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The Impact of Abrasive Grit Size on Roughness of Sanded Beech Wood Surface

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Abstract: The study assessed the changing of R_a, R_p, R_v and R_z roughness parameters of the sanded beech surface (*Fagus sylvatica* L.) as a function of different grit sizes and different measurement direction. The milled samples were ground with a belt sander BS-75 E-set from Festool with belt grit P60, P100 and P150. The sanding belts were Rubin 2 from Festool. Roughness was evaluated using a Keyence VHX-7000 digital microscope. The evaluation length of the roughness measurement was 12.5 mm (λc = 2.5 mm and λs = 8 mm). The R-parameters were measured in accordance with the latest standards ISO 21920 (2022) in the direction parallel to the grain, and in the direction perpendicular to the grain (profile). The paper proves the theoretical assumptions about the reduction of R-parameter values. The measurements showed that the sanded surface was less rough in the direction perpendicular to the grain at P150 sanding belt grit and in the grain direction at P100 grit.

Key words**:** surface roughness, belt sander, beech wood, Keyence VHX, digital microscopy

INTRODUCTION

Roughness as a type of surface unevenness can be characterized as a form of unwanted deviation from the desired (nominal) surface. The causes of its occurrence can be defined in two ways. First, it is a property that is partially inherent to the wood. According to Kúdela *et al.* (2018), Kminiak (2014), Sandak and Negri (2005), Magoss (2008) and Gurau *et al.* (2005) roughness arises because of the macroscopic, microscopic, or submicroscopic structure of wood. This is a deviation of the 4th to 5th row, which will be significantly influenced by the type of wood, the moisture content of the wood and the size of the cut cellular elements on the surface. In the second place, the cause of roughness is the action of rotating tools (saw blades, milling cutter or sanding belts). Precisely because of the kinematics of the rotating tool, it is not possible to achieve a physically completely smooth surface (Kúdela *et al.* 2018), (Kvietková *et al.* (2015 a,b), Gaff and Kaplan (2016), Kubš *et al.* (2016), (Kaplan *et al.* 2018 a,b). Among the technical reasons for the appearance of roughness, it is also necessary to mention the vibration of the tool or the wear of the cutting blade. The roughness will thus be a combination of anatomical roughness and processing roughness (Gurau *et al.* 2015). Roughness is expressed in metrological practice by a whole range of so-called R-parameters. Each of them can be considered important, as the individual parameters supplement the information about the profile itself. It is possible to analyse only the deviations of heights from the reference line (arithmetic mean height R_a), but in such research there is no information on the heights of the hills or the depths of the dales of the roughness profile (R_p, R_v, their sum R_z, or the parameter R_t). These could supplement the information on the extent to which the surface was smoothed during sanding. In this case, it would be a numerical expression of, how much the sanding belt sanded off the peaks (highest point of hill) of the profile or how much it sanded down deeper grooves. The reduction of roughness values is essential not only for the creation of a quality surface for subsequent sales (Zhong *et al.* 2013), but also for subsequent technological processes, for example surface treatment. It is the latter that requires pre-preparation of the surface by sanding. This woodworking process involves the action of a sanding tool with a certain grit size to achieve an overall reduction in the unevenness of the surface. By gradually smoothing with abrasive grains, a reduction of individual R-parameters of roughness is achieved. Abrasive tools (discs or belts) with a coarser grain (for example P60 or P80) serve, from a theoretical point of view, mainly to equalize the dimensions of parts made of wood. However, a coarse grain will create a surface with a much higher roughness in most cases than the roughness of the milled surface Kúdela *et al.* (2018). That is why the sequence of individual grit sizes is important when sanding, while with higher grit sizes unevenness is evened out over the entire surface of the wood (roughness values measured perpendicular to the grain are equalized to values measured parallel to the grain). At the same time, higher grit sizes will separate torn, imperfectly separated fibers and partially balance the differences between more sanded earlywood and less sanded latewood. This heterogeneity of the surface is most often caused by the action of coarse abrasive grains of a lower grit size.

