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Investigation into the Effects of Roller Pressing on Hardness, Roughness and Elastic Modulus of Wooden Workpieces

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Abstract: The paper investigates the effects of roller pressing on the hardness, roughness, and elastic modulus of wooden workpieces. For research purposes, a roller pressing device based on purely mechanical processing was designed and developed. Four different levels of pressing force have been applied to eight different types of wood: cherry, fir, alder, linden, beech, walnut, oak, and ash. The obtained results indicate that the proposed processing method can significantly improve the hardness, elastic modulus, and surface quality of wooden workpieces. The ash sample exhibited the largest relative increase in hardness (175.9%), while the most significant relative increase in the elastic modulus (66.73%) was measured on the linden sample. The largest relative decrease in surface roughness (54.75%) was achieved on the alder sample. For all types of wood except for fir, in which case an increase in pressing force did not produce the desired reduction of roughness, correlation coefficients indicate a strong relationship between the pressing force as an input variable and the elastic modulus, hardness, and roughness as output variables.

Keywords: roller pressing; wood; hardness; elastic modulus; roughness

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1. Introduction

Wood, along with metals, plastics, and composites, is one of the most widely used industrial materials. In addition to a lower price, the simplicity of processing and construction is one of its main characteristics. As an organic material with a beautiful natural texture, wood exhibits variations in its chemical, physical and mechanical properties even within the same species. Furthermore, the three principal axes define the differences in wood's structure and behaviour, and it responds in various ways to local temperature, humidity, and other influences. Therefore, the selection of appropriate parameters, both variables, and constants, is crucial when investigating wood processing [1]. Guitard [2] points out that on a macroscopic scale (10–200 mm), pure wood (without knots and deviations in grain size or other structural characteristics) is usually considered a homogeneous and continuous material. On the cellular level, the geometry and the internal cell arrangement can be defined via three local axes of material symmetry, the so-called longitudinal (L,1), radial (R,2), and tangential (T,3) directions. High-quality lumber is expensive and not always available in large quantities. Modification processes offer the possibility to improve the strength properties of wood, extend the lifespan of wood products, and expand the list of usable wood species. As the number of faster-growing species with shorter fatigue life increases, while quality wood becomes more difficult to acquire, modification processes become even more important. In a review paper, Sandberg et al. [3] define and describe three groups of modification processes that are most frequently used to improve the characteristics of wood: chemical processing (acetylation, furfurylation, resin impregnation, etc.), thermo-hydro processing (thermal treatment) and thermo-hydro-mechanical processing (surface densification). The chemical, physical and mechanical properties of wood depend on various factors such as the wood type and climate [4–6], growth conditions [7,8], and modification processes [9,10].

Thermo-hydro-mechanical processing of wood has been investigated from various aspects. Adachi et al. [11] applied roller pressing to mechanically remove water from flat sawn veneer and analysed the moisture content distribution after the processing. They also reported negative effects of compression on the thickness change and flexural strength. Inoue et al. [12] developed a method based on roller pressing to treat wood with either aqueous or non-aqueous solutions. Specimen length, thickness, compression rate, and feed speed were studied. Moisture contents, compression ratio, and the number of pressing cycles influenced the impregnation efficiency. Some researchers studied the surface densification of softwood by the use of a constant pressure in different thermo-hydro-mechanical (THM) treatments to improve the mechanical properties of wood. It is well known that the density of wood correlates with its mechanical properties. Furthermore, as a porous material, wood can be compressed until its density reaches the density of a cell wall, which is about 1.50 g/cm^3. That means that the density of the surface layer can be increased by up to 40% [13–16]. When heated, the wood softens and can be compressed without rupturing the cell walls. Sadatnezhad et al. [17] used a continuous press for wood panel production to apply constant pressure on low-density poplar samples along with the THM treatment. That led to densification within a few millimetres thick sub-surface zone. Considering the complex structure and anisotropic nature of wood, as well as the limitations of finite element analysis (FEA), Nairn [18] simulated the compression of wood using the material point method (MPM). The presented numerical calculations of densified wood structures provided insight into the relationship between wood anatomy and compression.

Elastic modulus and hardness are the two most important mechanical properties of wood. Reliable and accurate measurement of these properties is crucial to determining the durability of lumber in working conditions and selecting the appropriate type of wood for different purposes. The elastic behaviour of wooden elements loaded in bending is affected by many factors, including temperature, density and moisture content of wood, the geometry of the sample, and the loading rate. These influential factors have been the subject of many experimental studies [19]. The dimensions of knots are also a significant factor because the knot size negatively affects the mechanical strength of wood [20]. Various static and dynamic methods have been used for measuring elastic deformations and determining elastic modulus. Static methods are usually based on bending [21–27] or tensile testing [28], while dynamic methods include the resonance flexure method [29–31], ultrasonic methods [32–35], or the resonant (vibration) method [36]. Bending is often a preferred static method used to measure the elastic modulus [37,38], and it can be performed on a simple device with an accuracy of 2.6%, according to Miljojkovic et al. [39].

The hardness of the material is usually determined using the indentation technique. However, the hardness values depend on which tool is used and which parameters are measured. For wood, the anisotropy, heterogeneity, and hygroscopicity also affect the hardness measurement. Riggio and Piazza [40] described the advantages and limitations of existing methods for testing wood hardness. They pointed out that the first group of test methods, comprising standardised hardness test procedures based on static macro-indentation, such as Janka, Brinell, and Monnin, are not specially designed to estimate the hardness of the lumber. In contrast, a non-destructive method Piazza and Turrini, as a modification of the Janka method, is designed specifically for the mechanical characterisation of wood elements. Depending on the chosen measurement method, wood often exhibits qualitatively different behaviour. In order to mitigate the effect of visual measurements on the consistency and accuracy of the results, Lykidis et al. [41] proposed a modification to the Brinell method for determining the wood hardness. Instead of visual measurement of indentation diameter, they relied on the ability of modern testing devices to measure the indentation depth accurately. As a result, the obtained hardness values were in stronger correlation with the density of the material. The advantage of the modified Brinell method is that the reliability of the measured hardness values is less affected by the presence of coatings on the wood surface than the results of testing based on the original Brinell method. Koczan et al. [42] point out that rounded indenters, such as a ball (Brinell, Janka, Krippel, and Meyer tests) and a cylinder (Monnin test), are much better suited for wood. Due to the specific structure of wood, the hardness values at the longitudinal section are significantly lower than at the cross-section. Using beech samples, the authors tried to unify the methods of wood hardness testing according to Brinell, Janka, and Monnin, based on Meyer's law.

