et al*. 2007; Windeisen *et al*. 2009; Calonego *et al*. 2012). A recent example is that published by Borůvka *et al*. (2018) where they studied beech and birch wood samples.

Increased surface roughness of heat-treated of *Eucalyptus grandis* and *Pinus caribaea* as compared to untreated was also found after sanding by de Moura and Brito (2008) and de Moura *et al*. (2011). These studies contained a comparison between untreated and heat-treated wood for temperatures ranging from 140 °C to 200 °C subjected to sanding with following grit size combinations: 60-80; 80-100; and 100-120. The results showed a higher surface roughness in the case of heat-treated wood and this increased with the treatment temperature.

A different result was obtained by Tu *et al*. (2014) on *Eucalyptus urophylla* x *E. camaldulensis* subjected to heat treatments with temperatures ranging from 180 °C to 210 °C followed by sanding with a sequence 60-120 grit size. The surface roughness evaluated by parameter R_a showed slightly lower values for heat-treated wood, but with no significant differences between treatment temperatures.

The measuring length used in these studies was short, only 15 mm. Longer measuring lengths are preferable to cover the wood variation (Ostman 1983). In addition, the only roughness parameter quoted in much of the literature is R_a, despite the fact that it is known that it does not provide sufficient information about the surface topography, because very different surfaces can have the same R_a (Monetta and Bellucci 2012).

Fewer studies are available in the literature on the study of surface roughness of sanded heat treated wood in comparison with untreated wood. However, in order to further understand the effects of sanding on wood an in-depth analysis is required. This study improves on previous research by using a robust filtering procedure, by increasing the measuring length to cover more wood variation and by adding a large range of roughness parameters in order to give a comprehensive interpretation of data. In addition, this study also includes roughness profiles computed in MathCAD, which allow a visual comparison of the effect of grit size as well as of treatment on wood, supplemented by environmental scanning electronic microscopic (ESEM) images. The present study was based on beech wood (*Fagus sylvatica* L.) heat-treated by the ThermoWood method at 200 °C for 2.5 h and sanded with various grit sizes sequence that is typical prior to applying a finish, *i.e.*, P60, P100, and P150.

EXPERIMENTAL

Wood specimens of dimension, 400 x 50 x 28 mm, were cut from *Fagus sylvatica* L. Eighteen samples were kept untreated, while another 18 samples were heat-treated by the ThermoWood method (ThermoWood® Handbook 2003) in superheated steam in an industrial-scale TekmaWood kiln, manufactured by TekmaHeat Corporation (Lahti, Finland), according to the schedule presented in Table 1.

Table 1. Heat-treatment Schedule

Phase	**Conditions (Temperature / Time)**
Warming Up	100 °C / 3 h
Heating	100 °C…200 °C / 21 h
Actual Heat Treatment	**200 °C / 2.5 h**
Cooling	200 °C…30 °C / 13.5 h
Total Process Duration	**40 h**

All specimens were conditioned for 4 weeks at 20 °C and 55% relative humidity prior to sanding. The average moisture content of the samples after conditioning was 3% ± 0.2% for the heat-treated wood and 8% ± 0.5% for the untreated specimens. The mean density of the specimens at the moment of testing was 728 kg/m^3 for untreated beech wood and 617 kg/m^3 for heat-treated wood.

All specimens were then processed by sanding along the grain by using a wide belt sander with aluminium oxide belts, P60 grit size, at a contact pressure of 0.0055 N/m^2 and at a feed speed of 4.5 m/min. The depth of sanding was 0.3 mm/pass, and there were three passes for each specimen in order to make sure that irregularities from planing were completely removed. After this first sanding with grit size P60, 6 treated and 6 untreated specimens were kept for measurements and the others were further sanded with P100 by three passes though the machine. Again, 6 treated and 6 untreated specimens were retained and the others were sanded with P150 grit size in three passes.

According to Kantay and Űnsal (2002) and Budakçi *et al*. (2013), the surface roughness measurements have to be performed on the same type of surface (radial or tangential) and preferably not combined. Therefore, all sanded surfaces were tangential to reduce the influence of wood variability on the measured results.

The roughness measurements were achieved by using a MarSurf XT20 instrument manufactured by MAHR Gottingen GMBH (Göttingen, Germany), with a MFW 250 scanning head that has a vertical range of ±500 μm. The stylus used had a 2 μm tip radius and 90° tip angle. The specimens were measured at a lateral resolution of 5 μm recommended in Gurau *et al*. (2013), at a speed of 0.5 mm/s, and using a low scanning force of 0.7 mN.

Each specimen was measured three times using 42 mm traces across the grain (across the sanding direction) that were randomly positioned down the length of the specimen. Consequently, 18 profiles were obtained for each grit size. This length should be long enough to cover wood growth variability (earlywood and latewood areas) as well as to detect some longer wavelength components in the profile as waviness (Gurau *et al*. 2012). According to de Moura (2006), the values of roughness measured across the grain are usually higher than those measured along the grain.

The instrument had MARWIN XR20 software (MAHR, Göttingen, Germany) installed in it for processing the measured data.

The sequence of operations for an individual profile followed a standard procedure and began with removing the form error by best fitting a polynomial regression to the dataset so as to generate a primary profile containing waviness and roughness.

Roughness profiles were obtained by filtering each primary profile by using a robust filter RGRF (Robust Gaussian Regression Filter) described in ISO 16610-31 (2010). The cut-off used was 2.5 mm as recommended for wood in previous work of Gurau *et al*. (2006) and used by other researchers as well (Unsal and Ayrilmis 2005; Sevim Korkut *et al*. 2008; Korkut *et al*. 2009; Škaljić *et al*. 2009; de Moura *et al*. 2011; Salca *et al*. 2017).

A range of roughness parameters were calculated from each roughness profile including: R_a, R_q, R_{sk}, R_v, R_t, and R_{Sm} from ISO 4287 (1998); and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996). The sum of parameters R_k+R_{pk}+R_{vk} was used by Magross (2015) in a study on surface roughness of sanded wood and was also included in this study for comparison. Waviness parameters W_a and W_t, from ISO 4287 (1998) measured the longer wavelength components in the profiles.

