Surface Quality of Planed Beech Wood (*Fagus sylvatica* L.) Thermally Treated for Different Durations of Time

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Thermally treating wood improves its dimensional stability and durability. The chemical changes brought about by a heat treatment also affect the mechanical properties of wood. Consequently, a heat treatment also influences how a wood surface responds to machining. This study examined the impact of heat treatments at 200 °C between 1 h and 6 h on the subsequent surface quality of planed beech wood (*Fagus sylvatica* L.). The new approach was that surface quality was assessed by following a tested method from previous research regarding the measuring and evaluation recommendations meant to reduce the biasing effect of wood anatomy, Also, a large number of roughness parameters were used for interpretation of the combined effect of processing and wood anatomy after filtering the data with a robust filter. Among those, R_k is the parameter that is least biased by wood anatomy and that best expresses the effect of processing alone. Electron micrographs were taken to visually assess the resultant surfaces. The results showed a gradual increase in processing roughness, as distinctively measured by R_k, which increased with longer durations of the treatment. Vessel cavities were deeper than those caused by processing and that influenced, among other parameters, R_a, which is most commonly used in literature to assess surface quality. The ray tissue, especially, exhibited both greater pull-out of fibers and a sort of plasticization with increased treatment time. The length of the thermal treatment reduced surface waviness. The results also showed that it was necessary to calculate the roughness parameters to differentiate between two similar surfaces rather than relying on visual and tactile assessments alone.

Keywords: Surface quality; Surface roughness; Thermally treated wood; Treatment duration; Roughness parameters; Microscopic images

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INTRODUCTION

Thermal treatment improves the dimensional stability and bio-resistance of wood (Pelaez-Samaniego *et al*. 2013). Research on this topic has attempted to understand the overall effect of the treatment on wood characteristics and behavior. For example, a typical heat treatment has been applied at temperatures and durations ranging from 120 °C to 250 °C and from 15 min to 24 h, depending on the process, species, sample size, moisture content, and the desired target utilization (Korkut and Guller 2008; Salca and Hiziroglu 2014).

Researchers have examined various aspects of thermally treated wood, such as dimensional stability (Tjeerdsma *et al*. 1998; Esteves *et al*. 2008), durability (Militz 2002; Welzbacher and Rapp 2002), mechanical properties (Boonstra *et al*. 2007; Esteves *et al*. 2007), equilibrium moisture content (Bekhta and Niemz 2003; Esteves *et al*. 2007), mass loss (Zaman *et al.* 2000; Esteves *et al.* 2007), wettability (Hakkou *et al.* 2003; Kocaefe *et al*. 2008), color change (Militz 2002; Bekhta and Niemz 2003), and chemical modifications (Alén *et al.* 2002; Tjeerdsma and Miliz 2005). It is known that the physical, mechanical, and chemical properties of wood under a heat treatment begin to change at temperatures near 150 °C and they continue to change with increasing temperature (Yildiz *et al.* 2006; Korkut *et al.* 2008; Salca and Hiziroglu 2014). It has been observed that high temperatures reduce the mechanical strength of wood (Bekhta and Niemz 2003; Yildiz *et al.* 2006; Kocaefe *et al*. 2008; Mburu *et al*. 2008). As a consequence, according to de Moura Palermo *et al.* (2014), it was expected that the changes in mechanical properties might also have an effect on the machining properties and surface quality of machined wood.

Some studies have examined the surface quality of thermally treated machined wood (de Moura and Brito 2008; Budakçı *et al*. 2011; Tu *et al.* 2014, Pinkowski *et al*. 2016). Such research is necessary to see and understand how a thermal treatment might affect subsequent manufacturing processes. It has been observed that thermally treated wood tends to be more brittle and, perhaps as a consequence, generates more dust in comparison with untreated wood. The ThermoWood Handbook (2003) recommends the use of properly sharpened tools and tipped cutters that are used when working a hard material.

Budakçı *et al.* (2011) found that the surface roughness (R_a) of heat-treated Eastern beech (*Fagus orientalis* L.) and three other wood species increased with the severity of a heat treatment when machined with circular saws. In a later and similar study, Budakçı *et al*. (2013) determined the roughness perpendicular to the grain of Eastern beech wood (*Fagus orientalis* L.) that had been heat-treated at 140 °C and 160 °C for 3 h, 5 h, and 7 h and then milled. The roughness values (R_a), as measured by a stylus with a 5-μm tip radius, increased with the increasing duration of the heat-treatment. In contrast, Kvietkova *et al.* (2015) found no significant difference in the roughness (R_a), as measured along the feed direction by a stylus method, of planed beech wood (*Fagus sylvatica* L.) than that which been heat treated compared with the controls.

Tu *et al*. (2014) examined the surfaces of *Eucalyptus urophylla* × *E. camaldulensis* after they had been heat treated and processed either by planing, sanding, boring, mortising, milling, or turning. The surface quality was assessed by visual and tactile examination, with the exception of sanding, whose quality was assessed by R_a values obtained across the grain. The processed surface examined by human senses indicated a better quality after the thermal treatment for planing, boring, and milling. However, a heat treatment worsened the surface quality when mortising or turning, as these operations caused a severely torn and crushed grain. The R_a values observed after sanding were similar for a range of heat temperature treatments, but slightly smaller than for untreated wood.

In contrast to the research mentioned in the previous paragraphs, the planing operation preceded the thermal treatment for much of the research on the surface quality of heat-treated wood. In such studies, it appears that the surface roughness decreased with the temperature and duration of treatment. It was the case of Turkish river red gum wood-*Eucalyptus camaldulensis*, measured by R_a at 120 °C to 180 °C, for durations of 2 h to 10 h (Unsal and Ayrilmis 2005); red-but maple (*Acer trautvetteri* Medw.), measured using R_a and R_z for heat treatments at 120 °C, 150 °C, and 180 °C for 2 h, 6 h, and 10 h (Korkut and Guller 2008); Turkish hazel (*Corylus colurna* L.) (Korkut *et al.* 2008); and European Hophornbeam (*Ostrya carpinifolia* Scop.) (Korkut *et al.* 2009). Other studies with similar results were made on Rowan wood (*Sorbus aucuparia* L.) measured by R_a, R_z, and R_q for heat treatments at 120 °C, 150 °C, and 180 °C for 2h, 6 h, and 10 h (Korkut and Budakçı 2010); Oriental-beech (*Fagus orientalis*) measured by R_a, R_z, and R_q at 140 °C, 170 °C, and

200 °C for 2 h, 4 h, and 8 h (Baysal *et al*. 2014); alder (*Alnus glutinosa* L., Gaertn. ssp. *glutinosa*); and wych elm (*Ulmus glabra* Huds.) measured by R_a and R_z, perpendicular to the grain, at 180 °C and 200 °C for 2 h and 4 h (Aytin and Korkut 2016).