The surface quality is one of the essential properties of wood that affects the strength characteristics and the output quality of manufacturing processes such as joining and bonding. The main characteristic of surface quality is its roughness. Gurau and Irle [43], in their review paper, gave specific recommendations regarding the selection of instruments for roughness measurement, the measuring length, the measurement resolution, the elimination of form errors (with or without prior removal of wood pores), the use of a Gaussian regression filter, the appropriate cut-off length, the most useful roughness parameters for describing the processing roughness, and a method to separate the processing roughness from anatomical roughness. Tiryaki et al. [44] presented an artificial neural networks (ANN) model, which proved to be very useful for modelling the characteristics of wood surface roughness without conducting additional experiments, thus saving time and reducing the high costs of experimental investigations. Furthermore, to obtain higher surface quality, they suggested specific parameters of finishing tools and a high grit number of the abrasive for particular types of wood. To obtain lower values of surface roughness, a suitable method for the adjustment of process parameters is Taguchi [45]. The results of Taguchi analysis indicate that the variable that most significantly affects the surface roughness is the grit number of the abrasive.

Burnishing is a no-chip process in which the force applied to the material causes plastic deformation of a surface layer. During the burnishing process, a roller or a ball pushes surface materials from the peaks into the valleys, flattening the asperities, thus improving surface integrity, i.e., surface finish and hardness of a workpiece. This cold forming operation occurs on a small scale in which strain hardening enhances the surface hardness and strength, providing a mirror-like surface finish and compressive residual stress in the surface and subsurface layers resulting in better fatigue life [46,47].

The authors of this paper previously investigated how ball burnishing improves the mechanical properties of wood samples. Ball burnishing has a positive effect on surface roughness and can increase the hardness of surface layers of treated materials up to three times [48]. The treated samples have better water absorption resistance, of even more than 60%, depending on the type of wood [49]. The roller burnishing process requires less time than other finishing techniques. In addition, it achieves the best circularity of the holes, the highest microhardness, a more uniform structure of treated surfaces, an optimal combination of surface characteristics and mechanical properties, increased abrasion resistance of the finished surface, and the absence of notches. Finally, it is an environment-friendly process [50]. Dobrzynski et al. [51] wrote about the burnishing of wooden shafts in which the load, heat, and friction between the tool and the machined surface act simultaneously, improving the condition of the surface layer. Experiments were conducted on a lathe with a slide diamond burnisher and active (loading) forces of 30 N, 50 N, and 70 N. The treated elements were made of great maple (*Acer pseudoplatanus* L.). An arithmetical mean height of 2.85 μm was obtained with a relatively small dispersion of the results. Critical limiting factors during the investigation were the heterogeneous structure of the wood and the load force. During the burnishing process, an excessive increase in force applied to improve the hardness of wood can cause significant damage to the processed surface. On the other hand, densification of the surface layer of lumber by the use of this method reduces the consumption of varnishes and paints during the final processing of products such as balusters and mouldings. In certain wood processing methods, the applied pressure has significantly higher values than in the roller pressing process. In briquetting, high pressure is used to remove the air from the intermolecular space and cause the gradual densification of the material [52].

In previous research, wood processing was investigated from various aspects because the surface quality, hardness, and other factors related to the specific wood structure significantly affect the results. To achieve the most reliable and accurate values of wood characteristics, researchers continue to modify and improve standard measurement methods, using various statistical methods and process modelling based on artificial intelligence. Enhancement of wood characteristics by increasing the density of layers beneath the surface is accompanied by the improvement of chemical processing methods, heat treatment, and thermo-hydro-mechanical treatment of wood. However, the process described in this paper, although similar to both burnishing and rolling as it affects the enhancement of the surface layer by applying the pressure on the sample placed between two rollers, has not often been the focus of scientific studies.

In contrast to previous studies, this research aims to improve the characteristics of various types of wood by a process based on purely mechanical processing, i.e., roller pressing. A new method that uses pressure to achieve densification of the surface layer was developed, and a device for processing the wood samples by roller pressing was designed. The effects of the proposed processing method on hardness, elastic modulus, and roughness were analysed on eight different types of wood.

2. Materials and Methods

A schematic representation of a novel processing of wooden workpieces by roller pressing is provided in Figure 1. The workpiece, passing between two rotating rollers, is under the action of pressing force F. The force acts on surface A, whose size depends upon the rollers' diameter R. To achieve the identical depth of the deformed layer on both sides of the wood sample, the diameters of the rollers must be identical. The roller penetration depth h depends not only on the force and the size of surface A. It is also affected by angular velocity ω, which defines the holding time of load in a particular zone of the workpiece. Furthermore, due to the inhomogeneous structure of wood, the roller penetration depth is affected by the inhomogeneity of the material in the processing zone. Elastic deformation (elastic recovery) of the material, Δa_e, which occurs after the processing, and its influence on the final dimension (thickness) a_f of the processed workpiece, must be considered as well.

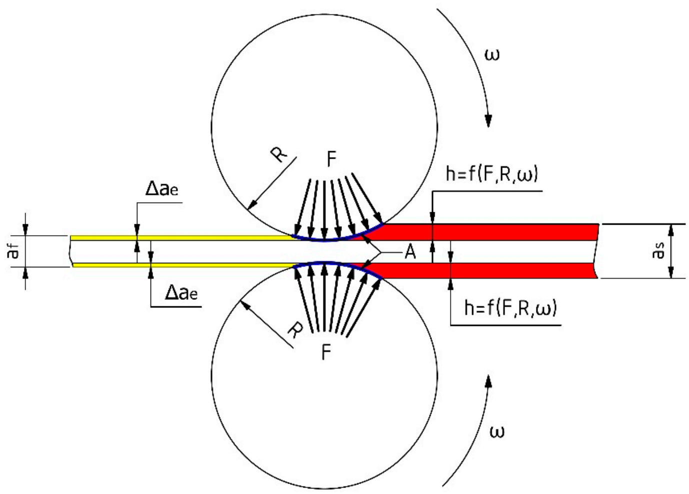

Figure 1. Schematic representation of roller pressing process.

Roller pressing is conducted on a specially developed device shown in Figure 2. The base plate (1) and vertical plates (2) are interconnected by bolts, forming a framed structure. The device is resting on horizontal support and levelled by the adjusting screws, which is important for the correct realisation of the normal force, i.e., the force of rollers' penetration into the material. Fixed to the base plate via carrier (4), a stepper motor (5) is connected by a belt drive (6) to the lower, i.e., drive roller (7), which has only one degree of freedom—rotation about its central axis.