Wood anatomy is known to bias not only the filtering process, but also the evaluation of the processing roughness parameters of wood, especially when the magnitude of inherent wood irregularities is greater than that caused by processing alone. However, when anatomy is not removed from the measured profile, R_k parameter was found to be a good approximation of the processing roughness (Westkämper and Riegel 1993; Gurau 2004; Sharif and Tan 2011). The parameter R_k measures the core roughness of a profile, and it is sensitive to wood processing and surface heat treatment. It is expected that in the case of sanding, the highest concentration of data points will correspond to the marks caused by the mean grit diameters occurring with the highest frequency. However, grit particles come as a range of values, where minimum and maximum grit diameters will have a low frequency. The grit particles that are larger than the mean value can be expected to create valleys that are deeper than the processing roughness.

Mean parameters R_a (the arithmetical mean deviation of the assessed profile) and R_q (the root mean square deviation of the profile) are common roughness indicators, but alone, they do not provide sufficient information about wood surface topography. The value of R_{sk} (skewness of the profile) is strongly influenced by the presence of isolated peaks or valleys. Surfaces with a negative skewness have fairly deep valleys below a smooth plateau. The R_{Sm} parameter (the mean width of the profile elements) is used in this study to characterize the effect of the sanding marks as far as their width is concerned. The R_t is the total height of the profile calculated as the sum of the maximum profile peak height (R_p) and the largest absolute value profile valley depth (R_v). Therefore, R_v is sensitive to the presence of large diameter vessels and deep processing marks caused by oversized grits or accidental damage.

The parameter R_k (the core roughness depth) is the depth of the core profile and is least influenced by wood anatomy because high peaks and low valleys are excluded from its calculation. This parameter should best indicate the core roughness caused by sanding (Gurau 2004; Magross 2015).

The R_{pk} parameter (the reduced peak height) is expected to be sensitive to fuzziness (fibres pulled out during sanding). The R_{vk} (the reduced valley depths) for beech, is typically associated with wood anatomical valleys, but can also be influenced, as R_v or R_t, by isolated high grit penetration in case of rough sanding.

The parameter W_a is similar to R_a, and W_t is similar to R_t, but they apply to the waviness profile, which excludes the shorter wavelength irregularities as roughness.

For each treatment and roughness parameter, a mean value and the standard deviation were calculated.

Individual roughness profiles taken across the grain were computed in MathCAD 2000 Professional (MathSoft Inc., Cambridge, MA, USA) in order to visualize the results. The core roughness (processing roughness) was separated from the other surface irregularities by upper and lower thresholds using a method described in Gurau *et al*. (2005) to allow visual comparisons between sanding with various grit sizes and wood treatment.

ANOVA and Duncan's multiple range tests were performed to test statistical significant differences between datasets (treatments and processing types).

The ESEM images were taken with a Quanta 250 made by FEI (Hillsboro, OR, USA). The photos were taken in Lovac mode at a pressure of 90 Pa. The surface relief was more easily observed if the specimen was tilted by 30°.

RESULTS AND DISCUSSION

From Fig. 1, it is difficult to notice any major differences in surface quality between untreated and heat-treated beech wood. However, it was observed that sanding traces were clearly visible as horizontal bands, and their depth and width were gradually reduced with the grit number. For all grit numbers, for both heat treated (HT) and untreated wood (UT), vessels were clearly visible, being uncovered by the grits ploughing into wood. The presence of vessels with simple pits was detailed by higher magnifications (400x) as shown in Fig. 2.

