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Investigation of ball burnishing processing on mechanical characteristics of wooden elements

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Abstract

Numerous research results indicate that the finishing processing of metal materials using ball burnishing has positive effects from the aspect of surface roughness decrease to the hardness increase in the surface layers of the processed materials. Little research has been devoted to this type of processing for nonmetal materials. This paper presents research results related to the influence of ball burnishing processing on the hardness increase of a wooden element. It was determined that the hardness can be increased up to three times for processing of wood using this technology, which is not the case for processing of metal materials.

Keywords

Ball burnishing, hardness, micro-hardness, nano-indenter, wood

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Introduction

Wood is the most widely used industrial raw material in the world. In industry, wood is used as an engineering material either in a natural or in a processed state. Despite the fact that today metals, plastics and composites are used more, wood is still much used for making different products. When choosing wood as an engineering material, one should take into account its physical characteristics such as: density, distribution layer and fibre, strength and elasticity, hardness, flexibility, tendency to shrinkage and swelling, humidity, heat and thermal conductivity, toughness, and colour and lustre after processing. Wood is composed of cellulose, lignin and inorganic materials. In terms of chemical composition, about half of the wood is carbon, approximately 40% oxygen, the remainder consisting of hydrogen, nitrogen and ash (K_2O, P_2O_5, CaO). From species to species wood does not change significantly in chemical composition, but the physical properties can be very different. One major influence on the mechanical properties of wood is humidity, whereby an increase of humidity to the point of fibre saturation leads to a loss of strength. Besides oxygen, the presence of moisture is one of the important factors that influences the development of putrefaction. In order to protect wood from putrefaction, basic processes such as different drying procedures and different protections of wood from moisture (i.e. polishing, painting, etc.) can be applied. Putrefaction of wood is due to the presence of moisture and oxygen in the tree.

Burnishing is a cold finishing process and no-chip process that applies a sufficient force over the yield strength of materials to produce plastic deformation of a surface layer, in which a roller or a ball pushes surface materials from the peaks into the valleys; thus the asperities are flattened.[1–6] Many previous investigations of burnishing processes have been focused on the ball burnishing process, due to its advantages.[3,7] Randjelovic et al.[3] used FEA and an experiment to demonstrate that the initial surface roughness has no significant effect on the surface quality achieved by ball burnishing. Tadic et al.[4] analysed the influence of ball burnishing tool stiffness on surface roughness. These workers compared the elastic burnishing tool with the high-stiffness burnishing tool. Lin et al.[8] analysed surface roughness from the perspective of tribological theory. The study proposed a useful parameter for assessing the optimum combination of burnishing

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parameters. Sequera et al.[9] investigated the effects of burnishing ball size and pressure on surface topography, roughness and hardness. Abu Shreehah[10] analysed the effect of an elastic ball burnishing tool on surface hardness and surface roughness. He found that all the burnishing parameters examined had a significant effect on surface roughness and surface hardness. Hamadache et al.[11] studied the effects of burnishing parameters as well as initial roughness on surface roughness and microhardness after the ball burnishing process. Their results showed that burnishing force, burnishing ball radius and number of tool passes had the most significant effects on surface roughness and microhardness. El-Taweel and El-Axir[12] studied the effect of the ball burnishing parameters on surface hardness and roughness. The Taguchi technique was employed to identify the effect of burnishing parameters on surface roughness and surface hardness. Ibrahim et al.[13] used a fixture (i.e. centre rest) as a burnishing tool. They utilised fuzzy logic to control the burnishing parameters. Esme[14] investigated the multi-response optimisation of the burnishing process using the Grey relational analysis and Taguchi method. Bougharriou et al.[15] performed an analytical study and FE modelling to predict the residual stresses and the influence of the burnishing parameters on the surface roughness. Gharbi et al.[16] developed a mathematical model to predict the surface roughness as a function of speed, force and feed rate. The results indicated that burnishing with an especially designed tool improved ductility but did not improve hardness. Babu et al.[17] reported the effects of burnishing parameters on the surface characteristics, microstructure and microhardness. Based on optimal burnishing parameters, they presented burnishing maps. Korhonena et al.[18] created a novel burnishing tool. They used this tool to improve the surface finish and surface hardness. Grzesik and Zak[19] investigated a sequential machining process of hard surfaces with cryogenic precooling. The microstructure and texture changes induced by burnishing were examined. Revankar et al.[20] employed the Taguchi method to determine the best combination of ball burnishing process parameters to minimise surface roughness and maximise hardness. Zak et al.[21] performed quantitative microstructure analysis. They analysed the distribution of micro-hardness in the subsurface layer before and after burnishing. Mohammadi et al.[22] employed different optimisation techniques to find the optimum burnishing parameters. The effect of burnishing parameters on the profile of the developed residual stress and plastic deformation were determined. Stalin John and Vinayagam[23] modelled and optimised burnishing process by the fuzzy neuro system. The system was used to model the surface roughness and hardness after the ball burnishing process. Grochała et al.[24] presented a kinematic–geometric model of the residual stress in the surface layer. They presented the results of a numerical experiment in the surface layer. Revankar et al.[25] used the Taguchi method for the optimisation burnishing parameters. They analysed the influence of burnishing parameters on the surface roughness and surface hardness. Travieso-Rodrigueza et al.[26] tested aluminum specimens to find the optimal vibration-assisted burnishing parameters. No significant consequences were found on hardness and residual stresses.