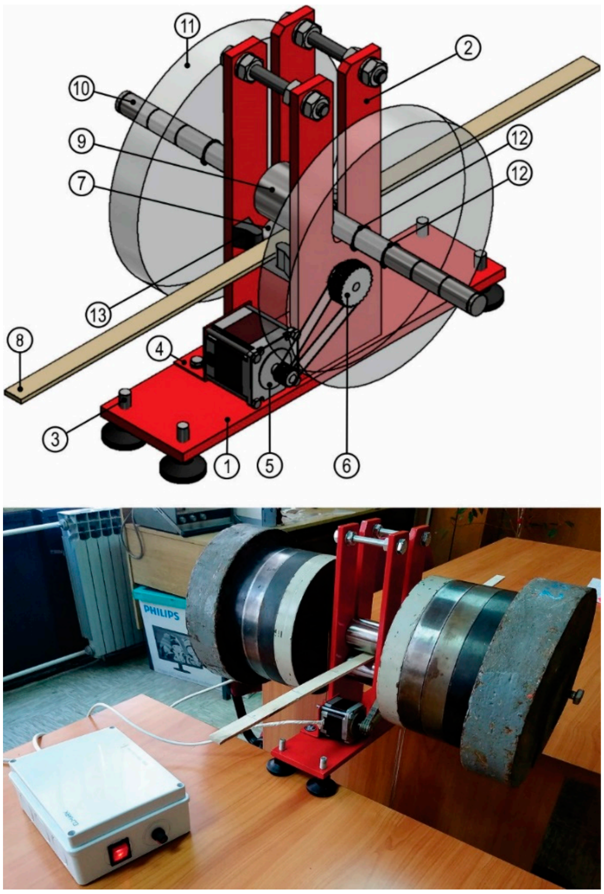

Figure 2. Device for the processing of wood samples by roller pressing.

The angular velocity of the drive roller is regulated by the control unit of the stepper motor. All tests were performed at an auxiliary speed of 250 mm/s. A workpiece (8) is placed between the lower, i.e., drive roller (7) and the upper, driven roller (9). The diameters of both rollers are 50 mm. On a shaft (10) passing through the upper roller, weights (11) are placed to achieve the pressing force. The construction solution enables translational motion of the upper roller, shaft, and weights along the groove on the vertical plate (2). The processing is performed at a constant force of rollers' penetration into the workpiece. The force is achieved by placing weights of identical mass left and right of the workpiece axis at equal distances. The Seeger rings (12) placed in the grooves on the shaft secure the weights' position on both sides. The limiters (13) prevent the workpiece movement in the axial direction of rollers.

Effects of the described roller pressing method were investigated on eight different types of wood: oak, beech, ash, walnut, fir, cherry, linden, and alder (Figure 3). All samples were with identical cross-sections of 40 × 10 mm. To achieve uniform test conditions, samples were prepared taking into consideration the fibre orientation. Testing of each type of wood was conducted on thirty samples to make the influence of factors such as material inhomogeneity or wood moisture negligible.

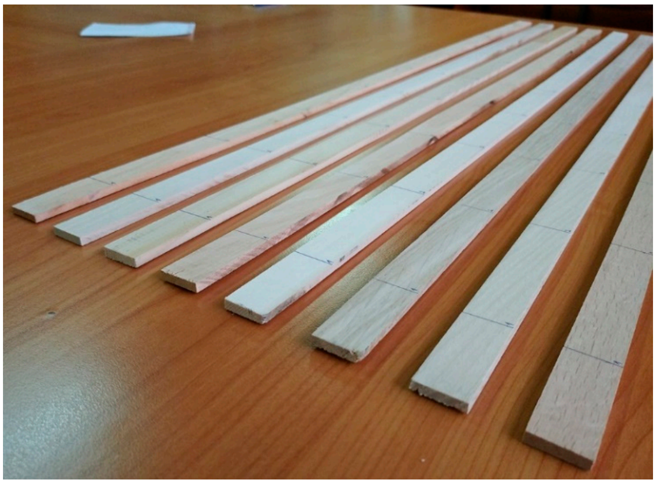

Figure 3. Test samples.

Before and after the roller pressing treatment, the hardness and roughness of the processed surface were measured and the mean values of the elastic modulus of samples were determined. The processing of wood blanks was performed by applying the following values of pressing force: 392 N, 785 N, 1177 N, and 1570 N. To achieve greater deformation of the surface layer, the processing was carried out in four passes. Measurements were repeated thirty times.

The hardness was measured according to the EN 1534 standard. A thin layer of black paint was applied to the indenter before each indentation to leave a visible trace, considering the weak reflection of the wood surface. The use of paint allows accurate reading of the results, reducing the error in measurement of the indentation diameter, especially in the direction of fibres. The indentation diameter was measured on a Meiji Techno M-50T optical microscope (Figure 4).

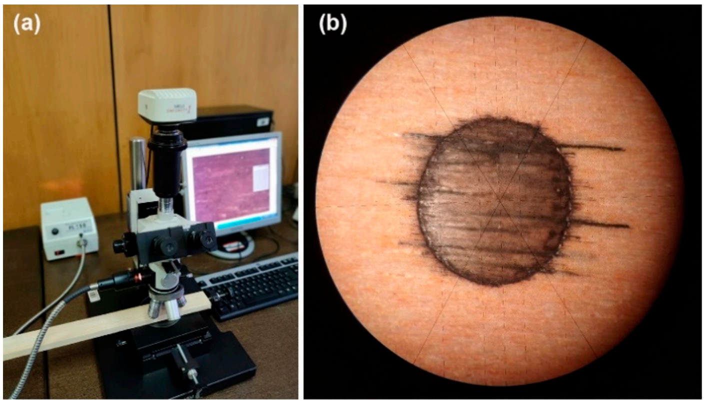

Figure 4. Hardness measurement: (**a**) the process, (**b**) the indentation.