Currently there is still limited information on the surface quality processed by belt sanders as a function of different grit sizes of belts and different measurement direction. Therefore, the objective of this study was to determine the surface roughness of beech wood processed by sanding with belt sanders using P60, P100 and P150 grit sizes. The change in surface roughness was expressed by changing the R_a, R_p, R_v and R_z roughness parameters.

MATERIALS AND METHODS

To measure the change in R-parameters of roughness, samples of dimensions 12 × 70 × 70 mm (thickness × width × length) from beech (*Fagus sylvatica* L.) were used. After the thickness using a thickness milling machine with a spiral cutter head, 12 radial samples were sanded with Rubin 2 sanding belts (Festool) with dimensions of 533 × 75 mm, with ground aluminum oxide grain as abrasive and sanding belt grit size of P60, P100, P150. The tool used was a belt sander BS-75 E-Set from Festool. The samples were conditioned to an equilibrium moisture content of 8 ± 2%. The change of individual roughness parameters was related to the roughness of 4 reference milled samples (R).

The surface quality of the sanded samples was defined through roughness parameters: R_a (arithmetic mean height), R_p (mean peak height), R_v (mean depth) and R_z (maximum height). The parameters were measured at an evaluation length of 12.5 mm while maintaining the number of basic lengths n = 5, according to the technical standard STN EN ISO 21920-3. For profile filtering, values of 2.5 mm for the L-filter (λ_c) and 8 μm for the S-filter (λ_s) were chosen.

Surface roughness parameters were measured in two directions – the direction perpendicular to the grain and the direction parallel to the grain. Sanding with a belt sander took place in the direction of the grain, and thus the created kinematic trace was also in line with this direction. From the point of view of the natural structure of beech wood, larger values are expected in the direction perpendicular to the grain, resulting mainly from the differences in the properties of earlywood and latewood (and thus the resulting different values of material removal, which results in the formation of unevenness). The second likely influence is the occurrence of cut cellular elements. Since the roughness of wood as a material is a combination of the roughness of the wood structure and the roughness created by the machining technology, the created track of the sanding belt will also have a significant influence when measuring perpendicular to the grain. Due to the significant heterogeneity of the surface, a higher value of the standard deviation, i.e., large differences between individual measurements, is expected in the direction perpendicular to the grain. For this reason, a total of 30 profiles (tracks) of surface roughness measurements for each direction were made for each sample. This number of measurements proved to be sufficient for the statistical description of the surface and the inclusion of outliers. The profiles were distributed evenly within the samples to preserve independent measurement results. The total number of measurements was 720 for each roughness parameter.

The measuring device for evaluating the roughness parameters was a Keyence VHX-7000 digital microscope, the construction of which is described in Fig. 1.

