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Testing the Processing-Induced Roughness of Sanded Wood Surfaces Separated from Wood Anatomical Structure

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Abstract: The metrology of processed wood surfaces is complex due to the presence of wood anatomical cavities, which are a factor of bias in several metrological steps, from the measuring to the evaluation of the surface quality. Wood requires special recommendations, and one regards the use of a robust Gaussian regression filter for filtering the roughness. The filter was previously tested with success on wood surfaces and was used in this paper. Furthermore, a reliable quantification of the processing roughness requires that independent wood anatomical data be removed from the evaluation. The paper presents a method of separating the roughness induced by processing from the wood anatomical structure. It was tested on different wood species, sanded with various grit sizes, and on a plastic material included for comparisons. The results showed similar values of the processing roughness for materials sanded with the same grit size, in spite of their different structures. The method could further be used for optimization of processing parameters at sanding.

Keywords: processing roughness; wood anatomical structure; separation; sanding

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1. Introduction

A processed wood surface and evaluation of its surface roughness may be affected by a large number of factors, including wood species (softwood, hardwood) [1–3], types of cells (especially large pores and their arrangement, as well as other cells with thin walls and large lumen) [4–8], differences in local density (for example earlywood–latewood) [3,7,9], type of surface (tangential, radial) [10], direction of processing as related to the grain [11], wood defects (grain deviation, knots, reaction wood–normal wood, others), [3,11,12], moisture content, type of machining (planing, sanding, others) [13], tool characteristics and processing variables [11,14], and type of measuring instrument [15].

The lack of specific standardization subjects the metrology of wood surfaces to bias and error [10–12,16]. The sequence of operations common in surface metrology is given by ASME B 46.1 [17]. The procedure begins with fitting a polynomial regression to the measured profile in order to remove form errors. The next step consists in filtering the waviness of the profile in order to obtain the roughness profile, from which roughness parameters, indicators of surface quality, are calculated. However, the presence in wood of deep anatomical cavities can cause a series of problems; for example, they can disturb the data acquired with some measuring instruments [11,15,18,19], require longer measuring length [20] and adapted measuring resolution [21], distort the primary profile during form removal [4,22], distort the filtered roughness profiles [5,10,11,23,24], and affect the values of roughness parameters [2,25].

In a review paper dedicated to wood surface metrology, Gurau and Irle [15] recommend best practices regarding the measurement: the choice of the measuring instrument, measuring length, and most suitable measuring resolution. The recommendations continue with advice regarding the evaluation of the measured data: appropriate selection of the filters, the cut-off length, and the roughness parameters. Some problems associated with wood anatomy in various steps of surface metrology are also presented, along with solutions to overcome them.

Among the recommendations for wood surfaces, it is important to properly select the filter which separates the waviness from surface roughness, without introducing distortions in surfaces with large and grouped pores. A filter tested and found suitable for wood surfaces is the robust Gaussian regression filter (RGRF), which was described in ISO/TS 16610-31 [26] and tested while it was a draft, before being reconfirmed by more recent research [5,6,8,10,11,23,24,27]. The RGRF filter is a modification of the filter from ISO 16610-21 [28] and is applied iteratively to a dataset until a convergence condition is met. Unfortunately, the computation time is long because the filter involves all profile data points in the evaluation. A modified RGRF algorithm that uses a reduced number of data points in the weighting window was proposed in [29]. The modified window was equivalent to 1.25λ (λ being the filter cut-off length, in mm). This maintained the accuracy of results while significantly reducing the processing time.

As stated before, the presence on a wood surface of different anatomical cavities together with those from the processing tool makes any reliable evaluation of surface quality difficult [7,8,11]. A measured surface may appear rougher than it should, especially when the wood anatomical cavities overpass in magnitude those caused by the processing tool [2,11]. A reliable evaluation of the processing quality implies that irregularities which are not a result of processing be removed from the analysis [5].

Several separation methods were tested in the literature with different degrees of success [2,30–34], but the most promising seemed to be the use of the Abbot curve and the derived parameters *Rpk*, *Rk*, and *Rvk* [2,35], which divide the surface in three regions: a region of peaks, a region of the core data, and a region of valleys. An Abbot curve is obtained by ranking all the ordinate values of the roughness profile in descending order (Figure 1). According to ISO 13565-2 [35], the central region is defined as the 40% of the curve whose secant has the smallest gradient, and this is the base on which the parameter *Rk* is constructed. The Abbot curve applied to a profile that contains both processing and anatomical roughness will give an approximate measurement for the profile fuzziness, *Rpk*; the processing roughness, *Rk*; and the wood anatomy, *Rvk* [36]. However, according to Riegel [37], standard Abbot curve parameters are only approximate indicators of the processing roughness, fuzziness, and wood anatomy. *Rk* was found to be almost insensitive to species variation for sanded surfaces containing processing and anatomical roughness [36].