The elastic modulus was measured on a specially developed measuring device (Figure 5) [39]. The elastic modulus was determined by measuring the test sample deflection f under the action of force F at a distance $L/2$ from each support. The deflection size is affected by the shape and dimensions of the cross-sectional area of the tested sample. Considering that the cross-section of tested samples is rectangular, the dimensions measured before and after each treatment are the thickness h and the width b. Based on the measured quantities, the elastic modulus is calculated using the Euler–Bernoulli beam equation:

$$E = \frac{F \cdot L^3}{48 \cdot f \cdot I} = \frac{F \cdot L^3}{48 \cdot f \cdot \frac{b \cdot h^3}{12}} \quad (1)$$

whereas E—the elastic modulus, F—the bending force, L—the distance between supports, f—the measured deflection due to the action of bending force, I—the momentum of inertia for rectangular cross-section, b—sample width, and h—sample thickness. During the processing, a certain amount of material on the sample sides is squeezed out due to the action of pressing force. Considering that the elastic modulus is calculated based on the rectangular shape of the cross-section, the sides of each sample were ground after processing to achieve the required cross-section.

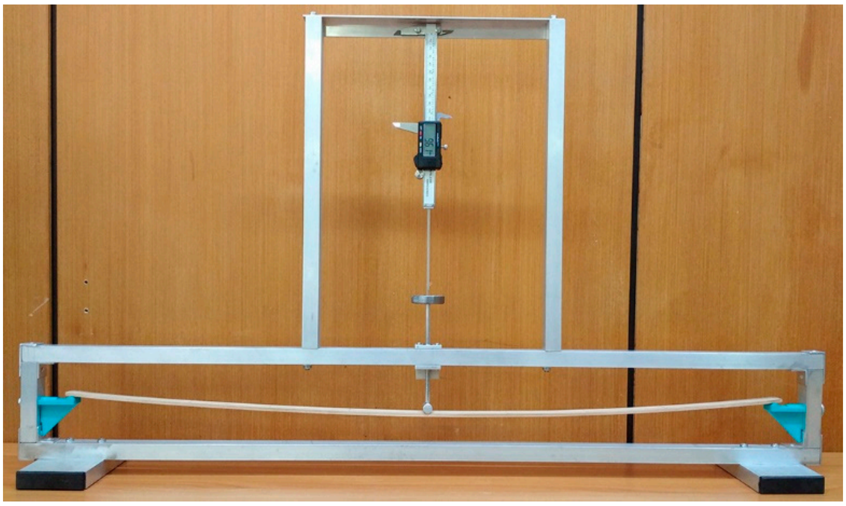

Figure 5. Elastic modulus measurement.

The surface roughness (arithmetic mean roughness Ra) was measured before and after processing on the device INSIZE ISR-C002 (Figure 6) by using the contact method. The force was 4 mN, the speed—0.5 mm/s, the cut-off length—2.5 mm (four cut-offs), the diamond stylus radius—5 µm, and the length of evaluation—10 mm.

Figure 6. Surface roughness measurement.

3. Results and Discussion

The results, i.e., the arithmetic mean values of hardness, elastic modulus, and roughness measurements performed before and after each roller pressing, are provided in Tables 1–4.

The results of hardness measurement (Tables 1 and 2, Figure 7) indicate an increase in hardness of all wood samples after roller pressing treatment. It is a direct consequence of the increase in wood density. The surface layer exhibits the most significant change in density, while the smallest changes occur at half the thickness of the processed samples. Figure 8 shows the microstructure of the maximum deformation zone, moderate deformation zone, and undeformed zone of the processed sample.

Table 1. Hardness, elastic modulus, and roughness of wooden workpieces before roller pressing.

Wood Type	HB	E (MPa)	Ra (μm)
Cherry	2.007	7997.82	6.731
Fir	2.102	10,227.18	5.774
Alder	2.188	8797.24	9.064
Linden	2.36	13,752.09	5.936
Beech	3.107	11,823.74	7.399
Walnut	3.372	8594.25	7.214
Oak	3.078	13,386.74	9.344
Ash	2.788	10,779.82	11.086

Table 2. Hardness of wooden workpieces after roller pressing.

Wood Type	Pressing Force F (N)			
	392	785	1177	1570
Cherry	2.095	3.225	3.365	3.954
Fir	2.603	2.739	2.823	2.36
Alder	3.084	3.439	3.517	3.512
Linden	2.46	2.579	2.955	2.516
Beech	3.587	4.146	4.394	4.686
Walnut	3.68	4.379	5.157	5.505
Oak	3.096	3.495	3.626	5.411
Ash	3.679	5.127	5.718	7.693

Table 3. Elastic modulus of wooden workpieces after roller pressing.

Wood Type	Pressing Force F (N)			
	392	785	1177	1570
Cherry	8319.65	9179.55	9633.2	9534.54
Fir	10,660.3	11,683.07	14,036.21	12,696.9
Alder	9014.75	9637.57	9942.77	9523.9
Linden	15,239.1	17,625.72	22,928.77	19,946.6
Beech	12,316	13,249.53	14,486.93	13,947.6
Walnut	8751.26	9249.76	9333.5	9569.54
Oak	14,018.2	15,821.92	15,999.43	16,020.3
Ash	10,785.1	11,362.02	11,485.04	11,250

Table 4. Mean arithmetic roughness of wooden workpieces after roller pressing.

Wood Type	Pressing Force F (N)			
	392	785	1177	1570
Cherry	4.771	3.37	3.635	4.291
Fir	5.106	7.255	10.768	11.525
Alder	5.261	4.37	4.101	4.301
Linden	4.229	3.524	3.536	3.711
Beech	6.082	5.593	5.485	5.6
Walnut	5.078	4.122	4.015	3.348
Oak	7.359	6.6	7.456	8.27
Ash	8.613	7.177	6.961	7.504

Regarding the increase in hardness, the presented method has better outcomes when used on certain types of wood: ash (175.9%), cherry (88.7%), oak (75.8%), walnut (63.2%), alder (60.5%) and beech (50.8%). The percentage increases in hardness, given in parentheses, were measured after the processing by applying the maximum normal force of 1570 N. The hardness of the cherry sample at the force of 1570 N is higher than the hardness of all untreated wood samples, including hardwoods such as walnut, oak, beech, and ash. The hardness of alder after the processing is approximate to the hardness of beech, walnut, oak, and ash before processing. Therefore, it can be concluded that, after being processed by roller pressing, cherry and alder can replace oak, walnut, ash, and beech in most structures where hardness is the most important quality criterion. Bearing in mind that cherry and alder have a less frequent industrial application than beech, oak, and walnut, their price is significantly lower [53–55], so the proposed method is associated with economic benefits as well.