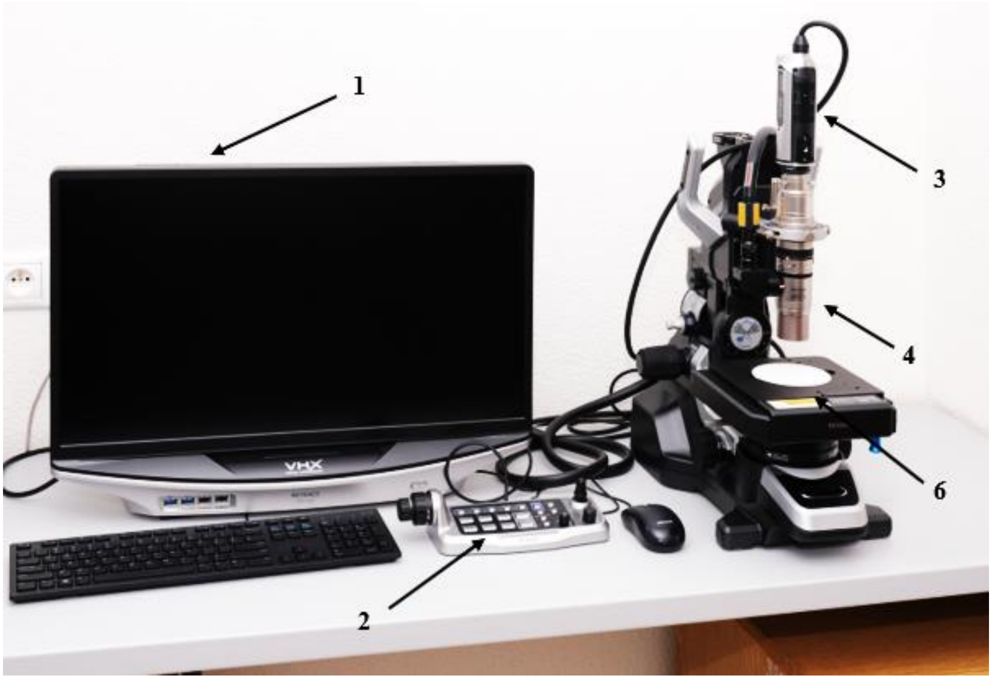
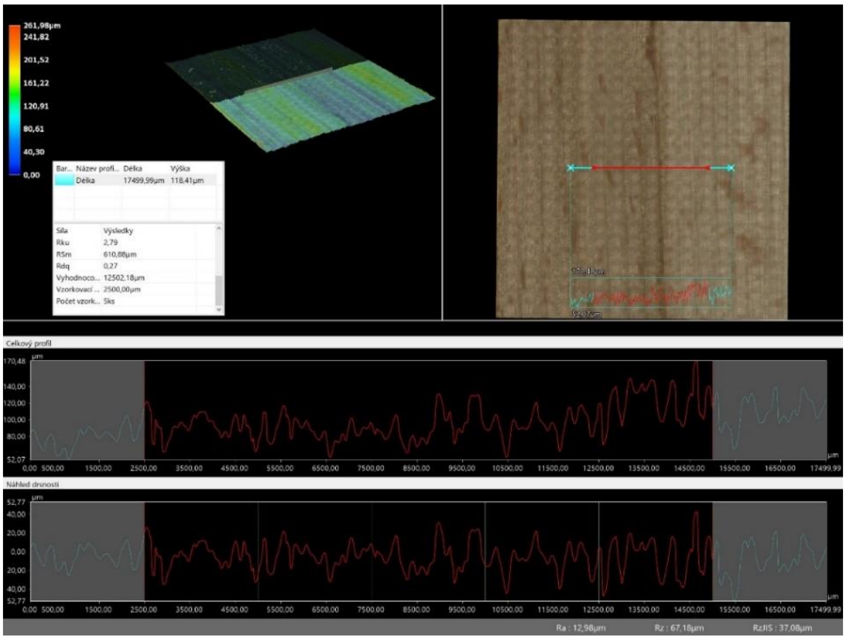


Fig. 1 Construction of the Keyence VHX-7000 digital microscope

1 – Main unit, 2 – Console, 3 –Camera, 4 – Wide-range zoom lens, 5 – Free-angle observation stand, 6 – XYθ eucentric motorized stage

An example of the software (VHX-H5M) used to measure the surface roughness can be seen in Fig. 2. It is a non-contact optical method of surface observation using incident and reflected light. The principle of the evaluation is the uniform interpolation of profiles (with the length according to the technical standard) on the scanned image of the surface. The microscope software then creates a digital profile of the surface as a copy of the real surface and then filters it using the set values. This profile will thus become the basis for evaluating the selected parameters (i.e., an evaluation length will be created from the scanned length and five section lengths from it). In this case, in the first step, the Keyence microscope evaluates R_a, R_p, R_v and R_z separately on the individual five section lengths according to the technical standard and then calculates one resulting value of the selected parameter using the arithmetic mean. This procedure is common to all parameters that are evaluated from section lengths according to the standard.