The modifications that wood undergoes during a heat treatment are likely to affect wood-tool interactions and, consequently, the surface roughness. In addition, commercial processes tend to heat treat and then machine the wood. Following this sequence, Skaljić *et al.* (2009) planed previously thermally treated beech (212 °C, duration unspecified) at 6 m/min, 12 m/min, 18 m/min, and 24 m/min feed speeds. None showed any significant differences in the surface quality, as measured by R_a along the feed direction, between thermally modified and control steamed beech wood specimens. Pinkowsky *et al*. (2016) researched plane milling of Scots pine (*Pinus sylvestris*) at 1 and 5 m/min, after previously thermally treating wood for 4 h at 190 and 220 °C. They found that the surface roughness measured by R_a, R_z, and R_t decreased with an increased modification temperature, In contrast, de Moura Palermo *et al*. (2014) examined the quality of *Eucalyptus grandis* thermally treated at 190 °C for 6.5 h and then planed at 15 m/min feed speed. They found that the R_a, as measured along and perpendicular to the grain, of thermally treated wood was slightly higher as compared with the control.

Gaff *et al.* (2015) studied the effect of plane milling on the arithmetic mean deviation of the waviness profile (W_a) for birch thermally treated for 5 h at temperatures of 160, 180, 210 and 240°C. The thermal treatment had no significant influence on the waviness parameter measured along the feed direction (along the grain).

As seen above, the various studies in the literature indicate a variety of results for the surface roughness of thermally treated wood (Pinkowski *et al.* 2016) and various approaches (processing happening either before or after the thermal treatment). Furthermore, an aspect that has not been considered in the literature was that a processed wood surface contains not only marks caused by its interaction with a tool, but also the inherent cavities caused by the cellular structure of wood. In other words, wood anatomy, and therefore species, influence the surface roughness parameters (Sinn *et al*. 2009). As a consequence, the interpretation of roughness parameters has to consider the presence of wood anatomical irregularities in combination with those given by the processing. It has been clearly demonstrated that wood anatomy can have a biasing effect on measuring and evaluating the surface roughness data (Gurau *et al.* 2005; Piratelli-Filho *et al*. 2012; Tan *et al.* 2012). Consequently, wood surfaces require a specific metrological approach for their evaluation.

A procedure for measuring and evaluating the surface roughness of a wood surface has been proposed in detail by Gurau *et al*. (2012) with the aim of reducing the bias from wood anatomy. The procedure includes recommendations regarding the selection of a measuring instrument (preferably a stylus), the measuring length (longer than 40 mm), the measuring resolution (5 μm or better), and data processing. The recommendations on data processing start with the removal of form errors and the use of a filter that is capable of extracting the surface roughness out of the longer wavelength irregularities without creating the bias of the Gaussian filter found in most common software attached to a measuring instrument. The Robust Gaussian Regression Filter (RGRF), proposed by ISO 16610-31 (2010), has been found to be appropriate for wood because is it more robust than the simple Gaussian filter and does not introduce the bias caused by groups of pores (Fujiwara *et al*. 2004; Gurau 2004; Piratelli-Filho *et al*. 2012; Tan *et al.* 2012).

Despite this, none of the previously published studies on the surface roughness of thermally treated wood have used a robust filter. In addition, the measuring length was often limited to 12.5 mm, which was considered too short for wood surfaces because of the material variations that are naturally present, *e.g*. the transition between earlywood and latewood. Gurau *et al.* (2012) recommends measuring lengths of over 40 mm. According to the research of Goli and Sandak (2016), the minimum number of annual rings should be at least four for the surface obtained to be representative of both early and late wood. They used an effective measurement length of 102 mm.

Many studies limit the description of surface roughness to R_a or sometimes R_q and R_z. These parameters alone do not accurately describe the surface (Sinn *et al*. 2009). When the anatomy is not removed, the Abbot curve parameters (R_k, R_{pk}, and R_{vk}) from ISO 13565-2 (1996) are more informative (Westkämper and Riegel 1993; Gurau *et al*. 2007). Furthermore, ISO 4287 (1997) contains the roughness parameters R_v, R_t, R_{Sm}, R_{sk}, and R_{ku}, which can be used for a broader understanding of surface characteristics.

The quality of wood surfaces processed by planing is characterized, on the one hand, by the surface roughness resulting from the interaction between the tool and the wood surface, but also by larger wavelength components (waviness) that result from the combined motions of the workpiece and tool. Parameter descriptors from ISO 4287 (1997), such as P_a, P_t, and P_{Sm} can be used for complementing the analysis of larger wavelength components.

The novely that this paper brings is the new approach, described above, in analyzing the surface quality of beech that was thermally treated at 200 °C for different durations (1 h to 6 h) and subsequently processed by planing. A robust filter and original recommendations from previous research regarding the measuring and evaluation of surface quality are used (Gurau *et al.* 2012). They are meant to reduce the biasing effect of wood anatomy on measuring, evaluating and interpretation of surface roughness of thermally treated wood processed by planing. In comparison with previous studies of literature, a larger number of parameters are discussed and explained in combination with microscopic environmental scanning electron microscopy (ESEM) images to help readers obtain an appreciation of what a surface may look like at given roughness parameter values.

EXPERIMENTAL

Materials

Beech wood (*Fagus sylvatica*) samples of 400 mm x 50 mm x 25 mm were heat-treated in an electric oven without air circulation, at atmospheric pressure, at 200 °C for 1 h, 2 h, 3 h, 4 h, 5 h, and 6 h. The heat-treatment schedule is presented in Table 1. Control samples with the same dimensions were kept untreated.

Table 1. Heat-Treatment Schedule in Air at Atmospheric Pressure for 25-mm Beech Strips

Phase	Heat treatment in air at atmospheric pressure
Pre-heating and oven-drying of wood	103 °C / 48 h
Heating	103 °C...150 °C / 6.5 h 150 °C…200 °C / 0.5 h
Actual heat treatment	**200 °C constant / 1h-2h-3h-4h-5h-6h**
Cooling	200 °C...30 °C / 15 h
Total process duration	**71...76 h**

Methods

The heat-treated and untreated samples were conditioned for four weeks at 20 °C and 55% relative humidity, and then 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. The cylindrical cutter head had helical cutters with Tungsten carbide inserts.

For each treating duration, three machined samples were selected at random for surface quality analysis. The faces of these samples had a mix of tangential, radial, semi-radial, or semi-tangential surfaces as is common in production process, although ideally there would have been only one surface type to reduce some of the variability due to wood anatomy (Budakçı *et al.* 2011).