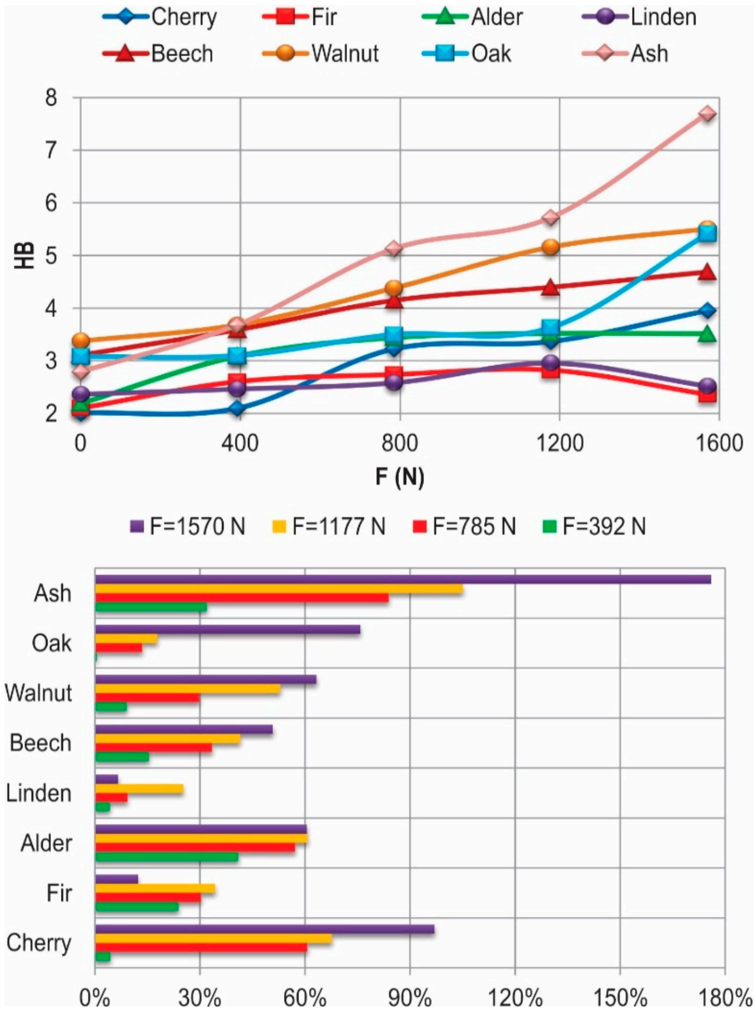

Figure 7. The change and percentage increase in hardness of wooden workpieces after roller pressing.

Figure 9 shows the change in hardness of wood samples depending upon the measured thickness reduction due to the surface densification during roller pressing. The points on each curve denote the pressing force of 392 N, 785 N, 1177 N, and 1570 N, respectively. The presented diagram indicates a significant thickness reduction of fir and linden samples whose hardness is not significantly increased. In hardwoods, i.e., ash, walnut, oak, and beech, a smaller change in thickness causes a greater increase in hardness. For each type of wood, the diagram enables one to determine the penetration depth needed to achieve the desired hardness. As both sides of the workpiece are almost equally deformed, the roller's penetration depth equals approximately half of the measured thickness reduction. Only the samples with no visible imperfections were selected to ensure the homogeneity of the test material, as recommended in the literature. Namely, according to Guitar [2], on a macroscopic scale (up to 200 mm), such samples can be considered homogeneous. As normal force affects both sides equally and the sample width is equal on both sides, as well as the diameters of rollers, the stresses and deformations are expected to be approximately equal on both sides. The experiments have proven that the proposed method of wood processing does not cause changes in the shape of the samples; thus, based on findings and literature sources, it can be concluded that the deformations of the samples were almost equal on both sides.

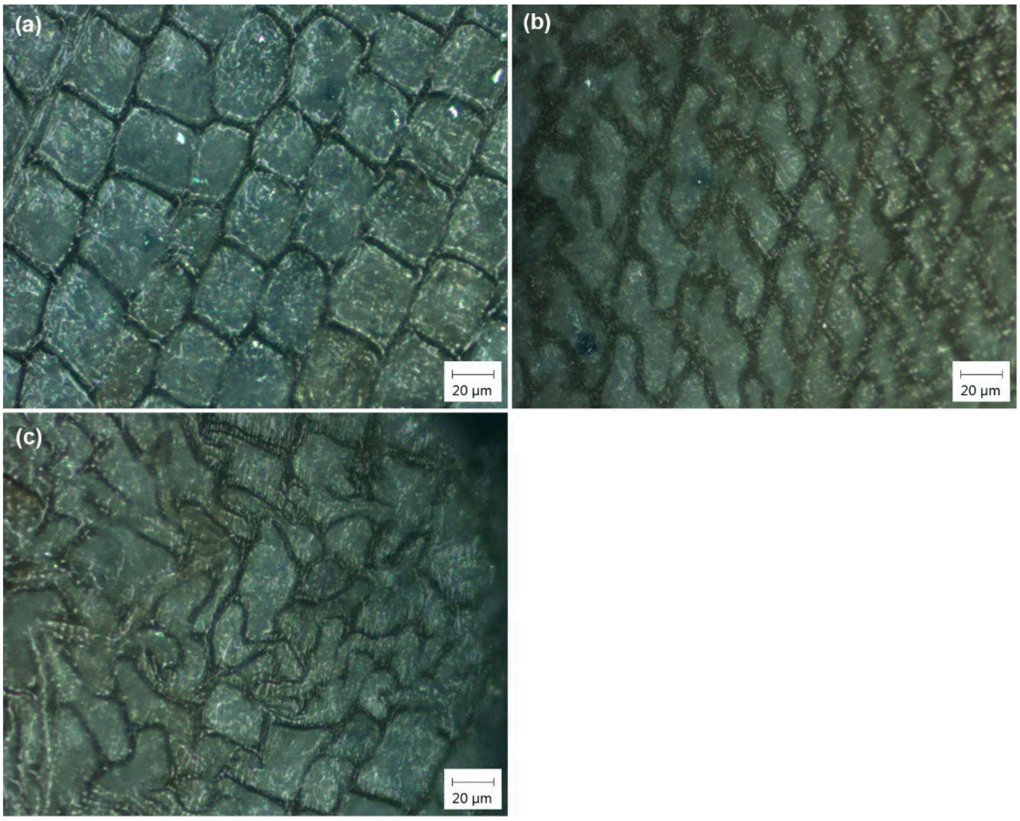

Figure 8. Microstructure linden sample after roller pressing: (**a**) at a depth h/2, (**b**) at a depth h/4, (**c**) the surface layer.