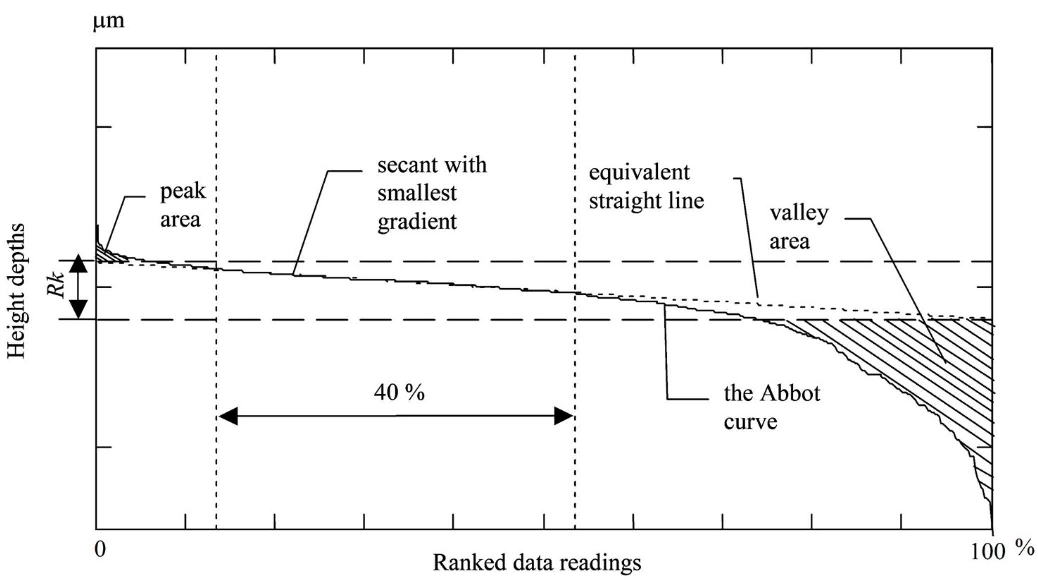

Figure 1. The calculation of the central region of the Abbot curve, based on the minimum gradient and *Rk* parameter [20]. © ISTE Ltd. 2011 Reproduced with permission from [Gurau et al.], [Wood Machining]; published by [ISTE Ltd. (UK) and John Wiley & Sons. Inc. (USA)], [2011].

Gurau [10] also observed that the standard Abbot curve parameters are imprecise to be used as a method of separating processing roughness from fuzziness and wood anatomy. A reliable delimitation of the core roughness requires a more sensitive identification of the outliers than the one contained in the general standard. The method described in this paper determines the boundaries of these regions. The process is based on detecting the inflection points in the Abbot curve without using a predefined fixed length condition of the linear region. The new approach is more flexible and adapted to a particular stratified surface such as wood [5]. This study aimed to test the efficacy of the separation method on evaluating the processing roughness of various wood species and of a homogeneous material, plastic (polyethylene), after sanding with different grit sizes.

2. Materials and Methods

2.1. Separation of Processing Roughness from Wood Anatomical Structure

The method of separation is based on detecting the changes between the central plateau and the outer regions, which creates transition points in the Abbot curve (Figure 2). The indexes of a transition point can be found by monitoring the variation of the second derivative of the Abbot curve. The index where the ratio of the absolute value of the second derivative to the standard deviation of the previous points exceeds a critical value (1) can be taken as the index of the transition point. ISO 13565-3 [38] recommends 6 as the critical value for this ratio, and this value was taken as a reference for this method.

$$critical\ value = \frac{|SD_{i+1}|}{stdev_{1..i}} \tag{1}$$

where SD_{i+1} represents the second derivative of the "$i + 1$" data point in the Abbot curve and $stdev_{1..i}$ represents the standard deviations of the previous "i" second derivative data points.

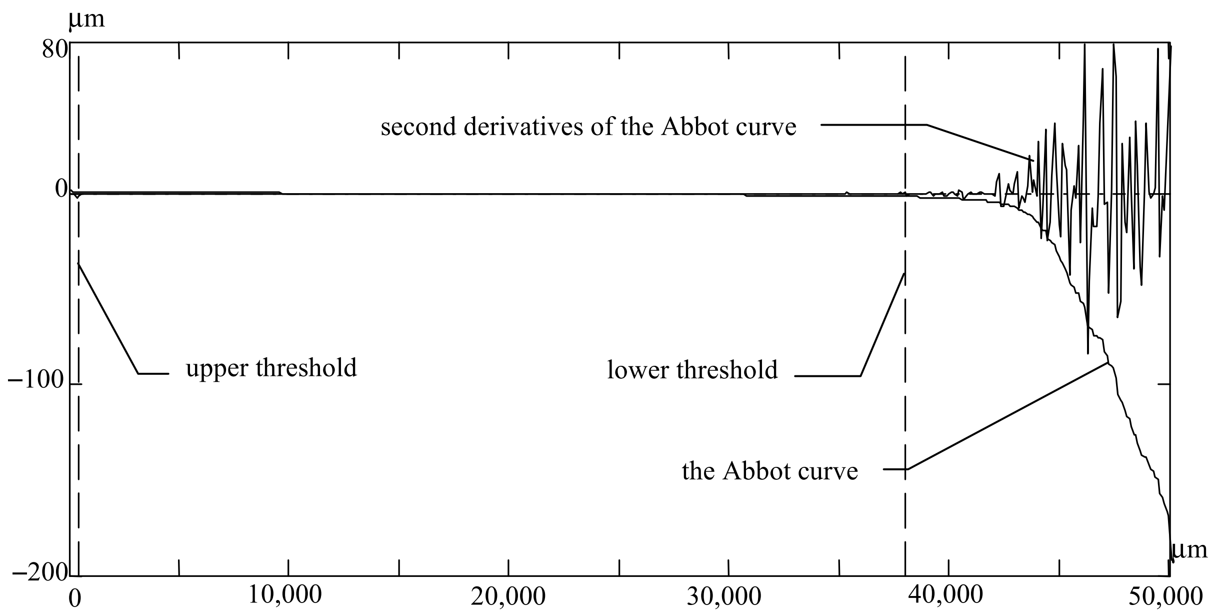

Figure 2. Use of the Abbot curve to find threshold values that delimit the processing roughness, oak sanded with P1000 [5] (Figure 12 © 2004, Springer Science and Business Media). Reproduced with permission from, [Gurau et al.], [Holz als Roh und Werkstoff]; [Springer Nature] license; published by [Springer], [2004].