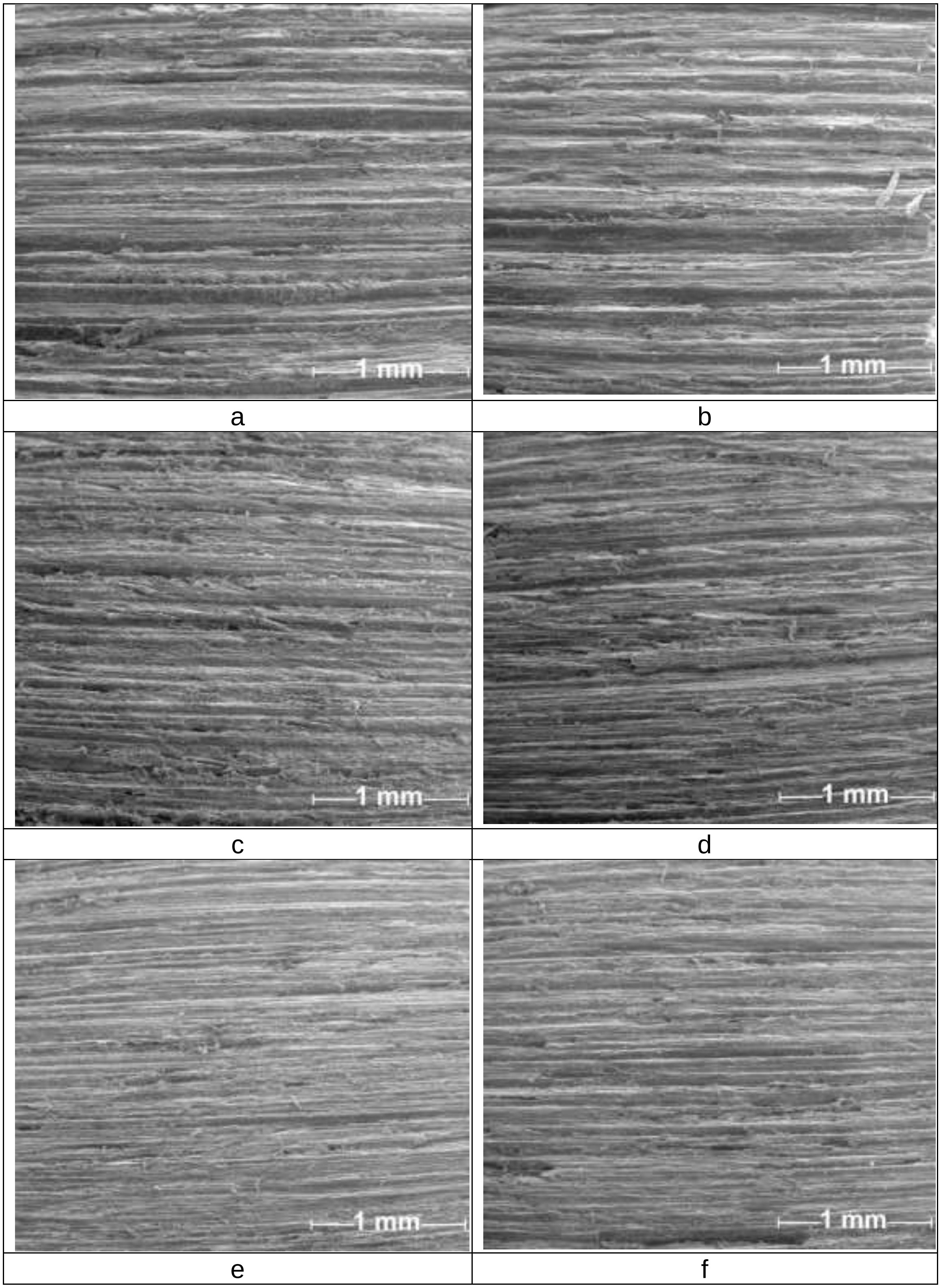

Fig. 1. Comparative ESEM images, with magnification 100x, of untreated (UT - a,c,e) and heat treated (HT - b,d,f) beech (*Fagus sylvatica* L.) sanded with grit sizes P60 (a,b); P100 (c,d); and P150 (e,f)

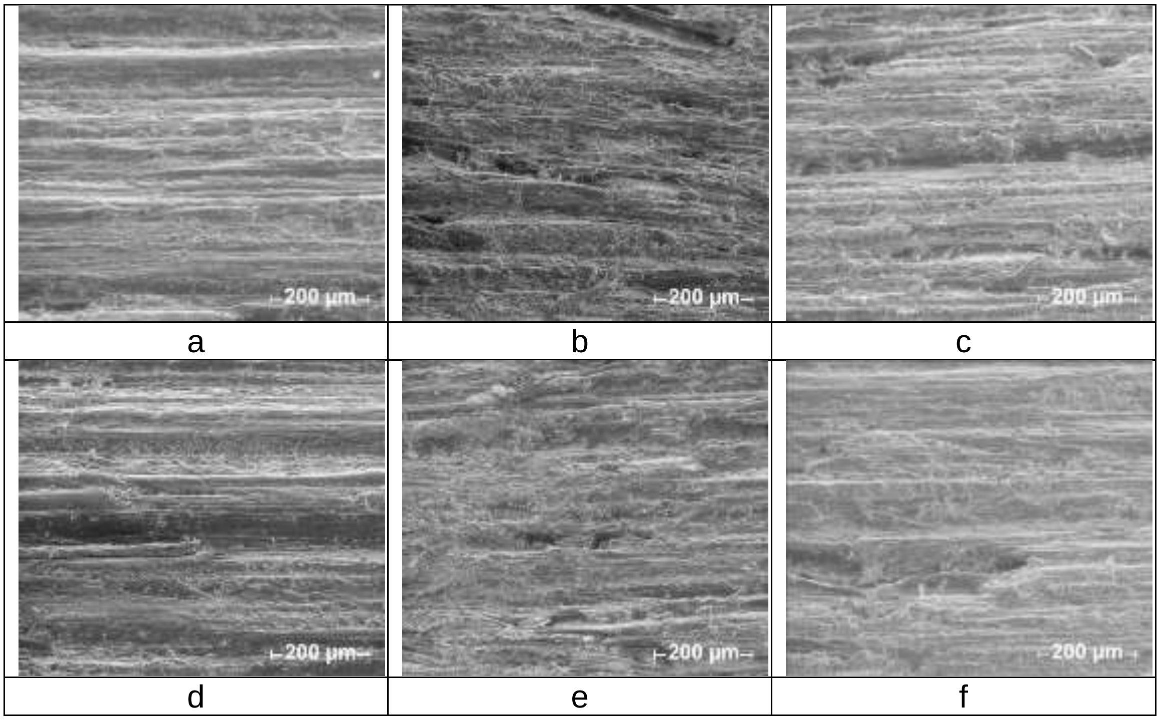

Fig. 2. Comparative ESEM images, with magnification 400x, of untreated (UT - a,b,c) and heat treated (HT - d,e,f) beech (*Fagus sylvatica* L.) sanded with grit sizes P60 (a,d); P100 (b,e); and P150 (c,f)

Table 2 shows that heat treatment at 200 °C for 2.5 h caused an increase in surface roughness after sanding for all the three tested grit sizes. These differences were significant for all roughness parameters and grit sizes with the exception of the parameters, which were sensitive to isolated features, R_v, R_t, and R_{pk} for grit sizes P100 and P150 and R_{vk} for all grit sizes.

The surface roughness of HT wood was approximately 2% to 11% higher than that for UT wood for all the roughness parameters except R_t for surfaces sanded with P100. These results were in agreement with Budakçi *et al*. (2013), who proposed that chemical changes caused by the heat treatment, especially those associated with hemicellulose changes, cause an increase in surface roughness.

Certainly it is well accepted that heat treatment changes the mechanical properties of wood and, in particular, making it more brittle. It is logical to conclude, therefore, that the mechanical response of heat treated wood to the action of a cutting tool will be different to that of untreated wood. Visual comparisons of the photographs in Figs. 1 and 2 do not reveal any dramatic differences that might explain the different roughness parameters given in Table 2.

Heat treatment reduces waviness such that W_a was smaller by 14% to 28%, and W_t by 10% to 14% than the values observed for the untreated wood. The differences were significant as tested with Duncan multiple range test (Table 3). Heat treatment had a marked effect on the mechanical properties of wood and, therefore, its response to mechanical solicitation, such as sanding, could be affected. This may explain the reduced surface waviness observed here and in previous studies on planed heat treated beech (Ispas *et al.* 2016).