Bar...	Název profi...	Délka	Výška
🟦	Délka	17499,99µm	118,41µm

Síla	Výsledky
Rku	2,79
RSm	610,88µm
Rdq	0,27
Vyhodnoco...	12502,18µm
Vzorkovací ...	2500,00µm
Počet vzork...	5ks

Ra : 12,98µm
Rz : 67,18µm
RzJIS : 37,08µm

Fig. 2 Measuring of the roughness of the sanded beech wood (profile)

RESULTS AND DISCUSSION

Before the data were subjected to statistical analyses using the STATISTICA 12 software, the outliers were removed from the data set that significantly bias the results of the parametric tests. The input data set was evaluated using descriptive statistics methods.

From the results of 960 measured values in Tab. 1 to Tab. 4, an improvement in the quality of the surface sanded with a belt sander is observed only when using higher abrasive grains. The given tables clearly prove the theoretical knowledge about the mutual correlation of R-parameters, which was showed by approximately the same rate of decrease for individual parameters.

Tab. 1 Descriptive statistics for the R_a parameter (n = 120)

Grit size	Measurement direction	R_a Average (µm)	R_a Std. Dev. (µm)	R_a - 95,00 % (µm)	R_a + 95,00 % (µm)
R	perpendicular	4,46	0,84	4,31	4,62
60	perpendicular	6,47	0,98	6,30	6,65
100	perpendicular	5,97	0,83	5,82	6,12
150	perpendicular	3,65	0,74	3,52	3,78
R	parallel	3,36	0,83	3,21	3,51
60	parallel	3,52	0,84	3,36	3,67
100	parallel	3,17	0,95	3,00	3,34
150	parallel	2,81	0,80	2,67	2,96

Arithmetic mean height R_a in Tab. 1 proves that, from a technological point of view, the quality of the surface will decrease by sanding (the unevenness of the surface will increase) with P60 and P100 grits in the direction perpendicular to the grain. The mentioned phenomenon can be explained by the presence of a kinematic trace (grooves) caused by the rotating grains of the belt. Since the evaluation profile is perpendicular to the grooves caused by the sanding belt, these irregularities will also be reflected by increasing the R_a parameter. From the table, it can be observed that there is a jump between the milled reference surface of beech wood and the surface sanded with P60 grit. The R_a parameter further decreases by 0.5 μm at P100 grit size, and then its sharp decrease occurs (P150). At grit size of P150, the measured surface already showed a better quality than surface milling on a thickness milling machine with a spiral cutter head (R), by approximately 18 %. In the direction of measurement perpendicular to the grain, it is possible from Tab. 1 also observe a decrease in the standard deviation and thus it is possible to claim that within the area the surface was gradually smoothed by the sanding belt and the values of R_a showed a smaller mutual difference. In the case of measurement parallel to the grain, the parameter R_a was lower since the evaluation profile was translated in the same direction as the grooves created by sanding belt. Even the deeper pores of the beech wood did not cause a significant increase in values here. Even in this case, a higher standard deviation confirmed the presence of an uneven surface, probably caused by wood pre-sanding of various sizes. From an overall point of view, it is possible to observe a reduction of surface irregularities in the direction parallel to the grain by approximately 16 % at grit size P150 compared to the milled surface (R).

Tab. 2 Descriptive statistics for the R_p parameter (n = 120)

Grit size	Measurement direction	R_p Average (μm)	R_p Std. Dev. (μm)	R_p - 95,00 % (μm)	R_p + 95,00 % (μm)
R	perpendicular	7,51	1,17	7,30	7,72
60	perpendicular	13,0	2,48	12,55	13,44
100	perpendicular	11,04	2,04	10,67	11,41
150	perpendicular	6,42	1,16	6,21	6,63
R	parallel	5,46	1,07	5,26	5,65
60	parallel	7,11	4,30	6,33	7,88
100	parallel	5,83	2,36	5,41	6,26
150	parallel	4,73	1,32	4,49	4,97