The surface quality was measured with a stylus MarSurf XT20 instrument manufactured by MAHR Göttingen GMBH (Göttingen, Germany), with a MFW 250 scanning head and a tracing arm in the range of ± 500 µm. The stylus had a 2-µm tip radius and a 90° tip angle. The surface profiles were measured at a speed of 0.5 mm/s and a low scanning force of 0.7 mN. Six roughness profiles were obtained for each specimen: three 42 mm long profiles were scanned across the grain (across the feed direction), and three profiles 100 mm long along the grain, at a lateral resolution of 5 µm, so that for each treatment and scanning direction nine profiles were analyzed.

The instrument had MARWIN XR20 software (MAHR, Göttingen, Germany) installed for processing the measured data. First, the software removed the form error, which characterizes the accuracy with which the specimen has been machined. The standard method of removing form errors for individual profiles is contained in ISO 3274: 1996 and consists of fitting a polynomial regression through the original data (total profile). A primary profile can be obtained by subtracting the regression from the total profile (Fig. 1). At this stage, some roughness parameters described later (P_a, P_t, and P_{Sm}) were calculated from the primary profile (containing both the roughness and waviness). Further, in order to get the roughness profile, the waviness was removed by filtering each profile using a Robust Gaussian Regression Filter, RGRF, as described in ISO 16610-31 (2010). The cut-off length used was 2.5 mm as recommended in previous research by Gurau *et al.* (2006).

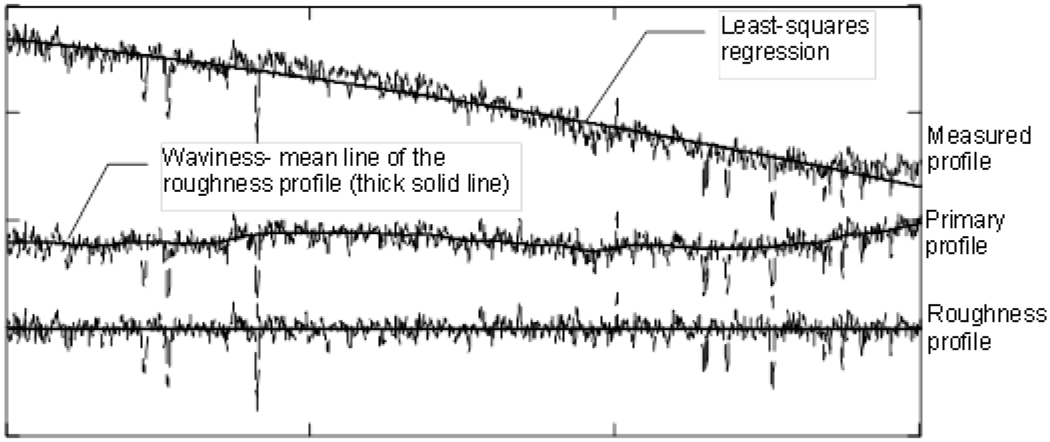


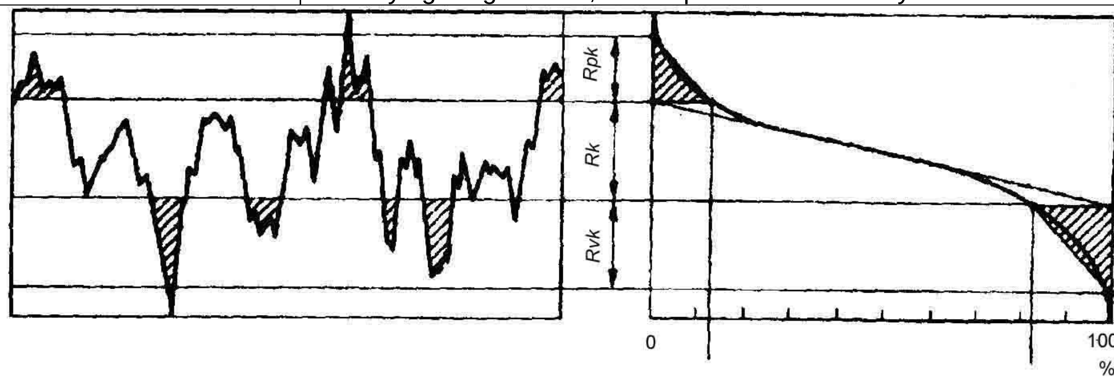
Fig. 1. Schematic filtering of profile irregularities

The roughness parameters calculated from the roughness profiles were: R_a, R_q, R_v, R_t, R_{Sm}, R_{sk}, and R_{ku}. In addition, the parameters P_a, P_t, and P_{Sm} from ISO 4287 (1997) were calculated from the primary profiles, and R_k, R_{pk}, and R_{vk} from ISO 13565-2 (1996) were calculated from the roughness profiles. A detailed explanation of the roughness parameters used in this research is given in Table 2. The parameters are calculated on individual measured profiles represented by a vector of length n of ordinate values Z_i.

Table 2. Explanation of Roughness Parameters Used in This Research

$Ra = \frac{1}{n}\sum_{i=1}^{n}\lvert Z_i\rvert$	The arithmetical mean deviation of the assessed profile is one of the most commonly used parameters. It was expected that this parameter would be influenced by wood anatomy if wood irregularities were kept in the evaluation (in μm).
$Rq = \sqrt{\frac{1}{n}\sum_{i=1}^{n} Z_i^2}$	The root mean square deviation of the profile is also a mean parameter, which can be biased by the presence of wood anatomy in the evaluation (in μm).
$Rt = \lvert \max Zp\rvert + \lvert \max Zv\rvert$	The total height of the profile is calculated as the sum of the maximum profile peak height (R_p=|maxZ_p|) and the largest absolute value profile valley depth (R_v=|maxZ_v|). It was expected to be sensitive to variations in local wood anatomy (in μm).
$Rsk = \frac{1}{Rq^3}\left[\frac{1}{n}\sum_{i=1}^{n} Z_i^3\right]$	The skewness of the profile is a measure of the asymmetry of the amplitude density function, and is a non-dimensional parameter. It is strongly influenced by the presence of isolated peaks or valleys. Surfaces with a positive skewness, $R_{sk} > 0$, have fairly high peaks that protrude above a smooth plateau, whereas surfaces with a negative skewness have fairly deep valleys below a smooth plateau. Skewness is particularly relevant when the wood anatomy is greater in magnitude than the processing (non dimensional)
$Rku = \frac{1}{Rq^4}\left[\frac{1}{n}\sum_{i=1}^{n} Z_i^4\right]$	The kurtosis, is a dimensionless parameter that is strongly influenced by isolated peaks or valleys. Profiles from wood surfaces, especially sanded and planed ones, tend to have R_{ku} values greater than 3 due to the presence of isolated and deep valleys caused by the anatomy (non dimensional).
$RSm = \frac{1}{m}\sum_{i=1}^{m} Xs_i$	The mean width of the profile elements is a parameter that measures the mean width of surface irregularities (X_{si}). It can be influenced by wood anatomy if cut cell lumens are larger than the width of the processing irregularities (in μm).