Table 2. Mean Values of Roughness Parameters and Standard Deviations for Treated (HT) and Untreated (UT) Beech Wood Subsequently Sanded with Three Different Grit Sizes

Grit size		R_a (μm)	R_q (μm)	R_v (μm)	R_t (μm)	R_{Sm} (μm)	R_{sk}	R_k (μm)	R_{pk} (μm)	R_{vk} (μm)	R_k+R_{pk}+ R_{vk} (μm)
P60 UT	mean	12.6	16.4	74.2	126.4	381.5	-0.8	37.8	13.2	22.5	73.5
	stdev	0.73	1.13	15.60	18.38	27.86	0.26	2.28	0.96	3.26	4.80
	signif	A	A	A	A	A	AB	A	A	A	A
P100 UT	mean	9.0	11.6	51.78	92.1	249.5	-0.7	27.8	9.1	14.5	51.5
	stdev	0.56	0.74	8.69	13.72	15.44	0.21	2.04	1.12	1.52	3.59
	signif	B	B	B	B	B	B	B	B	B	B
P150 UT	mean	5.8	7.5	39.79	63.2	198.8	-0.9	17.7	5.5	10.2	33.5
	stdev	0.37	0.50	7.67	10.35	9.12	0.19	1.13	0.60	0.99	2.09
	signif	C	C	C	C	C	AB	C	C	C	C
P60 HT	mean	13.4	17.5	81.98	139.3	390.3	-0.8	40.0	14.4	24.4	78.8
	stdev	0.57	0.96	14.31	20.56	23.65	0.31	1.70	1.79	3.13	4.18
	signif	D	D	D	D	A	A	D	D	D	D
P100 HT	mean	9.6	12.3	55.35	90.7	262.2	-0.8	29.4	9.2	16.2	54.8
	stdev	0.56	0.70	6.30	6.93	12.15	0.14	2.03	0.93	1.30	3.09
	signif	E	E	B	B	D	B	E	B	E	E
P150 HT	mean	6.4	8.4	44.37	66.5	211.7	-1.1	19.2	5.7	12.2	37.2
	stdev	0.34	0.47	5.22	5.10	7.02	0.16	1.04	0.56	1.27	2.04
	signif	F	F	C	C	E	A	F	C	F	F

Note: Groups with the same letters in columns indicate that there was no statistical difference ($p < 0.05$) between the samples according to Duncan's multiple range test. The meaning for stdev- standard deviation; signif- significance.

Table 3. Ratios of Mean Values of Roughness Parameters, Waviness Parameters, and Standard Deviations for Treated (HT) and Untreated (UT) Beech Wood Prepared by Sanding with Three Different Grit Sizes

	Grit size		R_a/ R_v	R_{pk}/ R_{vk}	W_a (μm)	W_t (μm)
UT	P60	mean	0.175	0.60	8.2	50.1
		stdev			1.38	9.76
		signif			A	A
	P100	mean	0.178	0.63	5.9	29.2
		stdev			1.41	5.39
		signif			B	B
	P150	mean	0.150	0.55	3.6	20.7
		stdev			1.21	6.46
		signif			C	C
HT	P60	mean	0.167	0.60	7.2	45.3
		stdev			1.08	9.16
		signif			D	D
	P100	mean	0.175	0.57	4.9	26.4
		stdev			1.23	5.73
		signif			E	E
	P150	mean	0.146	0.47	2.8	18.1
		stdev			0.55	5.56
		signif			F	F

Letters refer to the statistical significance in Duncan's test. The meaning for stdev- standard deviation; signif- significance.

The profiles in Figs. 3 to 8 show clear differences between grit sizes of the same treatment, but the difference between treatments was hard to observe. The processing roughness, highlighted in blue, was assimilated to the mean depth of penetration of the sanding grits, which is characterized by the profile data points detected within the upper and lower threshold and is measured by the distance between the two thresholds. It is best approximated by the roughness parameter R_k, which was greater for the treated wood by absolute values between 1.5 μm (for P150) to 2.2 μm (for P60), which were too small to be detected by eye. Therefore, a combination of ESEM images, roughness profiles, and roughness parameters was better for comparison rather than using one or the other.

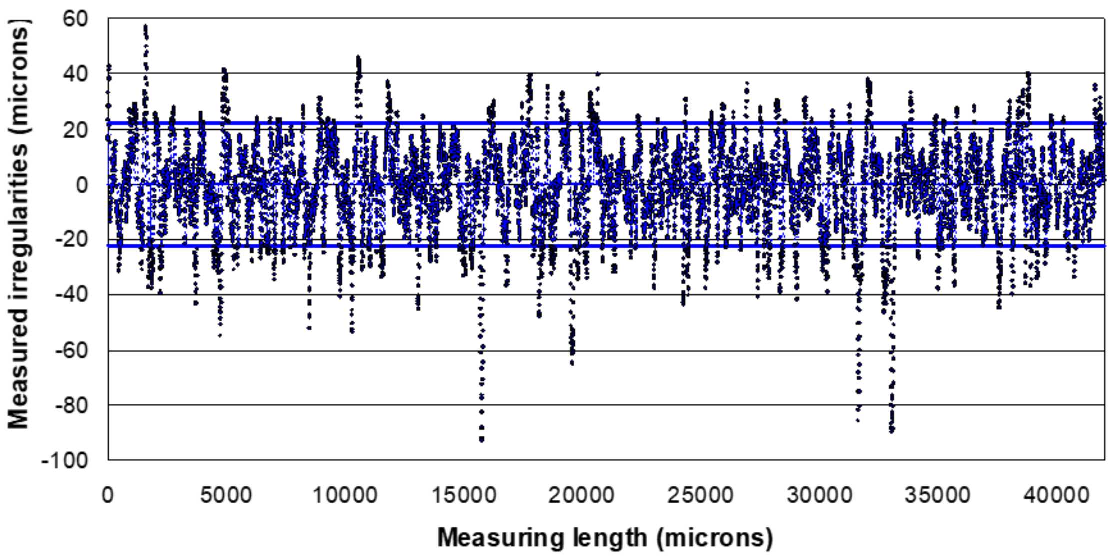

Fig. 3. Total roughness profile with thresholds delimiting the core roughness for heat treated beech sanded with P60 grit size