The complete procedure is described in detail in [5]. However, Muralikrishnan and Raja [39] stated that the points of transition in the Abbot curve are not always clearly defined. A study on the impact of varying the critical value from 3 to 11 was included in [10]. The suitability of each critical value was judged by the symmetry of the threshold positions and by the assessment of the roughness parameters. It was found that an increase in the critical value increases the roughness parameters. However, a value of 6 indicated a symmetrical distribution of data which implies that this is the best single value that can be recommended for separating outliers from the core data [10]. Piratelly-Filho et al. [8] have used the same metrological steps: the robust filtering with RGRF, followed by the separation algorithm, which monitors the second derivative in the Abbot curve. Nevertheless, they used a critical value between 3 and 4 to stop the iterations. According to a study in [10], a low critical value of 3 or 4 can include too many peaks as fuzziness, which sometimes move the lower threshold to zero or in the positive range.

For a critical value of 6, the core data are delimited by the upper and lower thresholds and should represent the processing marks (Figure 3). They will also include anatomical features, which are too small to be detected by the lower threshold. They cannot be separately identified, with the exception of the upper parts of valleys that extend below the lower threshold. Processing roughness was defined as the core roughness of a profile where the outlying peaks and valleys were replaced with zeros. The zero values were ignored in further calculations of roughness parameters. Data points above the upper threshold represent the fuzziness, while those below the lower threshold represent the anatomical features that exist on the surface independently of the processing.

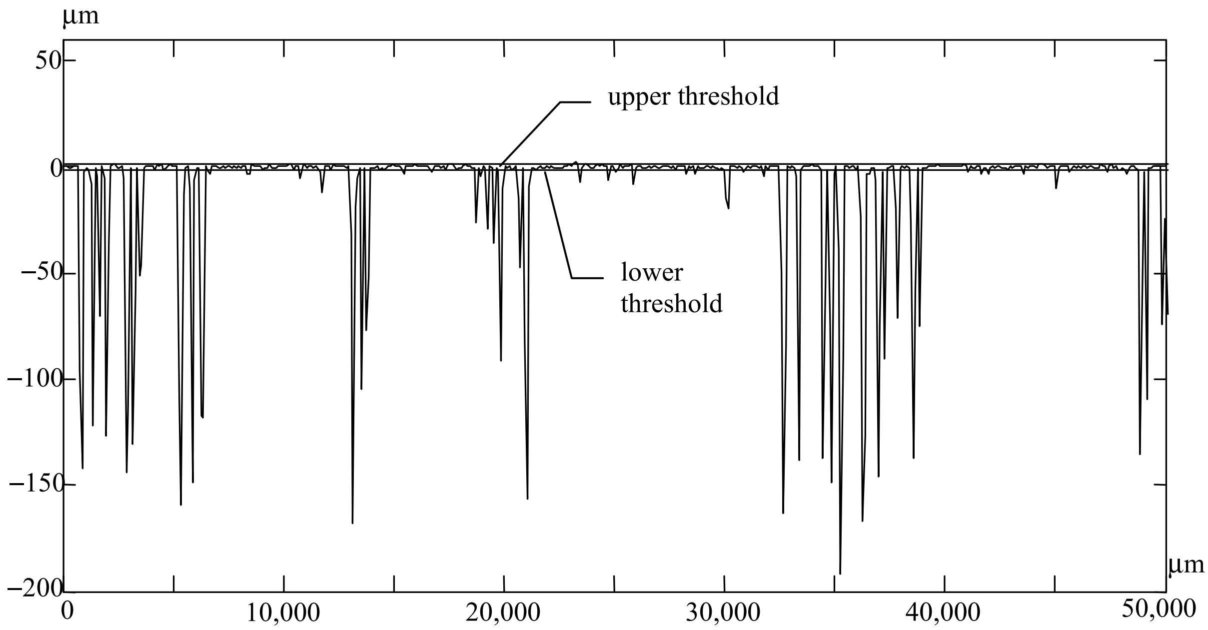

Figure 3. Location of the upper and lower thresholds as boundaries for the processing roughness, oak sanded with P1000 [20]. © ISTE Ltd. 2011 Reproduced with permission from [Gurau et al.], [Wood Machining]; published by [ISTE Ltd (UK) and John Wiley & Sons. Inc. (USA)], [2011].

If the processing roughness is separated from the general data of a profile, then the outlying data points below the lower threshold must belong to anatomical features [2,8]. These will generally be earlywood pores in hardwoods and earlywood tracheids and resin canals in softwoods [9]. The shaded areas in Figure 4 represent the area of the anatomical features found in this way for an oak surface sanded with P120.