R_k	The core roughness depth is the depth of the core profile excluding the height of the protruding peaks and deep valleys (in μm). It is the least influenced by wood anatomy. This parameter should best indicate the roughness caused by planing.
R_{pk}	The reduced peak height is the average height of the protruding peaks above the roughness core profile (in μm). It is sensitive to outlying irregularities, as fuzziness
R_{vk}	The reduced valley depth is the average depth of the valleys projecting through the roughness core profile (in μm). It is sensitive to outlying irregularities, as deep anatomical valleys.



Calculation of R_k, R_{pk}, and R_{vk} according to ISO 13565-2 (1996)

Planing operations can generate regular waves on the surface. These waves are considered as long wavelength irregularities. The *P* parameters P_a, P_t, and P_{Sm} are similar to their *R* counterparts, but are calculated from the primary rather than the roughness profiles (in μm). They should be sensitive to any variation in waviness.

For each heat treatment duration and each roughness parameter, a mean value and the standard deviation were calculated without previously removing wood anatomy from the profiles. However, to have a visual effect on the separation between the core roughness, as the highest concentration of data points and the outlying fuzziness and wood anatomical valleys, individual roughness profiles taken across the grain (feed direction) were processed with a method proposed and described in detail by Gurau *et al*. (2007). Their method separated the core roughness by an upper and a lower threshold. The core roughness that was delimited by thresholds should be sensitive to variations caused by the heat treatment.

An ANOVA analysis and Duncan's multiple range tests were performed to test significant differences between controls and heat-treated samples for various treatment durations.

Microscopic images were taken with a Quanta 250 environmental scanning electronic microscope (ESEM) 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 30°.

RESULTS AND DISCUSSION

Surface Quality– Roughness Parameters

Figures 2, 3, and 4 show typical roughness profiles taken across the grain (perpendicular to the feed direction) for the untreated beech and the beech heat-treated for

4 h and 6 h, respectively. The distance between the horizontal solid lines, which demarked the processing roughness, increased with heat treatment time, which indicated an increase in processing roughness.

The mean values and their standard deviations for the primary profile parameters and roughness parameters measured across the grain are included in Table 3, as well as the results from the statistical analysis using Duncan's multiple range test.

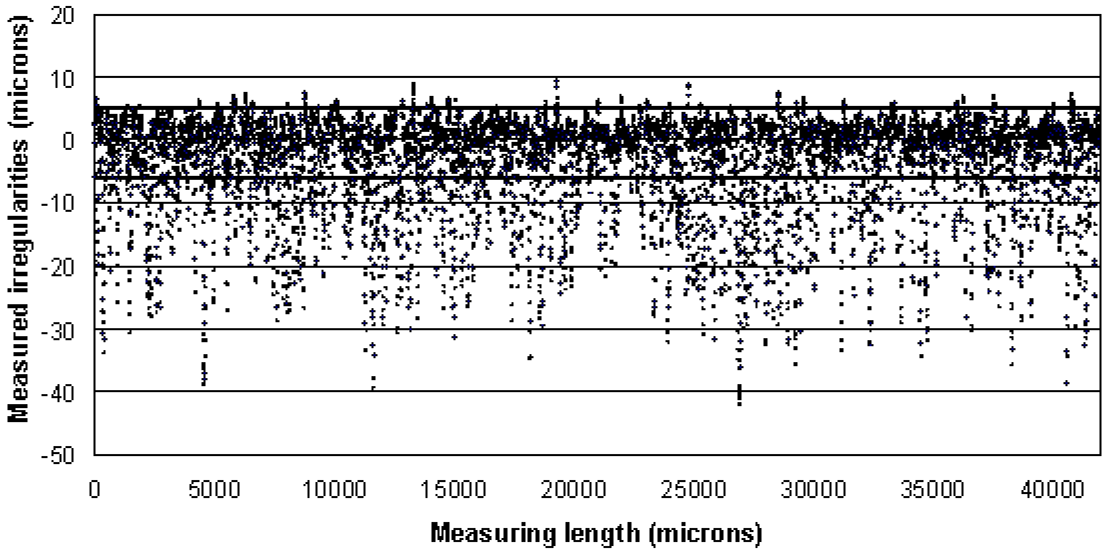


Fig. 2. The roughness profile (as measured points) of untreated beech processed by planning, showing the core roughness (the concentration of data points) delimited by thresholds (thick solid lines) (measurement was made across the grain)

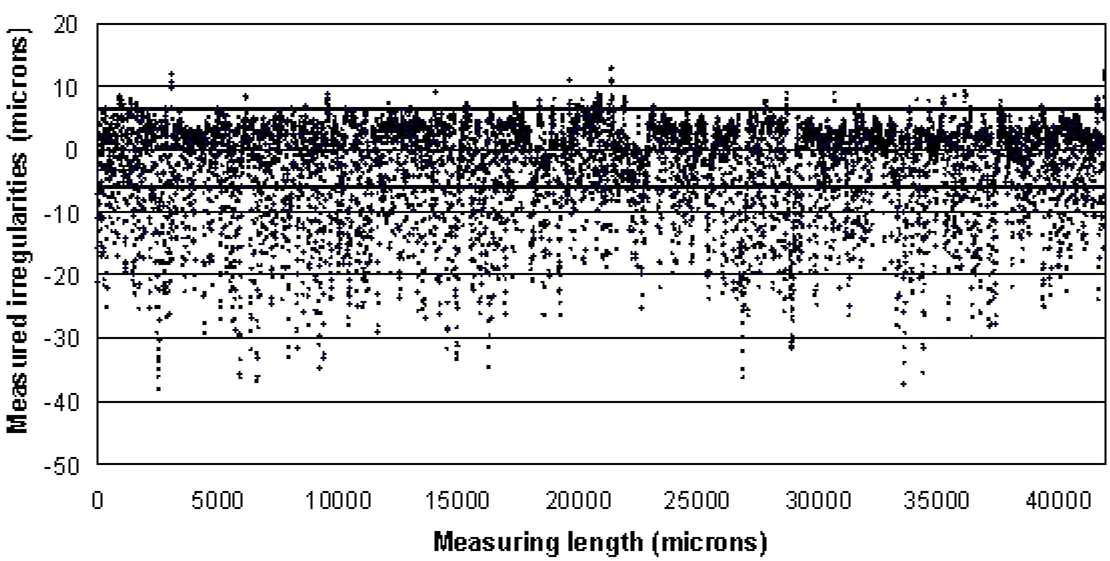


Fig. 3. The roughness profile (as measured points) of beech wood, heat-treated for 4 h at 200 °C and then planed, showing the core roughness (the concentration of data points) delimited by thresholds (thick solid lines) (measurement was made across the grain)