The R_p parameter, i.e., the mean peak height, can be primarily understood as a numerical expression of the degree of surface fuzziness in this case. From the point of view of wood sanding as a machining process, these are partially separated fibers from the surface of the wood, which are created by scraping with sanding belts. These fibers are many times so long that they are visible even with the naked eye and they occur especially after sanding with a low grit size (e.g., P40, P60...). The finer fuzziness of the wood surface can often only be detected by touch, but even this has a significant impact on the optical measurement of the R_p parameter. When evaluated, all these threads behave as a profile hills, which is defined by its highest point – peak (and therefore, with respect to the reference line, its highest height can be determined). Since the parameter R_p is evaluated on the section length, this causes to a certain extent less stability of the measured values compared to parameters that evaluate the parameter on the entire evaluation length. The proof is the high values of the standard deviation, which can be seen in Tab. 2. Also, it can be observed from Tab. 2, that the highest value of the standard deviation occurs at grit size P60 in the direction parallel to the grain. That can be explained by the presence of torn unseparated fibers, naturally located in the direction of their growth. From an overall point of view, larger values of the R_p parameter occur in the direction perpendicular to the grain, where they are mainly affected by torn fibers as well as the unevenness between the surface and deeper cellular elements. In the direction perpendicular to the ongoing wood grain, it occurs according to Tab. 2 sudden change in R_p after sanding the surface with a P60 grit size belt. Then a sharp drop after sanding with P100 and P150 grit size down to the level of the value of the reference sample (an improvement in quality occurred). The higher grit sizes of the sanding belt did not act as aggressively on the surface as P60, but on the contrary, they sanded away the uneven torn fibers, which smoothed the surface. This is also a logical explanation why R_p values decrease. The evidence of the smoothing of the projections of the roughness profile is also supported by the reduction of the standard deviation in both measured directions.

Tab. 3 Descriptive statistics for the R_v parameter (n = 120)

Grit size	Measurement direction	R_v Average (μm)	R_v Std. Dev. (μm)	R_v - 95,00 % (μm)	R_v + 95,00 % (μm)
R	perpendicular	14,53	2,46	14,08	14,97
60	perpendicular	21,50	4,25	20,73	22,27
100	perpendicular	19,81	2,62	19,33	20,28
150	perpendicular	10,89	2,04	10,52	11,26
R	parallel	9,86	2,22	9,46	10,26
60	parallel	9,47	2,19	9,08	9,87
100	parallel	8,41	2,50	7,95	8,86
150	parallel	7,44	1,49	7,17	7,71

The parameter R_v, i.e., the mean depth of the roughness profile, can be explained in two ways. For the most part, in the case of sanding, it is a numerical expression of the depth of the grooves created by the action of the sanding grains of the belt. By scraping, especially at lower grit sizes, they created deep grooves in the surface of the beech wood, which sharply increase the R_v values. In the second case, it is the presence of the cellular elements themselves in the wood, especially deep cut pores. From this point of view, the given parameter can be viewed as a combination of anatomical roughness and roughness created by the machining process, which will acquire higher values in the direction perpendicular to the grain and thus also in the direction perpendicular to the cellular elements and in the direction perpendicular to the grooves created by the abrasive grains (Tab 3). As with the arithmetic mean height of the profile expressed by the parameter R_a, R_v will increase at approximately the same rate in this case too. The parameter reaches the highest values in the case of belt grit size of P60 when the mark on the surface can be observed with the naked eye. The high value of the standard deviation for this grit size is evidence of different deep parts of the grooves, which can be explained by the uneven sanding of wood particles. In the case of higher grit sizes, the roughness depth decreases due to surface smoothing. Finer sanding will thus reduce the depth of the roughness itself. From a theoretical point of view, R_v values can only be reduced to a certain extent, when the mark created by the sanding belt will be lost, but the deeper pores natural to the wood structure will remain on the surface. It will be the same for R_v in the direction parallel to the grain.