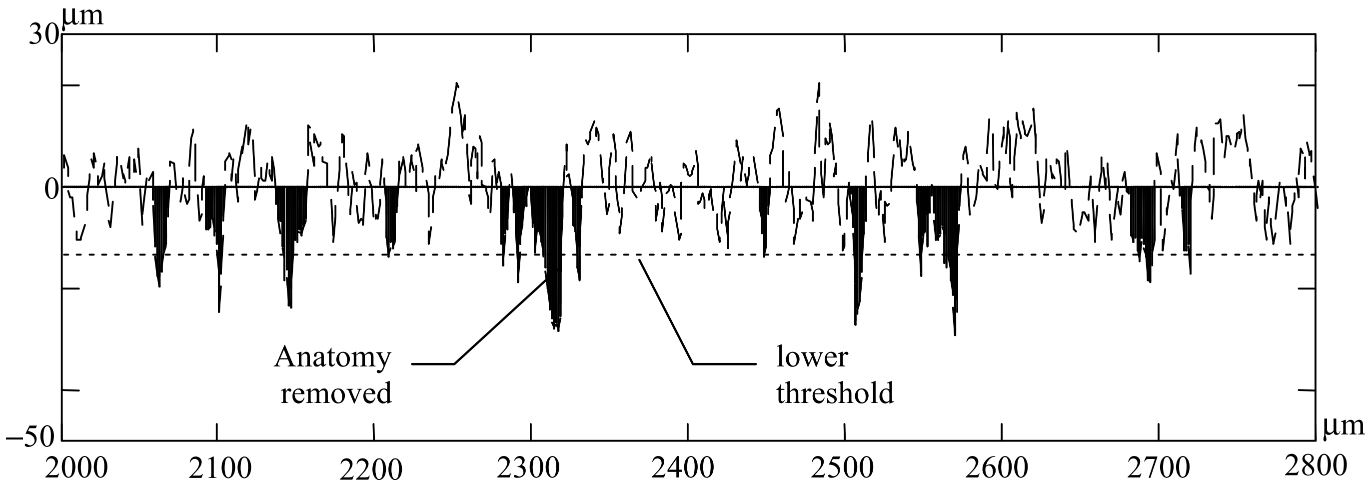

Figure 4. Black areas represent the anatomical cavities detected by the lower threshold (dotted line), on an oak surface sanded with P120 [10,40].

The following section will focus on testing the method of separating the processing-induced roughness from wood anatomical features.

2.2. Testing the Separation Method on Wood and Plastic Surfaces

The materials selected for this study were oak (ring-porous hardwood), beech (diffuse-porous hardwood), spruce (softwood), and plastic (polyethylene), sanded with different grit sizes. The aim was to test the separation algorithm on species with different anatomies and on a homogeneous material, i.e., plastic (polyethylene), having a density of 1500 kg/m^3. All wood samples were conditioned to a uniform moisture content of ~12% by storage in a climate-controlled environment. Three samples of oak, beech, and spruce, with surfaces 60 mm × 20 mm, were prepared by manual sanding with P1000. Such highly polished surfaces represent an extreme case of sanding, where the height variation due to processing is minimized while the effect of anatomy is maximized [13]. These surfaces allow the robustness of the separation method to be tested with a greater degree of reliability than surfaces prepared with larger grit sizes.

Other specimens, 100 mm × 90 mm × 20 mm, were oak sanded with P120 (new belt) and a plastic surface sanded with P120 (new belt). The two different materials were selected for comparison regarding the sanding marks left on the surface by the same commercial grit size. A preliminary dulling of the belt is recommended [41] to prevent any deep marks from forming due to the initial sharpness of unevenly distributed grit particles. However, in case of plastic it was not possible to dull the belt, and it was considered more important to use a clean belt without embedded residues than to dull the belt with a different material. For this reason, for both oak and plastic, a new belt was preferred. They were sanded on a portable belt sander made by Makita, with cloth-backed belts, 600 mm × 100 mm, close coated with aluminum oxide, at a belt speed of 350 m/min (approximately 5.8 m/s).

Finally, another specimen of oak, 100 mm × 60 mm, was prepared so that a strip of plastic 25 mm width, with the same characteristics as above, was inserted and glued in a longitudinal groove (Figure 5). The specimen was sanded with P240, along the grain, on the same portable sander, with the purpose of having both materials, wood and plastic, sanded at the same time and with a fine sand paper.

The surface measurements were carried out on a Talysurf instrument at 3M's premises. The scanning head was a stylus with 2.5 µm tip radius, a 90° tip angle, and 0.001 N pressing force. Measurements of the surface were made across the sanding marks at a speed of 1 mm/s, 50 mm long for wood specimens and 20 mm for plastic. In total, 20 profiles were measured for oak sanded with P1000, at a lateral resolution of 10 µm, and 12 profiles were measured for the other materials, at a lateral resolution of 5 µm. This variety is due to the fact that the samples were available from previous research studies of the author, but useful for the scope of this paper.