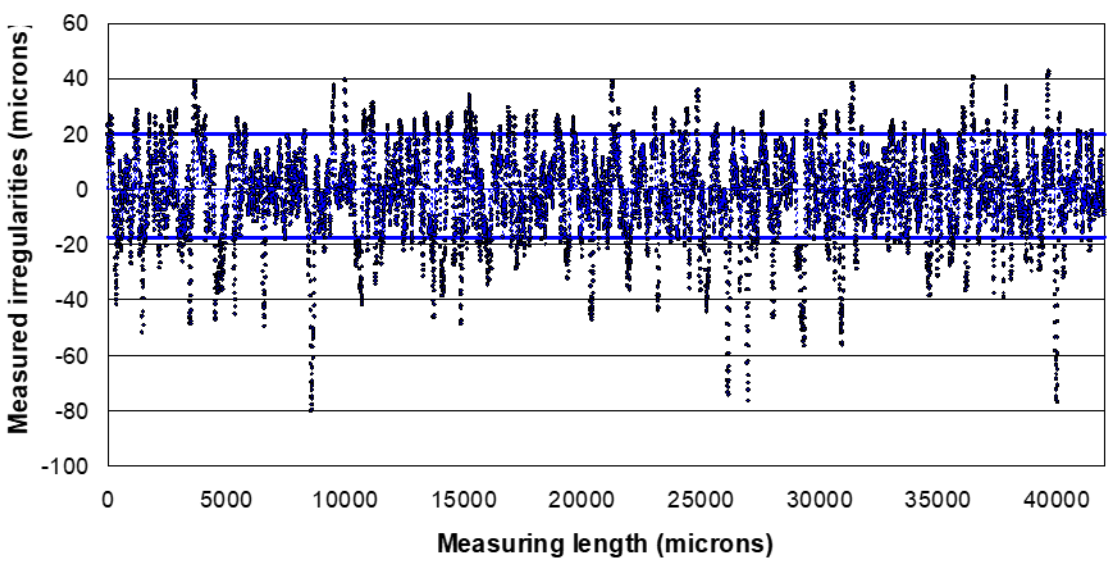

Fig. 4. Total roughness profile with thresholds delimiting the core roughness for untreated beech sanded with P60 grit size

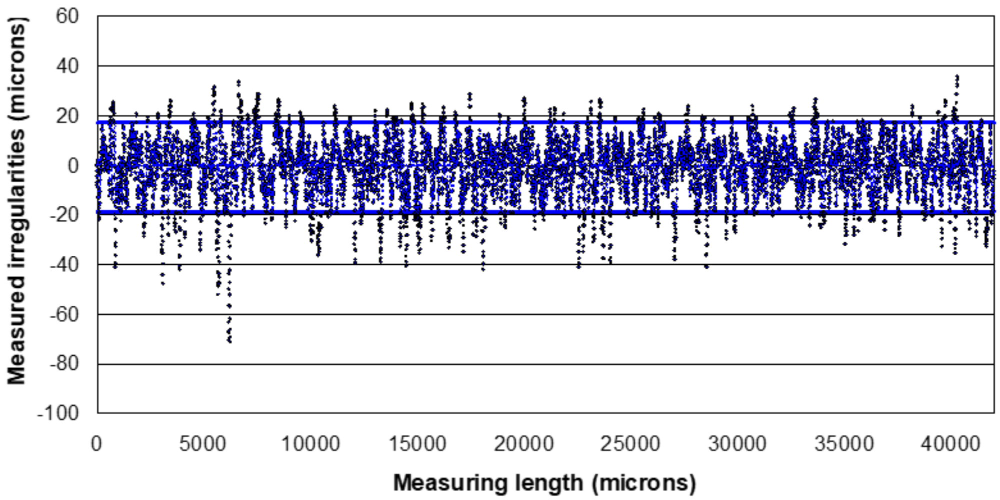

Fig. 5. Total roughness profile with thresholds delimiting the core roughness for heat treated beech sanded with P100 grit size

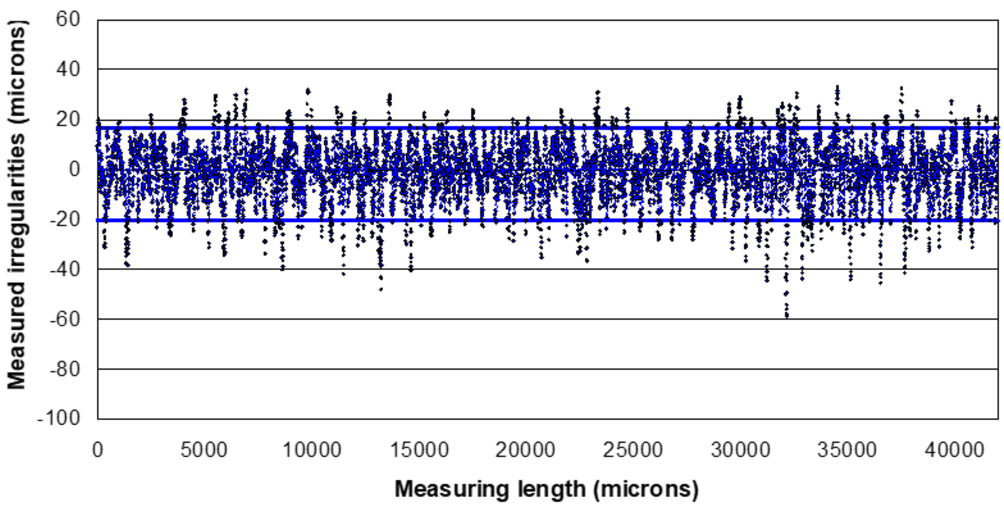

Fig. 6. Total roughness profile with thresholds delimiting the core roughness for untreated beech sanded with P100 grit size