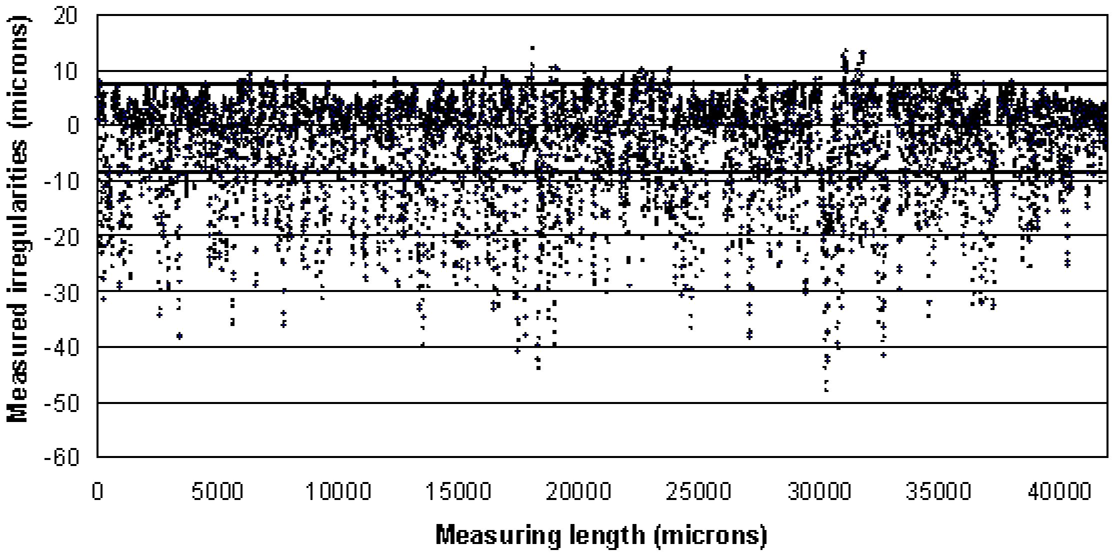


Fig. 4. The roughness profile (as measured points) of beech wood, heat-treated for 6 h at 200 °C, and then planed, showing the core roughness (the concentration of data points) delimited by thresholds (thick solid lines) (measurement was made across the grain)

Similar observations were made for profiles taken along the grain. The core roughness seemed to increase as the heat treatment duration increased and was clearly higher for the heat-treated wood compared with the untreated wood (Table 4).

Table 3 shows that the skewness, R_{sk}, was negative for all profiles tested, while the kurtosis, R_{ku}, was much higher than 3. The combination of these two parameters indicated that the presence of valleys in the profile that extended below the core roughness were more common than the peaks that protruded above the core roughness. A high occurrence of valleys below the lower threshold in Figs. 2, 3, and 4 was due to beech anatomy, *i.e.* vessels, which were much deeper than the roughness caused by the planing. Anatomical studies of beech have found average vessel diameters of 55.3 µm (Hass *et al.* 2010) and 56.4 µm (by calculation from data presented) (Sass and Eckstein 1995). The deep valleys shown in Figs. 2, 3, and 4 were shallower than the typical diameters of beech vessels (the R_v values) because the stylus was unable to enter the cavity and touch the other side unless a large part of the vessel had been removed by machining.

Table 3. The Roughness and Primary Profile Parameters Measured Across the Grain for Treated and Untreated Beech Processed by Planing (Mean Values in Microns and Standard Deviations); Statistical Analysis Used Duncan's Multiple Range Test ($p < 0.05$)

	R_a	R_q	R_v	R_t	R_{sk}	R_{ku}	R_k	R_{pk}	R_{vk}	R_{Sm}	P_a	P_t	P_{Sm}
Control	**5.7^{A}**	**8.9**	**45.1**	**55.1**	**-2.2^{A}**	**6.1^{A}**	**9.2^{A}**	**2.2**	**18.3**	**329.2**	**10.8^{A}**	**83.7**	**729.9^{A}**
stdev	0.54	0.77	6.22	6.82	0.06	0.44	0.63	0.25	1.31	30.8	2.62	18.62	283.38
1 h	**5.8^{A}**	**9.0**	**42.2**	**56.2**	**-2.1^{A}**	**5.8^{AB}**	**9.3^{A}**	**3.3**	**18.0**	**339.5**	**8.7^{B}**	**69.5**	**417.6^{BD}**
stdev	0.37	0.66	4.66	6.95	0.11	0.43	1.23	1.35	1.89	90.2	0.69	8.03	77.88
2 h	**5.9^{AB}**	**9.3**	**50.6**	**60.2**	**-2.2^{A}**	**6.2^{A}**	**9.5^{A}**	**2.5**	**18.4**	**333**	**8.5^{B}**	**67.9**	**367.1^{BCD}**
stdev	0.73	1.19	10.5	9.99	0.16	0.81	1.86	0.38	2.58	104.2	0.94	24.36	48.95
3 h	**6.0^{AB}**	**8.8**	**42.3**	**56.6**	**-2.0^{B}**	**5.4^{BC}**	**10.6^{AB}**	**2.7**	**16.6**	**238.5**	**8.4^{B}**	**71.6**	**285.9^{C}**
stdev	0.85	0.99	3.61	4.19	0.13	0.60	1.73	0.60	1.47	45.6	0.30	5.44	54.98
4 h	**5.6^{A}**	**8.0**	**38.6**	**51.0**	**-1.9^{B}**	**5.1^{C}**	**10.6^{AB}**	**2.2**	**14.6**	**209.1**	**7.7^{B}**	**60.8**	**284.3^{C}**
stdev	0.28	0.18	4.46	6.32	0.13	0.25	1.68	0.53	0.84	54.6	0.80	6.72	53.92
5 h	**6.0^{AB}**	**8.5**	**44.0**	**56.0**	**-1.9^{B}**	**5.3^{BC}**	**12.3^{B}**	**2.9**	**15.1**	**219**	**7.7^{B}**	**65.2**	**290.6^{C}**
stdev	0.54	0.52	7.96	11.48	0.16	0.47	2.65	0.99	1.03	37.6	0.68	9.86	57.03
6 h	**6.5^{B}**	**9.5**	**44.1**	**57.0**	**-2.0^{B}**	**5.3^{BC}**	**12.3^{B}**	**2.8**	**17.8**	**275.3**	**8.4^{B}**	**68.1**	**327.5^{CD}**
stdev	0.29	0.36	3.01	4.21	0.11	0.38	2.63	0.76	1.42	65.66	0.91	6.09	53.23