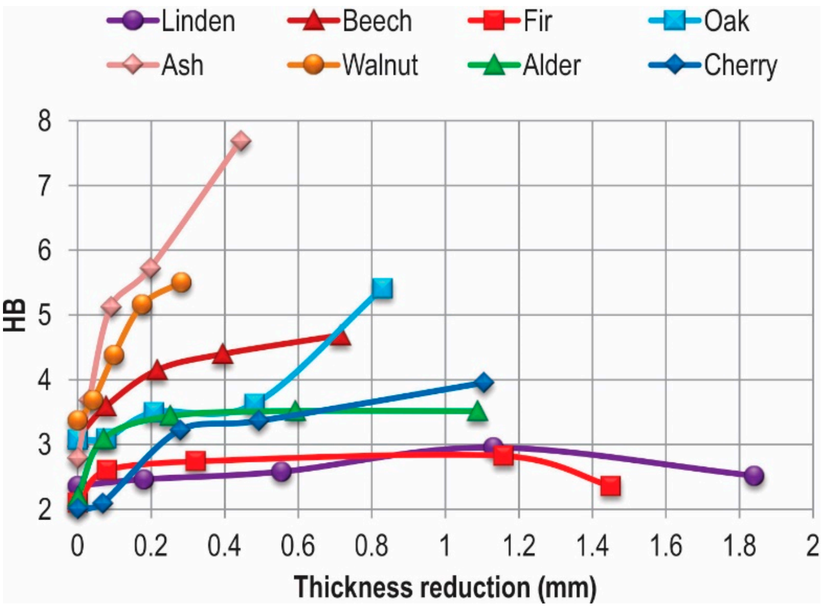

Figure 9. Change in the hardness of wooden workpieces after roller pressing, depending upon the penetration depth, i.e., the thickness reduction.

In the case of fir and linden, the achieved improvement of hardness was not very significant. The maximum increase in hardness of these two types of wood was observed after processing them by applying the force of 1177 N. The hardness of fir was increased by 34.3%, while the increase in hardness of linden was 25.2%. A further increase in the pressing force does not produce a greater hardness, so it has no practical significance. As shown in Figure 10, the pressing force, when increased from 1177 N to 1570 N, destroys the wood structure, which reduces the hardness of the fir sample.

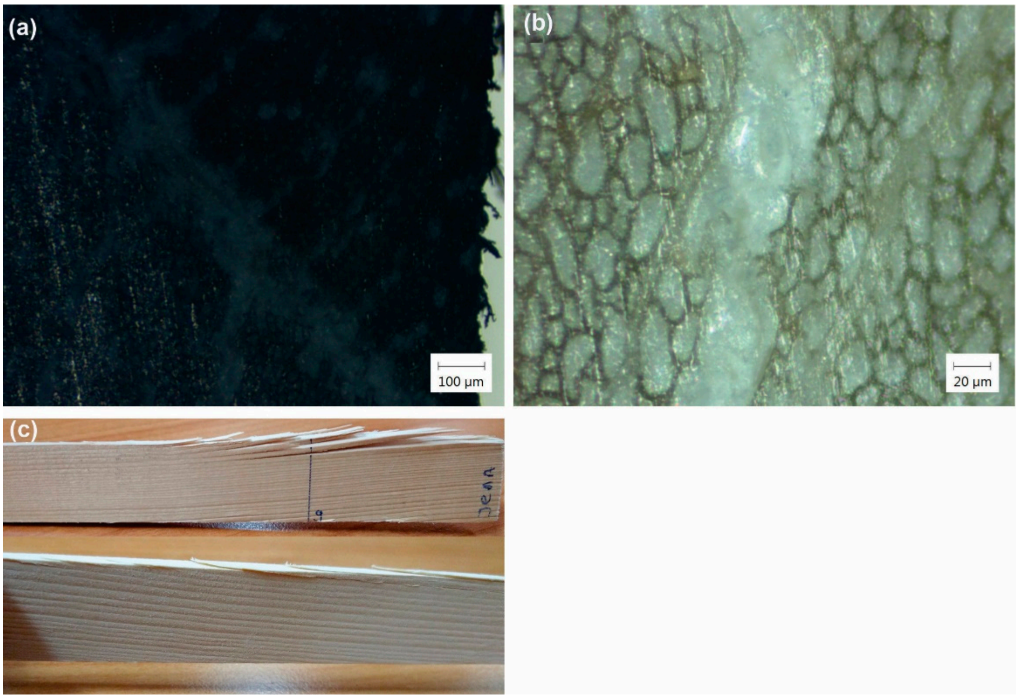

Figure 10. Structure of the fir sample after the processing by applying the force of 1570 N: (**a**) cracks, magnified 5×, (**b**) crack, magnified 20×, (**c**) damaged macrostructure.

Results of the elastic modulus measurement (Tables 1 and 3, Figure 11) indicate that all wood samples had an increase in the elastic modulus after being processed by roller pressing. The most significant relative increase in the elastic modulus of 66.73% was measured on a linden sample, processed with the force of 1177 N. Elastic modulus of a fir sample increased by 37.24% after being processed by applying the force of 1177 N. As discussed before, a further increase in the pressing force has no practical significance because it only leads to the damaging of the wood structure (Figure 10). From the measurement results, it can be concluded that the most significant relative increase in the elastic modulus was achieved on softer types of wood, i.e., on samples that, under the action of a specific pressing force, suffered the largest plastic deformations, which caused the largest increase in density (Figure 12).

The diagrams in Figures 7, 9, 11 and 12 and Tables 2 and 3 clearly show that the relative increase in hardness is not associated with an identical relative increase in the elastic modulus. For example, the diagram in Figure 12 indicates that the elastic modulus of oak, ash, and walnut samples increased after the treatment with pressing forces of 392 N and 785 N. Larger values of pressing force did not produce a significant increase in elastic modulus, but they did improve the hardness (Figure 9). Therefore, it can be concluded that the proposed method has great potential in the processing of hardwood elements (ash, beech, oak, and walnut) for the furniture industry, where hardness is considered a primary quality criterion.