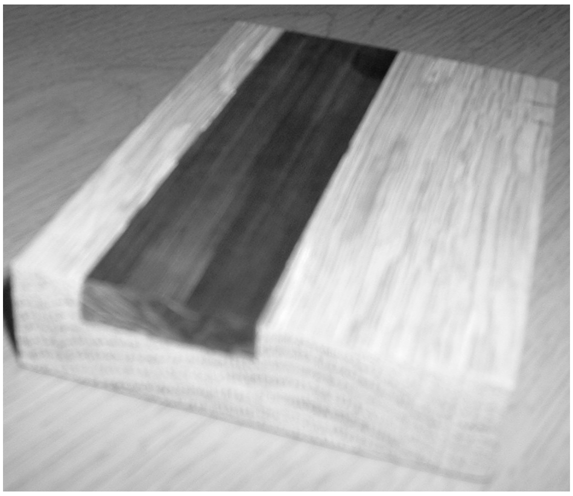

Figure 5. Specimen of oak containing an insertion of plastic and sanded with grit P240.

For the mixed sample, oak–plastic, only one profile was randomly taken, 50 mm long, so that it contained half plastic and half oak. It was used for a visual comparison of the effectiveness of the separation algorithm.

Data were processed with algorithms self-written in MathCad. For all profiles, form error was removed based on a procedure given in ISO 3274 [42]. A first-order polynomial was used for oak sanded with P1000, and a second-order polynomial was used for the other surfaces. The primary profile was filtered with the robust Gaussian regression filter, using a smoothing window of 1.25λ [29]. A cut-off length, λ, of 2.5 mm was used, except for the oak sanded with P1000, where a value of 8 mm was recommended [23]. Next, the algorithm separating the processing roughness from anatomical roughness was applied.

Plastic has no anatomy, so its roughness should represent only the processing roughness. Therefore, initially a set of data was produced where the separation algorithm was not applied to the plastic surface (Plastic P120 (a)). Another set of data (Plastic P120 (b)) was also obtained by applying the separation algorithm to compare the results with those for oak sanded with P120.

Once the processing roughness was obtained, roughness parameters were calculated, such as *Ra*, *Rq*, *Rku*, and *Rt* from ISO 4287 [43] and *Rk*, *Rpk*, and *Rvk* from ISO 13565-2 [35]. The calculations were performed directly on evaluation lengths, equal to the measured lengths, rather than standard sampling lengths. This is because a division of the roughness profiles into sampling lengths is not representative for the earlywood and latewood variation [40]. For each profile tested, the corresponding roughness parameters and upper and lower thresholds were recorded. Then, the mean values and coefficients of variation for roughness parameters and thresholds among the profiles were calculated. The coefficient of variation is the ratio between the standard deviation and the mean value of the parameter.

3. Results

Table 1 shows the means and the coefficients of variation for the thresholds and roughness parameters.

The mean values were very similar for materials sanded with the same grit size, which is an indication that the algorithm for separation was sensitive to the grit size. As expected, there were close results for oak and beech sanded with P1000, with slightly higher values for spruce P1000, which shows that the algorithm for separation is sensitive also to species. Previous research has shown that lower-density species will exhibit slightly higher roughness after sanding in the same conditions [9].

Table 1. Mean values of processing roughness parameters (μm) for different materials and grit sizes. In brackets are the values for the corresponding coefficients of variation (%). UT—location of the upper threshold. LT—location of the lower threshold.

Parameter	**Material and Grit Size**					
	Oak P1000	**Beech P1000**	**Spruce P1000**	**Oak P120**	**Plastic P120 (a)**	**Plastic P120 (b)**
Ra	0.463 (7.671)	0.297 (11.74)	1.333 (27.42)	5.311 (11.37)	5.257 (1.558)	4.823 (7.660)
Rq	0.551 (8.432)	0.352 (10.73)	1.555 (25.16)	6.126 (9.864)	6.576 (1.676)	5.629 (6.730)
Rku	2.291 (6.063)	2.345 (8.313)	2.352 (8.619)	2.079 (3.317)	3.061 (8.037)	2.072 (4.56)
Rt	2.262 (12.47)	1.478 (15.44)	6.087 (22.87)	24.40 (10.80)	44.28 (13.20)	21.06 (10.85)
Rk	1.422 (6.969)	0.919 (7.688)	3.068 (9.686)	16.61 (6.569)	17.19 (2.726)	16.02 (3.818)
Rpk	0.261 (25.50)	0.233 (16.41)	0.835 (11.26)	2.730 (21.70)	5.230 (7.199)	2.529 (40.85)
Rvk	0.549 (18.08)	0.31 (25.07)	2.285 (27.24)	4.235 (23.71)	7.056 (9.153)	2.872 (36.22)
UT	0.996 (10.55)	0.781 (8.949)	2.404 (7.381)	11.491 (9.224)	–	10.321 (9.064)
LT	−1.16 (16.31)	−0.696 (29.02)	−2.908 (28.38)	−12.91 (15.44)	–	−10.463 (15.41)
Number of profiles	20	12	12	12	12	12

The parameters *Ra*, *Rq*, and *Rk* for plastic P120 (a) were very close to the corresponding results for oak P120 (Table 1), although the separation algorithm was not applied for plastic. However, because a new belt was used, the plastic P120 (a) surface retained some occasional outliers (Figure 6) caused by the presence of some large grit particles, which affected *Rt* and had a value of 44.278 μm for plastic as compared with 24.401 μm for oak P120. This result could, also, be attributed to the difference in material characteristics between wood and plastic: plastic has no pores and has greater ductility.