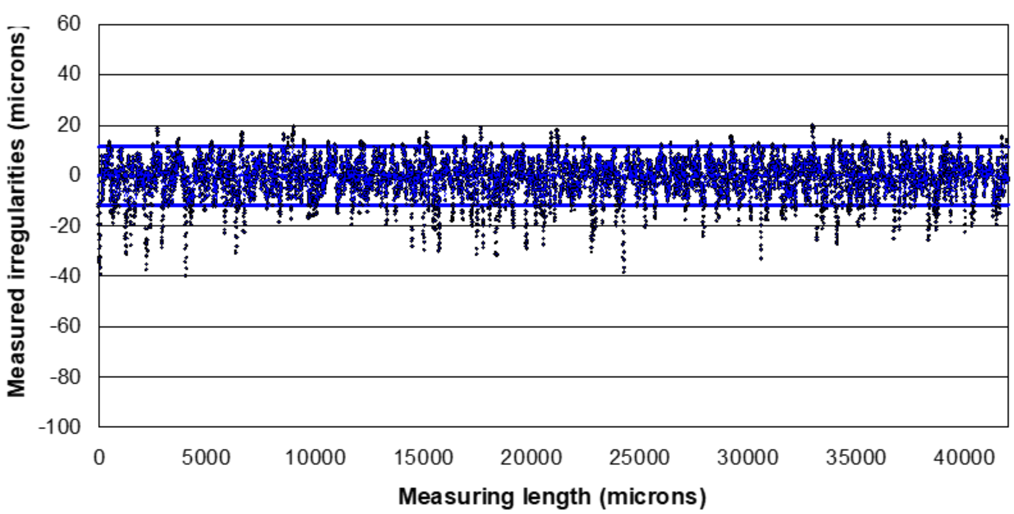

Fig. 7. Total roughness profile with thresholds delimiting the core roughness for heat treated beech sanded with P150 grit size

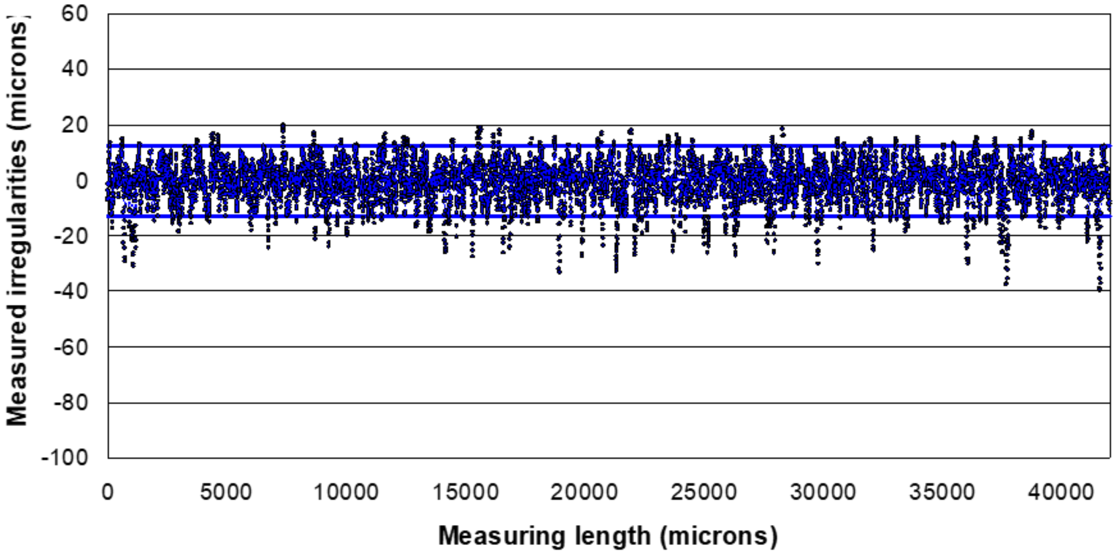

Fig. 8. Total roughness profile with thresholds delimiting the core roughness for untreated beech sanded with P150 grit size

If the roughness profile region with blue colour is depicting the processing roughness, the next question is what may the features above or below the lower threshold represent? Above the sanding marks, the operation of sanding is creating a fuzzy aspect with fibers partly detached from the surface occasionally. This is clearly visible in Figs. 1 and 2 for all grit sizes for UT and HT wood. Sanding with P60 created higher magnitude isolated peaks than the other grit sizes. This was indicated by the highest R_{pk} values, which decreased with increasing grit size. The lower threshold is marking the lowest level of the highest concentration of sanding marks. The features below the lower threshold may very well be anatomical cavities. From Fig. 2, it is clear that wood anatomical features are uncovered by sanding, but it is not sure how much they extend below the lower threshold.

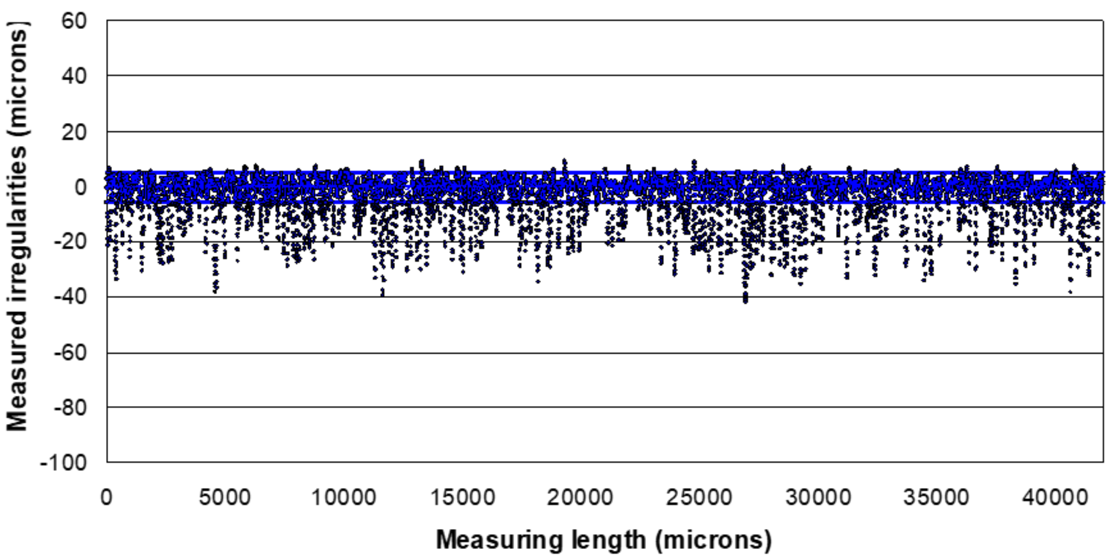

Fig. 9. Total roughness profile with thresholds delimiting the core roughness for untreated beech processed by planing