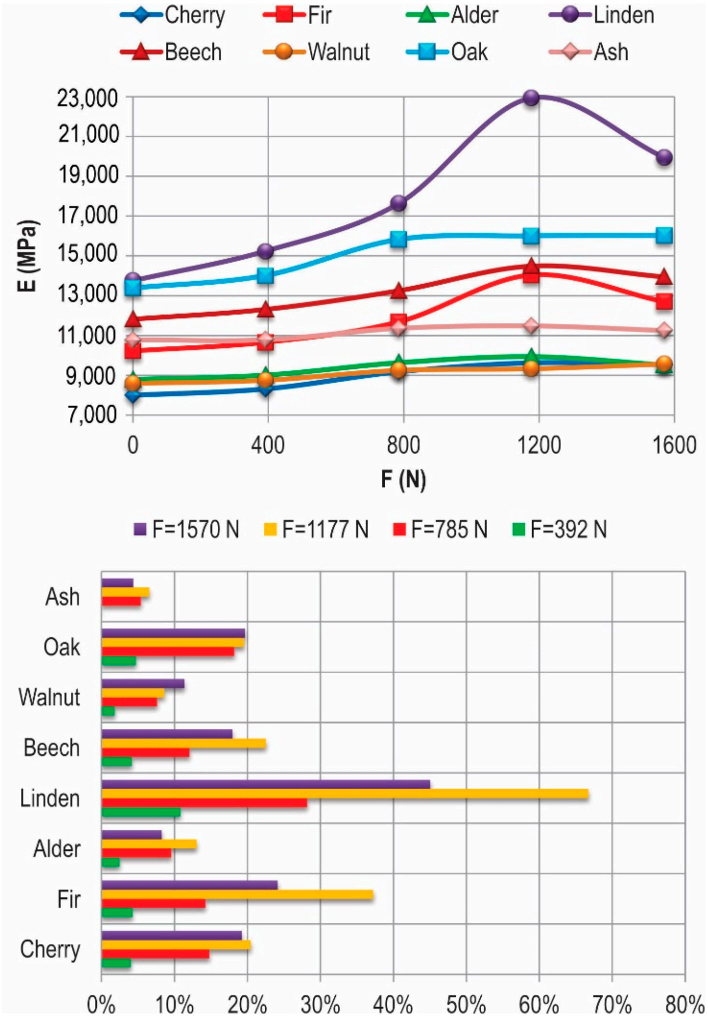

Figure 11. The change and percentage increase in elastic modulus of wooden workpieces after roller pressing.

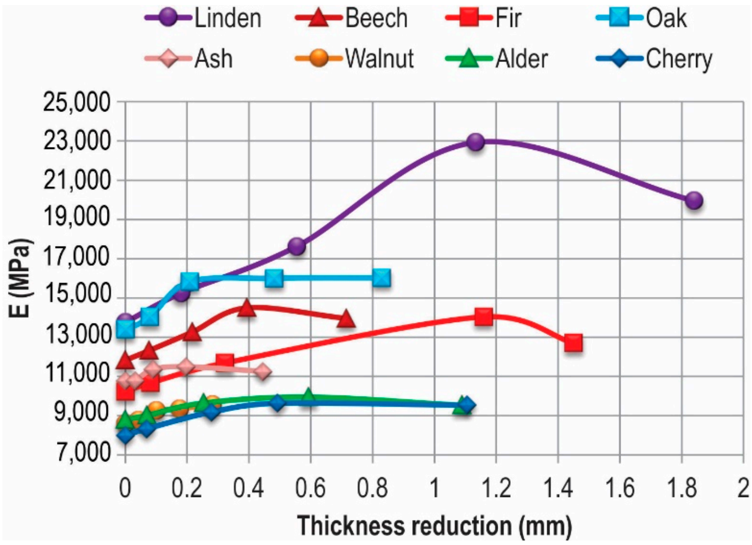

Figure 12. Change in the elastic modulus of wooden workpieces after roller pressing, depending upon the penetration depth, i.e., the thickness reduction.

The obtained experimental results related to the elastic modulus prove that softer, more lightweight, and cheaper types of wood (linden and fir) have a significantly higher relative increase in stiffness after being processed using the proposed method. Therefore, they can be used as construction materials instead of heavier and more expensive wood types (oak, beech, ash, walnut) if the primary quality criterion is the elastic modulus, i.e., stiffness. Furthermore, bearing in mind that linden and fir grow faster than beech, oak, walnut, and ash [7], the proposed method is associated with economic benefits as well.

The analysis of the results related to the quality of the treated surface (Tables 1 and 4, Figure 13) leads us to conclude that the proposed processing method has positive effects in reducing the surface roughness. The achieved relative reduction of the arithmetic mean deviation of roughness profile Ra ranges from 11.57% on the fir sample to 54.75% on the alder sample. As the diagrams in Figure 13 show, different types of wood require different pressing forces to achieve the minimum surface roughness. On fir, the minimum surface roughness was measured after applying the force of 397 N. Larger values of pressing force have only led to the deterioration of the surface quality due to the damaged surface structure, as discussed before. The best results in surface roughness on linden, oak, and cherry samples were recorded when the force of 785 N was applied. Achieving the minimum surface roughness on beech, ash, and alder samples required the force of 1177 N. The largest relative decrease in surface roughness of 53.6% was measured on the walnut sample at 1570 N.