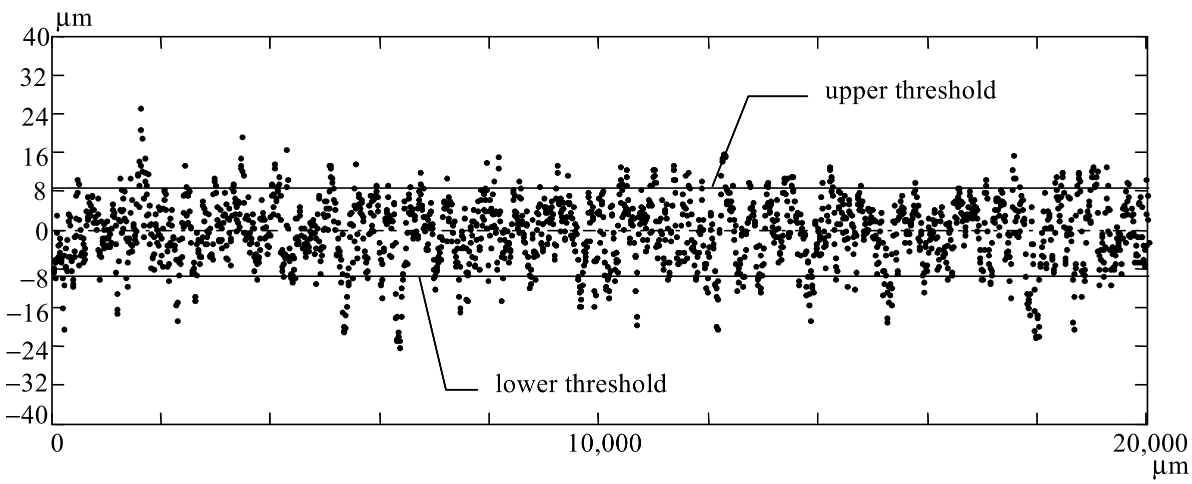

Figure 6. Roughness of a plastic profile sanded with P120 (new belt). Thresholds separate the processing roughness from outliers.

When the separation algorithm was applied to the plastic profiles (Plastic P120 (b)), all the roughness parameters were very close to those for oak P120, but slightly lower. The density of the plastic was 1500 kg/m^3, which is close to that of the wood cell wall. However, compared with plastic, wood is a porous material with thin cell walls. Compared with plastic, the occurrence of fuzziness is very likely with wood, which causes a rougher surface.

It can be seen in Table 1 that more variability occurred in the lower thresholds than the upper thresholds for all species and grit sizes and also for plastic. Similar coefficients of variation for oak P120 and plastic P120 (b) can indicate that the variation in locating the thresholds is due to the variation in the grit marks left on the surface.

Small changes in the thresholds added or removed a few peaks or valleys but did not change the core data to any great extent. As shown in Table 1, there are low coefficients of variation for oak sanded with P1000 and P120 and for beech sanded with P1000 grit size, for the parameters *Ra*, *Rq*, and *Rku*.

Earlywood and latewood areas in spruce have very different densities, which leads to sanding marks of different depths [9,44]. In addition, the percentage of these areas within different profiles varies. The position of the thresholds that delimit the core roughness is clearly determined more by the roughness of the earlywood than the latewood [10]. In consequence, the coefficient of variation for the majority of parameters was highest for spruce. In low-density species such as spruce, the grit particles produce deeper marks and a fuzzier surface than for denser species such as oak and beech.

Rku, as a shape parameter, had little variation and constantly indicated a flat distribution of data after the separation.

Besides *Rku*, *Rk* had the lowest coefficient of variation for each species, which indicates that the core data were successfully retained in all the roughness profiles. The small variation makes *Rk* the most reliable reference for the processing roughness.

The parameters with the most variation were *Rt*, *Rpk*, and *Rvk*. This result may indicate that there was some variability in the algorithm for finding the threshold limits, which had little effect on *Ra*, *Rq*, *Rku*, and *Rk*, but a greater effect on *Rt*, *Rpk*, and *Rvk*, which are sensitive to the small changes. Taking oak P120 as an example, this variability is shown in Figures 7–10. Compared with profile 1, the data points in profile 2 are less evenly distributed around the mean line, which has pushed the threshold locations further out. Plots of the two oak profiles sanded with P120 showed that a variation of the threshold location occurs, as expected, when data from different profiles are differently scattered relative to the mean line.

Figure 11 shows the profile extracted from the oak–plastic surface sanded with P240. The upper and lower thresholds were calculated from the oak surface alone.