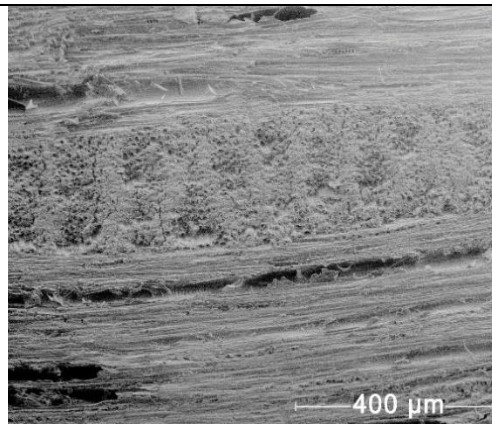
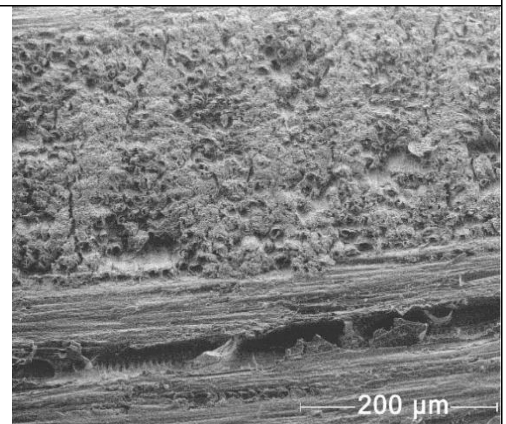
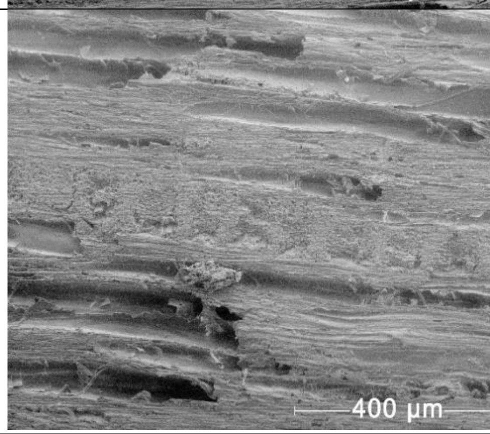
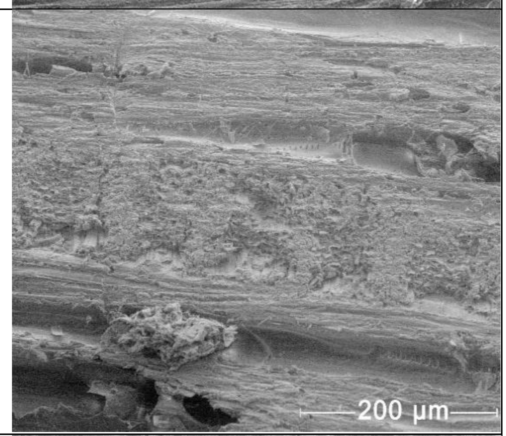
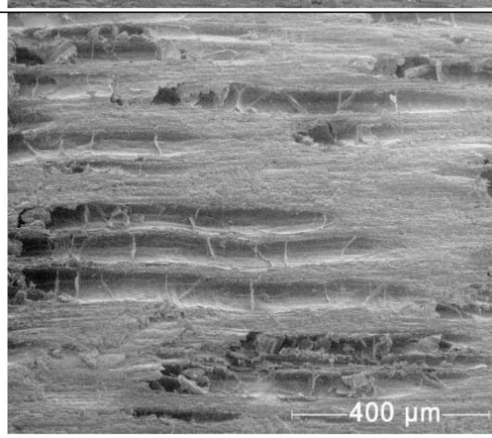
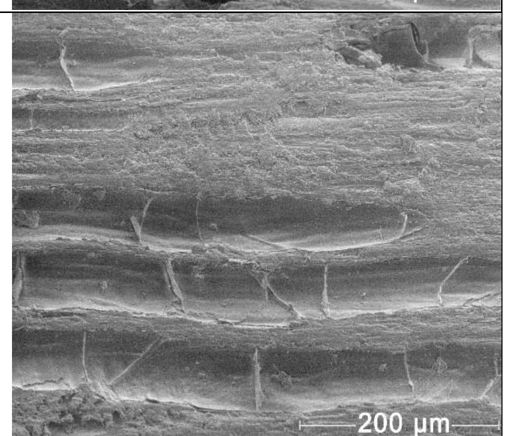
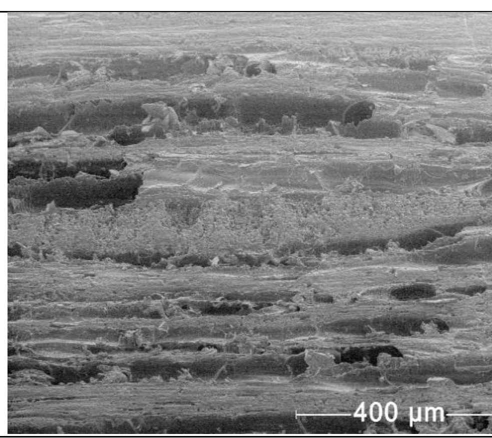
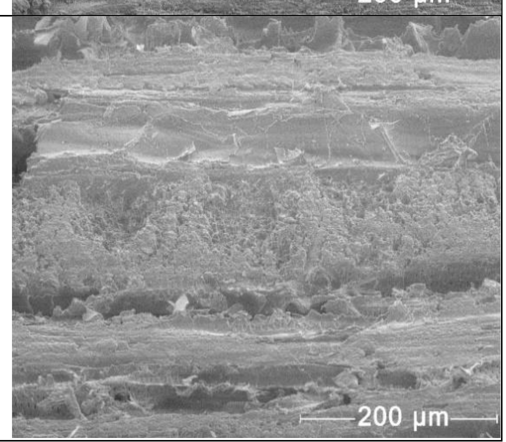
Table 4. The Roughness and Primary Profile Parameters Measured Along the Grain for Treated and Untreated Beech Processed by Planing (Mean Values in Microns and Standard Deviations)