In this respect, a roughness profile measured from a planed beech surface from a previous study was taken in this analysis (Gurau *et al*. 2017). The surface was planed at a feed speed of 10 m/min and a rotation speed of 4567 rpm on a FELDER D963 (Felder Group, Absam, Austria) thicknesser by a cylindrical cutter head with helical cutters having tungsten carbide inserts. The profile is represented in Fig. 9.

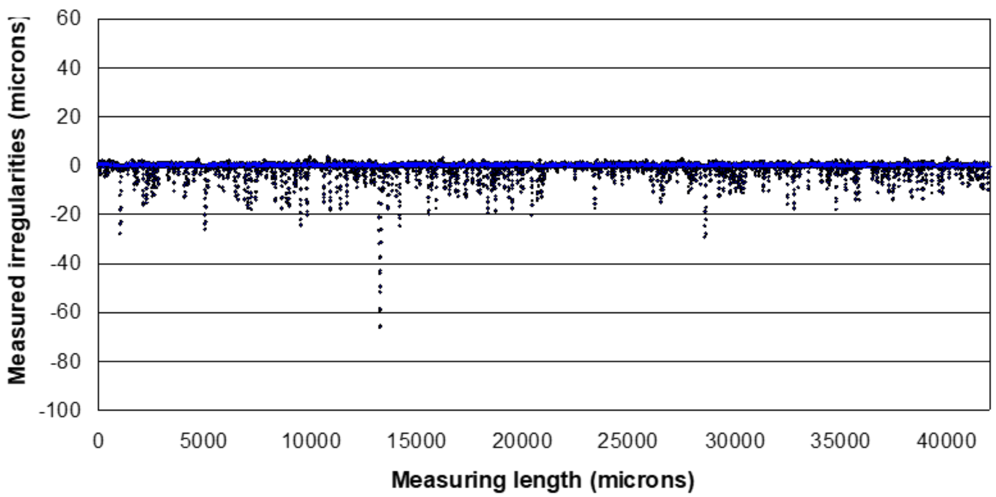

Fig. 10. Total roughness profile with thresholds delimiting the core roughness for untreated beech sanded with P1000 grit size

Gurau *et al*. (2017) found that valleys extending below the lower threshold in Fig. 9 were much deeper than the roughness caused by the planing, and they were attributed to the anatomical cavities. Wagenfuhr (2000) reported mean vessels diameter for beech (*Fagus sylvatica* L.) as 45 µm; Hass *et al*. (2010) found average vessel diameters of 55.3 µm, while Sass and Eckstein (1995) (by calculation from data presented) measured 56.4 µm. Figure 9 indeed display beech anatomical features below the lower threshold. Upon comparing the profile from planing with those from sanding, it can be observed that the former provided more detailed anatomical features than sanding. Some authors reported that "sanding reduces the number of open cell capillaries" (de Meijer 2004). Magross (2015) also observed that sanding caused a clogging effect on the surface and decreased the number and size of wood anatomical cavities of beech. Figure 10 shows a profile taken from a former set of data of beech wood sanded with an extremely fine grit size, P1000, in order to minimize the effect of sanding marks and enhance the presence of wood anatomical irregularities (Gurau 2004). A surface sanded with such fine grit size should display wood anatomical cavities below the lower threshold. However, a reduced density of anatomical valleys in comparison with the profile in Fig. 9 can be observed, which confirmed that sanding operation tends to obscure the wood anatomical cavities of beech in comparison with planing. When comparing anatomical depths in Figs. 9 and 10 with valleys in Figs. 3 to 8, it can be seen that sanding with P60 created some cavities deeper than the mean pore diameter or even deeper than the maximum pore diameter. Those features, most probably, were caused by grits higher in magnitude than the mean sized grits from FEPA 43-1 (2006), and were extending below the lower threshold and even beyond the anatomical cavities. Similar observations were made by Laina *et al*. (2017) regarding the sanding with P60 grit size. This is not surprising, since there is a range of values for grit particles that characterizes every grit size, where mean values have the highest occurrence in characterizing the core roughness.

The grit size is defined as the nominal size of abrasive particles that corresponds to the number of openings per linear inch in a screen through which the particles can just pass (Lee 1989). FEPA 43-1 (2006) defines the nominal diameter of the abrasive particles corresponding to a specified grit size as a range, whereby a middle value is usually taken as a reference. It is assumed that the mean grit diameter influences the core roughness or processing roughness, measured by R_k. Other scratches caused by isolated grits higher in magnitude than the mean, would influence parameters such as R_v, which measures the deepest feature on a surface and this can be true as long as wood anatomical cavities do not obscure the sanding depths by a higher magnitude.

The next question is: how deep can a grit particle penetrate the surface? According to Chung *et al*. (2011), the abrasive grit penetration (surface roughness) depends on the grit diameter, the number of grits per unit area, the nominal pressure per particle, and the modulus of elasticity of the sanded material. A simplified approach comes from Nastase (1981), who considered that the grit depth of penetration in wood varies directly proportional with the diameter of the grit and inversely with the specimen density. A relationship is given by Eq.1 as shown below, where it is considered that the penetration is higher for a new belt than for a worn belt,

$$H = (110 \pm 20)\frac{d}{\rho} \tag{1}$$

where H is the height of the grit penetration (μm), d represents the abrasive grit diameter (μm), ρ is the wood specimen density (kg/m^3), while (+) stands for a new belt and (-) for the case when the belt is worn.