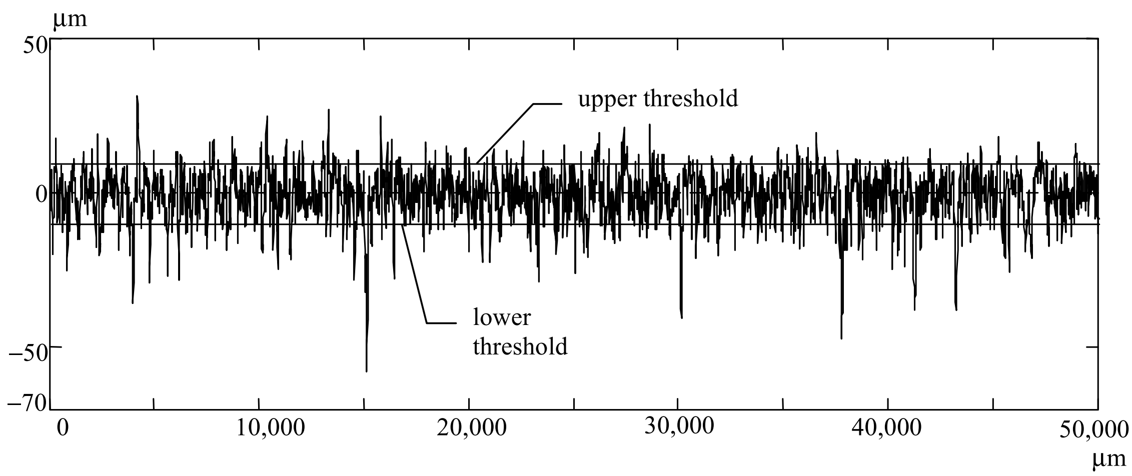

Figure 7. Thresholds for oak sanded with P120 (profile 1).

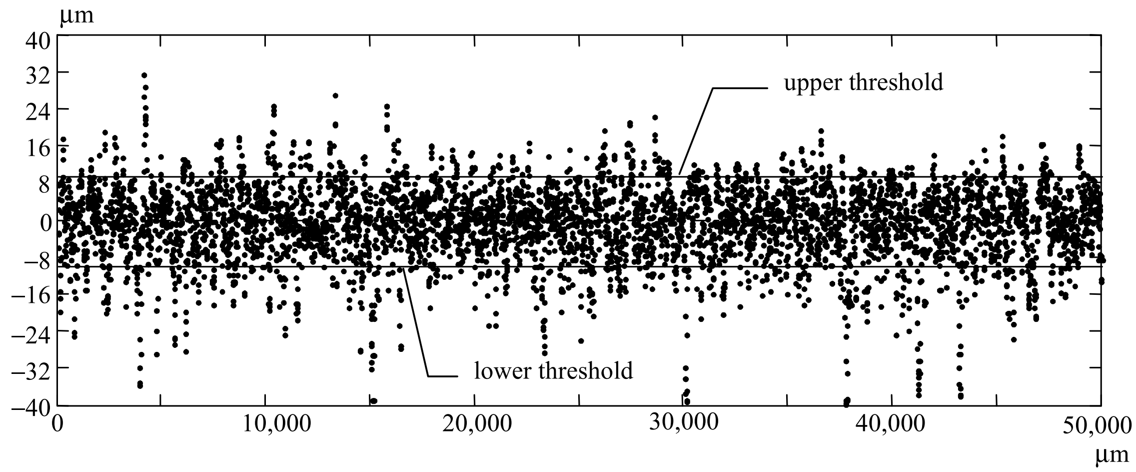

Figure 8. The same profile as in Figure 7, but detailing the core data, which appears delimited by thresholds. Representation as data points (profile 1).

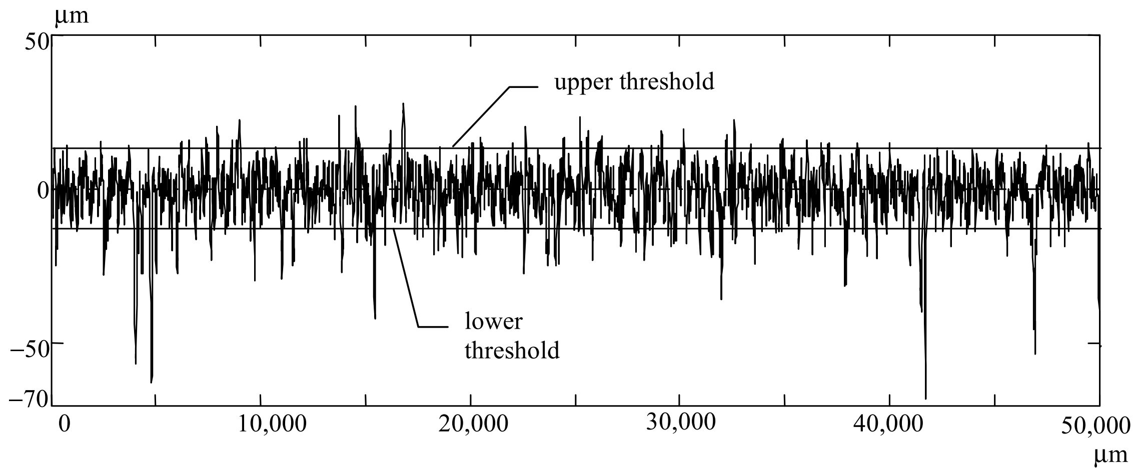

Figure 9. Thresholds for oak sanded with P120 (profile 2).