	R_a	R_v	R_t	R_k	R_{pk}	R_{vk}	P_a	P_t	P_{Sm}
Control	**5.5**	**41.6**	**66.8**	**9.5**	**7.8**	**18.1**	**11.8**	**90.4**	**3507.2**
stdev	0.92	4.75	8.55	3.08	1.62	1.63	1.37	14.44	1336.22
1 h	**6.0**	**41.8**	**66.4**	**11.5**	**7.8**	**17.7**	**13.4**	**92.5**	**2781.4**
stdev	0.82	7.14	8.63	1.61	2.41	2.93	1.67	7.02	742.80
2 h	**5.8**	**49.9**	**77.8**	**11.4**	**7.9**	**17.2**	**12.1**	**97.8**	**2893.7**
stdev	0.61	14.81	13.6	2.98	2.11	3.30	1.14	11.57	654.76
3 h	**5.9**	**43.6**	**77.2**	**13.2**	**9.0**	**15.7**	**16.0**	**105.5**	**4154.4**
stdev	0.67	9.93	17.57	2.67	2.12	1.24	4.28	21.50	1597.74
4 h	**5.8**	**41.9**	**69.1**	**13.0**	**8.1**	**14.6**	**14.4**	**87.0**	**3302.1**
stdev	0.55	7.26	11.9	2.06	1.76	0.96	1.88	8.57	1061.99
5 h	**5.8**	**39.7**	**69.3**	**12.6**	**9.8**	**14.8**	**12.2**	**79.4**	**3136.3**
stdev	0.65	7.02	9.51	2.84	1.73	1.80	2.66	16.19	1243.43
6 h	**6.5**	**45.1**	**72.4**	**14.6**	**7.9**	**17.0**	**12.6**	**95.0**	**2305.9**
stdev	0.87	7.47	10.91	4.03	2.48	1.30	0.88	16.99	302.47

In an attempt to help the reader relate the surface features to the data given in the tables, electron micrographs with magnifications of 300x and 600x are provided in Fig. 5. During a careful surface observation, it was noticed that the primary changes seemed to occur in the ray tissue. These changes might have occurred because this tissue was “softer,” in the sense that it was non-structural and more easily altered by the heat treatment followed by processing.

The differences between processing and anatomical roughness were clear in the micrographs, where the processing roughness was seen as fine longitudinal traces and the vessels were large valleys (Fig. 5). In addition to anatomical valleys, there were other valleys caused by the pull-out of the material by the planing knives. These pull-out regions were visible in the soft ray tissue in all of the micrographs and seemed to follow a regular pattern not visible elsewhere. Even though this pull-out occurred in the control and thermally treated samples, the pull-out seemed more extensive in samples that were heated for longer durations.

Table 3 shows that there was little difference in the roughness parameters of untreated beech and that which was heated for 1 h or 2 h; significant differences began to appear after beech was heated for 3 h. The parameter most interesting for assessing the effect of planing following after the thermal modification is R_k, which is also the parameter the least influenced by the presence of wood anatomy (Gurau 2004). The variation in R_k, as measured by the standard deviation values, increased with the heat treatment duration. The gradual increase of R_k reduced the number and size of valleys that hung below the lower R_k threshold, thus reducing the skewness, R_{sk}, and kurtosis, R_{ku}. As a result, the effect of wood anatomy on surface quality decreased with the treatment duration. Because the valleys were caused by vessels, it was logical that R_{vk} also decreased with the heat treatment length.

	300x	600x
CONTROL		
1TT		
2TT		
3TT		

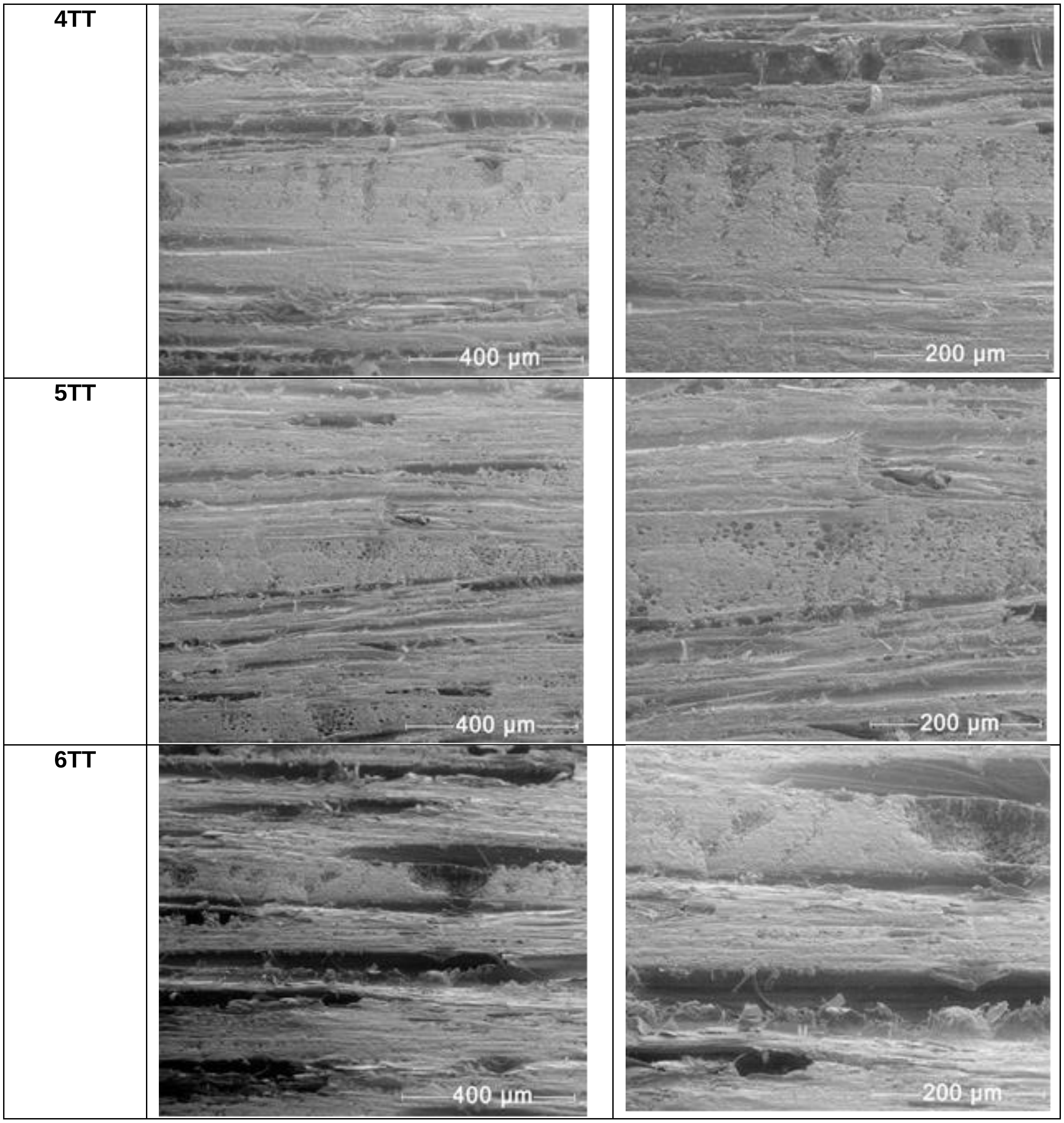


Fig. 5. Microscopic images of beech, untreated and thermally treated with different durations

From the electron micrographs (Fig. 5) it would appear that certain anatomical features became increasingly obscured in samples subjected to long heat treatments. Compare, for example, the ray tissue in the control to the ray tissue shown in samples heat treated for 6 h. It was not clear if the ray cells collapsed under the tool pressure or whether the cutting tool displaced the cut material and pressed it into the surface. A certain level of plasticization of the cell wall was reported also by Salca and Hiziroglu (2014) after thermally treating black alder (*Alnus glutinosa* L.), red oak (*Quercus falcata* Michx.), Southern pine (*Pinus taeda* L.), and yellow poplar (*Liriodendron tulipifera* L.) for 3 h to 6 h at 190 °C. This masking of anatomical features did not result in a smoother surface.