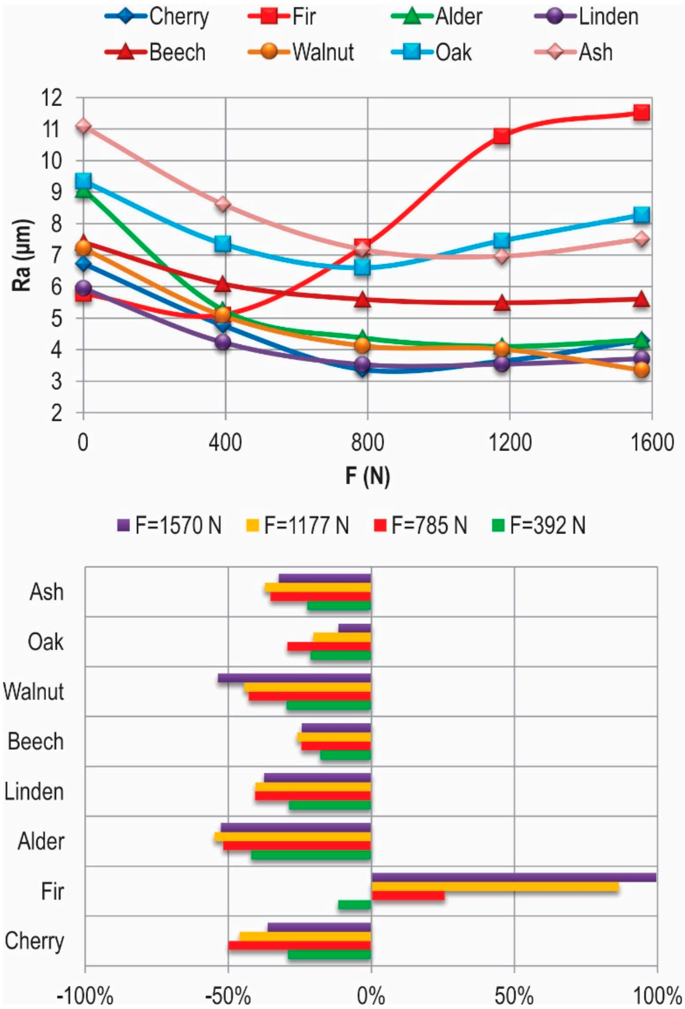

Figure 13. Change and percentage increase/decrease in the arithmetic mean deviation of roughness profile after roller pressing.

Figure 14 indicates how the rollers' penetration depth affects the surface roughness in different types of wood. The optimum penetration depth, corresponding to the minimum surface roughness, can be determined for each type of wood by analysing the diagrams in Figure 14. This information is valuable in practice when the processing is based on the specified penetration depth instead of the force of penetration (pressing force). It is important to note that, in the case of linden samples, the force values that are larger than the optimal 785 N corresponding to the minimum value of Ra have almost no influence on the surface roughness (Figures 13 and 14). That leads to the conclusion that linden has an excellent ability for plastic deformation without structure destruction, which results in a large relative increase in the density and elastic modulus.

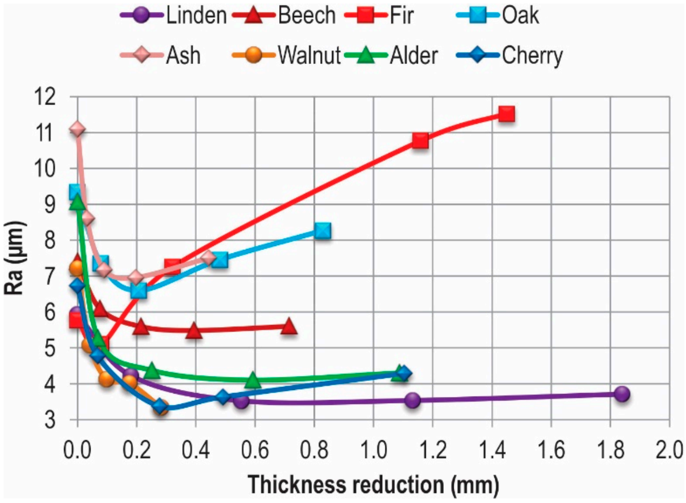

Figure 14. Change in the arithmetic mean deviation of roughness profile after roller pressing, depending upon the penetration depth, i.e., thickness reduction.

The calculated correlation coefficients between the pressing force as an input variable and the elastic modulus, hardness, and roughness as output variables, are given in Table 5.

Table 5. Values of the correlation coefficients between the pressing force and the elastic modulus, hardness, and roughness.

Wood Type	Hardness	Elastic Modulus	Roughness
Cherry	0.93	0.96	−0.90
Fir	0.92	0.94	0.88
Alder	0.92	0.98	−0.89
Linden	0.94	0.99	−0.90
Beech	0.98	0.98	−0.92
Walnut	0.98	0.96	−0.92
Oak	0.95	0.96	−0.71
Ash	0.99	0.93	−0.94

For all tested types of wood, high values of correlation coefficients (>0.9) indicate a strict dependency of both the elastic modulus and hardness on the pressing force, which confirms the effects of roller pressing on the improvement of mechanical properties of wood.

As the values of the correlation coefficients between force and roughness indicate, cherry, linden, beech, walnut, and ash exhibit a strict negative dependence. Therefore, roller pressing is certainly a recommended method for reducing the surface roughness of these types of wood. The remaining wood types show high negative dependence, except for fir. Roller pressing cannot reduce the roughness of fir, so it is not a recommended method for that type of wood.

4. Conclusions

The paper considered the roller pressing applied to different types of wood to improve their mechanical and other characteristics. The conducted experimental research focused on analysing how the change in hardness, surface roughness, and elastic modulus depends upon the pressing force, i.e., upon the thickness reduction at various values of force and the corresponding increase in the density of the wood. The obtained results indicate that roller pressing has positive effects on the hardness, elastic modulus, and roughness of the processed surface. The ash sample exhibited the largest relative increase in hardness, while the most significant relative increase in the elastic modulus was measured on the linden sample. The correlation coefficients confirm the strongest relationship between the mentioned characteristics (and wood types) and the pressing force. After being modified by roller pressing, the types of wood with otherwise inferior mechanical characteristics become suitable for application wherever higher values of strength and hardness are required. They could be a proper alternative to higher-quality wood types which are becoming increasingly difficult to acquire. The largest relative decrease in surface roughness was achieved on the alder sample. The surface quality is one of the most important properties of solid wood, closely related to its strength characteristics as well as the joining and bonding quality [44,56,57]. The potential enhancement of mechanical and other properties is especially significant for lower-quality wood, considering the declining availability of high-quality lumber and its market price.

Limitations of the research are related to the fact that initial conditions concerning the humidity were not identical for all samples. Therefore, absolute data comparison between different types of wood was not possible. However, all tests on one type of wood were carried out on the same day and under controlled conditions, which allows a relative comparison of the results.

Future investigations should focus on optimising the pressing force to determine its critical value, i.e., the value that wood samples can withstand without being destroyed. The aim is to achieve the maximum increase in the density of the surface layer, that is, to increase the hardness and elastic modulus while reducing roughness. Furthermore, future research should deal with other parameters, such as rollers' diameters and rotation velocity that affect samples' mechanical and physical characteristics. Additionally, the research may be directed towards multi-criteria evaluation and multi-criteria optimisation of output parameters for different input parameters of the processing.

In further research, the obtained results should be correlated with the chemical, physical and energetic properties of wood. As mentioned earlier, wood properties differ even within the same species and strongly influence wood performance. Due to the complex nature of wood, a single approach is not sufficient to completely define its properties. The correlation between the obtained results and the properties of wood would further elucidate and help optimize and improve the performance of investigated wooden workpieces [52,58].

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