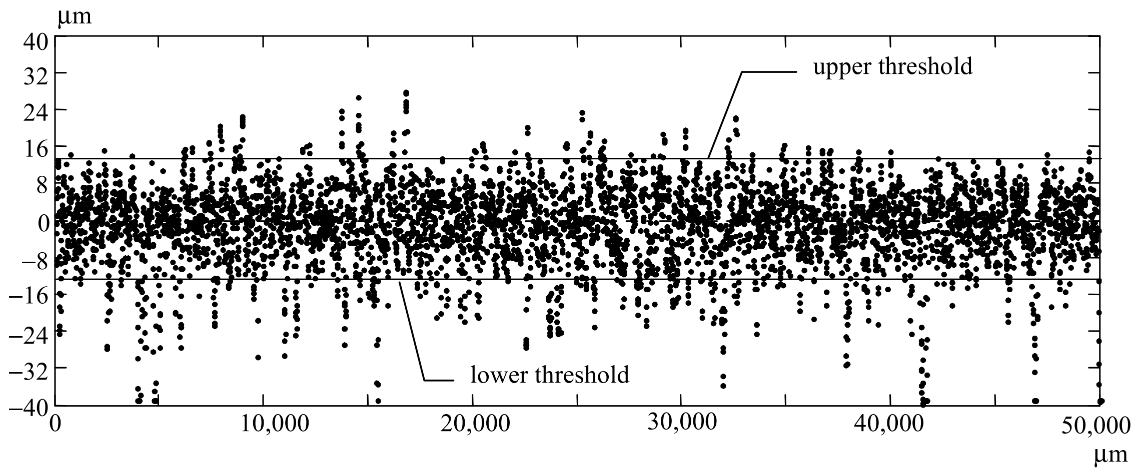

Figure 10. The same profile as in Figure 9, but detailing the core data, which appears delimited by thresholds. Representation as data points (profile 2).

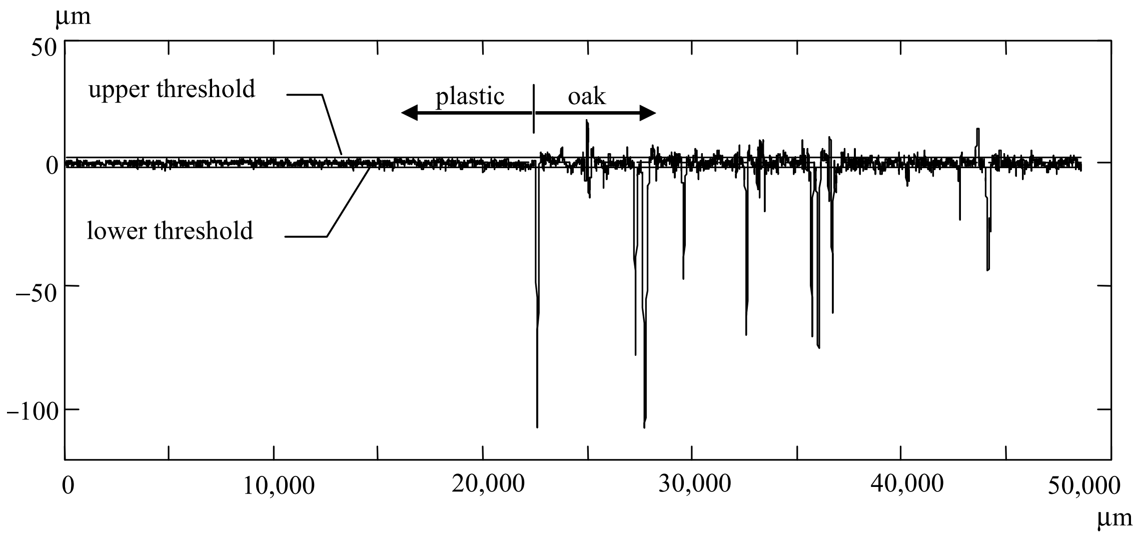

Figure 11. Profile subtracted from a mixed surface oak plastic sanded with P240 grit; the processing roughness of oak is delimited by an upper and lower threshold.

The result showed a good agreement between the processing roughness of oak and the roughness of plastic, with almost all the data points in the plastic profiles falling between the thresholds determined from the oak profile.

4. Discussion

This new series of tests included, apart from wood, a homogeneous material, i.e., plastic, used for comparisons. The algorithm for separation proposed by Gurau et al. [5] seemed sensitive to the grit size. A similar result was found by the author when using the same separation procedure in the cases of oak [45], beech [25], and oak and beech [1] sanded with different grit sizes, from coarse to very fine. A logarithmic correlation between processing roughness parameters and grit size was found. *Rk*, defining the core of data or processing roughness, appeared a reliable parameter in those studies when calculated after the separation from wood anatomy. In all cases above, the evaluation of processing roughness was made after removing wood anatomical features. Furthermore, all studies have shown that wood anatomy is a factor of bias if not eliminated from the analysis of the processing roughness. In the majority of studies regarding the influence of grit size on surface roughness, the anatomical roughness has not been removed [2,14,46–53]. Even though a trend of decreasing roughness with increasing grit number was unanimously reported, the exact quantification of the processing roughness produced by each grit size was not performed.

In conclusion, eliminating the wood anatomy data from the measurements can offer a more reliable base for comparisons between various results offered by literature. At the same time, the separation of processing roughness from inherent wood anatomical features can open the gate to understanding and reliable evaluation of the effect of processing parameters on the quality of wood and process optimization.

5. Conclusions

The influence of statistically outlying anatomical valleys or high isolated peaks can be excluded from the evaluation of processing roughness by monitoring the variation of the second derivative of the Abbot curve. The separation algorithm proved to be effective in distinguishing between different species and grit sizes. There were close results for species sanded with P1000, with higher values for spruce. Oak sanded with P120 and P240 had a processing roughness very close to that of a plastic surface sanded in the same way. The parameters *Ra*, *Rq*, and *Rk* had less variability with the location of thresholds than *Rt*, *Rpk*, and *Rvk*. *Rk* was the most reliable measure of the processing roughness.

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Conflicts of Interest: The author declares no conflict of interest.

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