Tab. 4 Descriptive statistics for the Rz parameter (n = 120)

Grit size	Measurement direction	R_z Average (µm)	R_z Std. Dev. (µm)	R_z - 95,00 % (µm)	R_z + 95,00 % (µm)
R	perpendicular	22,04	3,28	21,44	22,63
60	perpendicular	34,50	5,92	33,43	35,57
100	perpendicular	31,37	4,50	30,56	32,19
150	perpendicular	17,31	2,77	16,81	17,82
R	parallel	15,32	3,09	14,76	15,87
60	parallel	16,58	5,54	15,58	17,58
100	parallel	14,24	4,55	13,41	15,06
150	parallel	12,17	2,51	11,72	12,63

The parameter R_z, i.e., the maximum height, is defined as the sum of the mean peak height of the roughness profile and the mean depth of the roughness profile, evaluated on the section length, according to the the STN EN ISO 21920 standard as well as the previous version of STN EN ISO 4287. From this point of view, it can be considered a less stable parameter, highly influenced by hills (fuzziness of the surface) and dales of the profile (cellular elements or kinematic trace of the tool). This fact can also be observed from the very high values of the standard deviation in Tab. 4. As a result of the sum of the R_p and R_v values, the R_z parameter itself will also increase at the same rate, and therefore the highest values will be presented when sanding with a P60 belt. The table further shows that the roughness height for P60 is higher in both measured directions than in the case of the reference surface. The reason is the presence of grooves from the sanding grains, which caused partial fuzziness of the surrounding surface, but also the creation of deep grooves in the profile, which caused a significant increase in the measured parameter. By sanding with a belt with a higher grit size, the roughness gradually decreases and in the case of P150 it is finally lower than for the milled surface (R). Since the R_a parameter itself does not present individual roughness heights, R_z is a suitable expression of the extent to which the used sanding belt causes surface unevenness due to the impact of the sanding mark.

The measured values of the roughness parameters for the surface sanded with a belt sander were compared with the measurements of other authors. However, it is necessary to consider several factors that greatly complicate these comparisons. In many cases, the authors do not define with which filters they measure the roughness. Different L-filters and S-filters significantly affect the roughness parameter values. Differences in roughness values between individual works can also be caused by the measurement technique used. Therefore, with optical measuring devices, different parameter values can be measured than, for example, with stylus profilometer. In the case of grit size of P60, the value of the parameter R_a in the direction perpendicular to the grain can be as high as 12.60 µm (Gurau *et al.* 2019), or 9.30 µm (Demirci 2019). These values are higher than in the case of this paper, when R_a was at the level of 6.47 µm. A similar value was also measured by (Kilic *et al.* 2006), namely 6.90 µm for the direction perpendicular to the grain. The differences that arose with this grit size can be caused by different sanding parameters (speed of the sanding belt and its stability during the sanding process, different type of belt abrasive). From the P60 grit size, it is further possible to compare the value of the R_z parameter, which in this paper was at the level of 34.50 µm versus 74.24 µm in the case of (Kilic *et al.* 2006). This is the proof of the theory that although the value of the R_a parameter may be at the same level, the height of the measured roughness itself may be significantly different. Even in the case of the equality of R_a, the roughness profile can show larger hills or dales of the profile. From this point of view, it is therefore advisable that the measurements be supplemented with the parameter R_z or, for example, R_t. At grit size P100, the measured average value of R_a in the direction perpendicular to the grain was equal to 5.97 µm. This value is also lower than in the case (Gurau *et al.* 2019), where R_a was equal to 9.00 µm in the same direction. It is also possible to compare the R_v parameter with the mentioned publication, which in the case of this paper was 19.81 µm and in the case of (Gurau *et al.* 2019) 51.78 µm. It is therefore possible to claim that in this case the sanding belt did not create such deep grooves and therefore the average value of the R_a heights will be lower. A similar value of R_a in the direction perpendicular to the grain was also measured by (Aslan *et al.* 2008), namely 6.05 µm. In the direction parallel to the grain, the R_a value equal to 3.17 µm can be compared, for example, with (Cota *et al.* 2017), where the roughness parameter reached a value of 3.71 µm. The measured value of the parameter $R_a = 3.65$ µm for the direction perpendicular to the grain was measured for the surface treated with a P150. In the same direction, Gurau *et al.* (2019) measured 5.80 µm or 4.33 µm (Gurau 2013) and approximately 5.00 µm (Kúdela *et al.* 2018). For the direction parallel to the grain, the value $R_a = 2.81$ µm was the same as in the case of (Kúdela *et al.* 2018). Of the other parameters measured at P150 grit size, R_v can be mentioned. The value of which in this paper is equal to 10.89 µm for the direction perpendicular to the grain. In the same direction, Gurau et al. (2019) measured a value of 39.79 µm. In the case of the parameter R_z, the value in the direction perpendicular to the grain was equal to 17.31 µm, unlike Kúdela et al. (2018), where R_z was equal to approximately 43 µm. In the direction parallel to the grain, R_z was equal to 12.17 µm, while in the case of Kúdela et al. (2018) the average value was equal to approximately 20 µm. In the case of both R_v and R_z parameters, it can therefore be claimed that the height of the roughness was significantly lower at the P150 grit size. The sanding belt did not leave deeper grooves after sanding, which probably lowered the R_v value as well.