R_a and R_q generally increased slightly for heat treated wood in comparison with untreated wood, but they fluctuated as wood anatomy can be a factor of bias. The maximum heights of the profiles, R_t, did not show any trends in relation to the length of heat treatment. This absence might have been expected, as R_t is a sum of the highest peak (R_p) and the deepest valley (R_v), and the latter was determined by anatomy unless the material pull-out was greater than the vessels. This was not shown in the micrographs or in the values of R_v (Table 3). The R_{pk}, as a measure of surface fuzziness, only slightly increased for the thermo-treated material and showed no clear trend with the treatment duration. The presence of vessels, which were much deeper and wider than the peaks and valleys caused by the knives, would clearly have a marked effect on the R_{Sm} values. This probably explained why the heat treatment did not seem have an influence on this parameter.

Kinematic waviness caused by planing was a combination of tool-piece motions, but also could have been influenced by an individual material's elasticity response. The planer used in these experiments had helical knives, which caused some waviness across the grain. The primary profile parameters P_a and P_{Sm} in Table 3 generally showed a decrease in magnitude with the duration of the heat treatment and were statistically relevant lower for the heat-treated specimens as compared with the untreated beech wood. Lower standard deviation values were observed for the *P* parameters for the heat-treated wood in comparison with the untreated beech. These observations were only valid for measurements across the feed direction, because along the grain (feed direction), there was no specific trend.

Table 4 shows that among the roughness parameters measured along the grain, only R_k showed a specific trend, which increased with the treatment length. Compared with untreated wood, the R_k increased 53% after 6 h of heat treatment. When measuring along the grain, the biasing effect of wood anatomy could have been higher and the measurement influenced by the location of the scanned profile (along a wood pore, outside the area of pores, areas with predominantly latewood or earlywood, *etc*.). Possibly, because of this anatomical variation, for measurements taken along the grain, no conclusion could be drawn that concerned the waviness in the profile. From these results, it appeared that the measuring direction perpendicular to the processing direction was more informative, and the measured parameters were more consistent with the duration of the heat-treatment.

R_k was the only roughness parameter that showed a clear trend with increased heat treatment duration in both scanning directions. R_k gave the clearest estimate of processing roughness, as the protruding peaks and valleys were not included in its calculation. Figure 6 shows that the processing roughness increased systematically with heat treatment time. Because the machining operation was the same for all of the specimens, these differences must have been due to the effects of the heat treatment on the physical and mechanical properties of the wood cell walls.

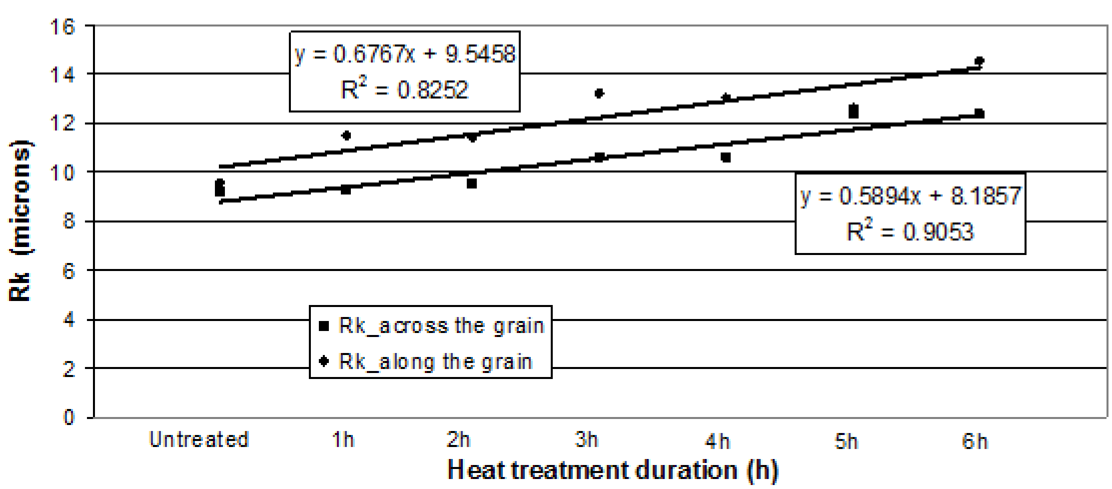


Fig. 6. R_k measured along and across the grain as a function of the treatment duration

These findings indicated that R_k was a useful expression of the processing roughness after planing wood that was heat treated for different treatment durations. At the same time, it was difficult to correlate the increasing R_k values with any changes in the electron-micrographs, except for the greater pull-out of the ray tissue. The valleys created by this pull-out were unlikely to have influenced R_k because they were too deep. This finding demonstrated that it was necessary to calculate the roughness parameters to differentiate between two similar surfaces, as visual and tactile assessments were insufficiently sensitive.

CONCLUSIONS

The main conclusions regarding the surface quality of thermally treated beech wood (*Fagus sylvatica* L.), treated for different durations of time, and processed by planing can be summarized as follows:

1. The processing roughness of heat-treated beech as measured by R_k increased systematically with heat treatment time.
2. The overall roughness as indicated by R_a, R_q, and R_t did not change much. This lack of change was due to the presence of vessels that provided deep valleys in the roughness profiles. R_{pk}, as a measure of surface fuzziness, only slightly increased in thermo-treated material and showed no clear trend with the treatment duration.
3. Profiles obtained across the grain were more sensitive to the duration of the heat treatment than those obtained along the grain.
4. The effect of wood anatomy on the surface quality decreased with the treatment duration. This decrease was indicated by a reduction of the negative skewness, R_{sk}, a decrease in kurtosis, R_{ku}, and in R_{vk} measured across the grain.
5. The visual assessment of micrographs in the control and in thermally treated samples showed a kind of surface plasticization, as well as pull-out regions in the soft ray tissue, which seemed more extensive in samples that were heated for longer durations. However, these pull-out zones seemed shallower than the vessels, as shown by small variations in R_v and R_t.
6. The waviness across the grain, sensed by P_a, P_t, and P_{Sm}, showed a statistically relevant decrease in magnitude for the heat-treated wood as compared with the untreated wood, and decreased with the duration of treatment. This decrease could indicate that the planed material had a different elasticity response.

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