This formula (Eq. 1) was used to calculate theoretical scratch depths for both HT and UT wood and the data are presented in Table 4.

Table 4. Estimated Values of Grit Penetration in Wood as Function of the Mean Grit Diameter, Material Density, Belt Processing Stage (New *vs.* Worn) in Comparison with Roughness Parameters R_k, R_v, and Pores Diameter

Wood Treatment		UT			HT		
Grit size		P60	P100	P150	P60	P100	P150
Mean grit diameter (μm) FEPA 43-1 (2006)		269	162	100	269	162	100
	Grit penetration-new belt (μm)	48.0	28.9	17.9	56.7	34.1	21.1
	Grit penetration-worn belt (μm)	33.3	20.0	12.4	39.2	23.6	14.6
	Mean value grit penetration (μm)	40.7	24.5	15.1	48.0	28.9	17.8
R_k (μm)- Mean values		37.8	27.8	17.7	40.0	29.5	19.2
R_v (μm)- Mean values		74.2	51.8	39.8	82.0	55.4	44.4
R_v (μm)- Max. values		110.8	75.6	54.4	118.3	70.4	57.9
Mean pore diameter (μm)		45 (Wagenfuhr 2000); 55.3 (Hass *et al*. 2010)					
Max. pore diameter (μm)- Wagenfuhr (2000)		85					

A mean value, from new and worn belt scenarios, of the grit depth of penetration was calculated. It is interesting to note that the calculated mean depth of penetrations were relatively close to the processing roughness parameter, R_k (Table 4). The correlation between R_k with the mean grit penetration depth was linear, with an R^2 value of 0.965 when the data from UT and HT beech were combined.

For grit size P60, the deepest valleys seemed to have been caused by isolated grits with diameters higher than the standard mean, and for P100 and P150, the highest sanding marks seem to overlap with beech wood anatomical cavities. If judged by maximum R_v values (Table 4), for both UT and HT wood, and considering the fact that stylus may not be able to measure the wood pores to their maximum real depth (Gurau *et al*. 2017), the deepest features in surfaces sanded with P100 may belong to sanding marks. However, it was hard to decide in case of P150 whether deepest features belonged to the sanding marks or to the anatomy. Maybe the answer comes from the parameter R_{sk}, which suddenly increased in negative value from P100 to P150. This cannot be explained by a phenomenon attributed to sanding, but rather to wood anatomical cavities, which increased the occurrence of features in the valleys domain and increased the data skewness. The trend to a more skewed surface is indicated by the R_{pk}/R_{vk} ratio, which decreased sharply from P100 to P150. Also, the ratio R_a/R_v decreased with finer grit sizes (Table 3). This is logical, as R_v is dependent on anatomical features such as the presence of vessels. The diameters of these features are not affected by sanding, so therefore fine finishing reduces R_a but much less so for R_v. The value of R_v can be reduced due to fine dust partially filling the vessel lumina. A similar observation was made by Gurau *et al*. (2015).

The next target was to evaluate how the roughness parameters correlate to the mean grit diameter. A good correlation means a strong influence of grit size on the surface quality evaluated by roughness parameters. A weak correlation would indicate that surface roughness is biased by other type of features on the surface apart from marks from sanding, for example, wood anatomical cavities or maybe accidental processing gaps in the surface.

Table 5 contains the coefficients of determination, R^2, of roughness and waviness parameters with the grit mean diameter for treated (HT) and untreated (UT) beech manufactured by sanding with three different grit sizes.

Table 5. Coefficients of Determination, R^2, of Roughness and Waviness Parameters with the Grit Mean Diameter for Treated (HT) and Untreated (UT) Beech Surfaces Sanded with Three Different Grit Sizes

R_a	R_q	R_v	R_t	R_{Sm}	R_{Sk}	R_k	R_{pk}	R_{vk}	$R_k+R_{pk}+R_{vk}$	W_a	W_t
UT											
0.986	0.990	0.999	0.989	0.990	0.064	0.976	0.986	0.999	0.991	0.977	0.992
HT											
0.990	0.995	0.993	0.998	0.991	0.361	0.979	0.998	0.998	0.995	0.986	0.995

Table 5 shows that, with the exception of R_{sk}, all roughness and waviness parameters had a very high linear correlation with the mean grit diameters, for both HT and UT wood. Also, it can be observed that slightly better correlations occurred for HT wood compared to UT wood. This result may be due to the fact that, by heat treatment, the wood anatomical cavities tend to be attenuated/obscured by a phenomenon of cell collapse and surface texture changes that often resemble melting, which increased with heat treatment duration (Boonstra *et al*. 2006; Bakar *et al*. 2013; Salca and Hiziroglu 2014;

Gurau *et al*. 2017). As wood anatomical cavities are a factor of bias for roughness parameters, a slight reduction in data density for these irregularities may explain the slightly better correlation of roughness parameters with the mean grit diameters in the course of sanding of HT wood.

Further work may focus on the influence of different temperatures and heat treatment durations on the surface quality of beech after sanding in order to have a broader view about wood behaviour.

CONCLUSIONS

1. The surface roughness of beech wood was increased by heat treatment of beech by the ThermoWood method at 200 °C for 2.5 h followed by sanding with various grit sizes that are typically used to prepare surfaces for finishing, *i.e.*, P60, P100, and P150. This was likely to be linked to a different mechanical response of heat-treated (HT) wood during the sanding operation.
2. Lower waviness was observed on HT beech wood surfaces in comparison with untreated (UT) beech wood.
3. All roughness and waviness parameters had a strong linear correlation with the mean grit diameters for both UT and HT wood.
4. The R_k values closely approximated the calculated mean grit penetration depth for all grit sizes applied to HT and UT beech wood.
5. The influence of wood anatomy in the valley domain increased as the grit size became finer. Sanding with P150 grit size increased the surface skewness in comparison with P100 and P60 for UT and HT wood.

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