CONCLUSION

The following can be stated from the measured results:

1. The grit size of the sanding belts affects the roughness of the beech wood surface.
2. The roughness of the surface after sanding is higher with grit sizes of P60 and P100 than with the surface of the samples thickness using a thickness milling machine with a spiral cutter head. This was reflected in all measured roughness parameters. The surface, especially in the case of P60, can be defined by significant fuzziness, which was manifested by an increase in the values of the parameter R_p, and by deep grooves after the action of the abrasive, which were showed by an increase in the value of the parameter R_v.
3. The reduction of the values of R-parameters below the value of the reference sample (milled surface) occurred at grit size P150 in the direction perpendicular to the grain and at grit size P100 in the direction parallel to the grain. With the parameter R_a as the arithmetic mean height, there was a reduction in roughness of approximately 18 % in the direction perpendicular to the grain and approximately 16 % in the direction parallel to the grain. The reduction of other parameters was in an approximately similar percentage range.

4. The results confirmed the general theory of higher values in the direction perpendicular to the grain and lower values in the direction parallel to the grain. In most cases, a lower standard deviation was also measured in the direction parallel to the grain.
5. The theoretical assumption was confirmed that even in the case of the equality of the parameter R_a, the parameter R_z supplemented the information about the smaller measured hills and dales of the profile. Thus, even at the same R_a, different sanded samples can show a smoother or rougher surface.

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Streszczenie: W pracy oceniono zmianę parametrów chropowatości R_a, R_p, R_v i R_z szlifowanej powierzchni buka (Fagus sylvatica L.) w funkcji różnej wielkości ziarna i kierunku pomiaru. Zmielone próbki szlifowano szlifierką taśmową BS-75 E-set firmy Festool o ziarnistościach taśmowych P60, P100 i P150. Taśmy szlifierskie to Rubin 2 firmy Festool. Chropowatość oceniano przy użyciu mikroskopu cyfrowego Keyence VHX-7000. Długość ewaluacyjna pomiaru chropowatości wynosiła 12,5 mm ($\lambda_c = 2{,}5$ mm i $\lambda_s = 8$ mm). Parametry R zostały zmierzone zgodnie z najnowszymi normami ISO 21920 (2022) w kierunku równoległym do włókien oraz w kierunku prostopadłym do włókien (profil). Artykuł potwierdza teoretyczne założenia dotyczące redukcji wartości parametru R. Pomiary wykazały, że szlifowana powierzchnia była mniej chropowata w kierunku prostopadłym do włókien przy ziarnistości taśmy ściernej P150 oraz w kierunku włókien przy ziarnistości P100.

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