These studies were mostly focused on the effects of ball burnishing parameters (viz. burnishing force, burnishing speed, burnishing feed rate, burnishing number of passes, ball burnishing diameter, etc.), workpiece/burnishing tool materials, burnishing tool shapes and contact types, on surface hardness and surface roughness, as well as on residual stresses. The analysis of previous investigations points to the conclusion that ball burnishing can be successfully applied to various types of materials, such as: steel, aluminium alloys, titanium alloys, magnesium alloys, brass alloys, etc. Notably, there have been no studies dedicated to the application of ball burnishing on wood workpieces in order to increase their hardness and resistance to moisture.

In contrast to the previous works, the goal of this study is to investigate the influence of ball burnishing on the mechanical characteristics of surface wood layer, while determining the optimal depth of ball penetration into the wood workpiece. Our major assumption is that wood finishing by ball burnishing treatment can significantly increase its hardness and the density of the surface layer. It was also assumed that high contact pressures lead to a substantial increase of wood hardness. This, in turn, increases surface layer density and reduces the flow of oxygen and moisture from the environment into the inner structure of wood; thus it is realistic to expect a longer service life of the items treated in this manner.

Experimental investigation

For experimental investigation, treated beech wood was selected. Before proceeding to ball burnishing, the wood is dried, planed and polished in order to ensure identical initial conditions for all examined samples. The process of ball burnishing was performed at single spindle vertical milling machine numerical HAAS Toolroom Mill TM-1HE.

To perform the experiment, a rigid tool[4] for ball burnishing was used, with different values of the contact pressure generated by varying the values of the penetration depth of the balls.

The stiffness of the tool is very high and is determined by the deformation that occurs in the contact balls and three radial bearings that are arranged under the spatial angle of 120° degrees relative to the direction of penetration balls in the material of the workpiece. This concept of tool with reliance balls in the region of three points ensures the complete rolling balls in the plane of processing. Figure 1 shows

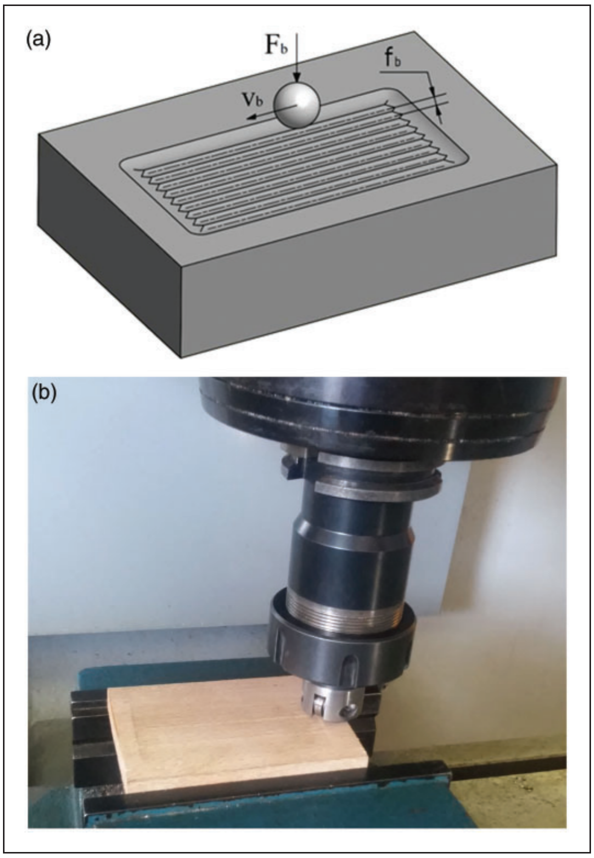

Figure 1. Ball burnishing. (a) schematic view (F_b—ball burnishing force, v_b—ball burnishing speed, f_b—ball burnishing feed rate), (b) photographic view.

a schematic view of the ball burnishing process and a photographic view of the burnishing tool in the process of machining.

The experiment was performed with a ball that is made of steel A 295 52100, the hardness of 65 HRC and surface roughness of 0.02 µm. The dried, milled and polished wooden plate (workpiece) with a thickness of 11 mm is placed in fixture on the vertical milling machine tool. The normality of the axis milling machine tool spindle and the surface of the workpiece, as well as determining the depth of penetration balls, is checked by a comparator (3D-Taster), which is placed in the machine tool spindle. Figure 2 gives a photographic view of the control regularity of locating and clamping the workpiece in the fixture.

Ball burnihing is performed on a single workpiece of wood in the field length 80 mm and width 10 mm. In order to define the optimum process parameters, the penetration depth ranging from 0.05 to 0.75 mm in steps of 0.1 mm were varied. The process is carried out with a ball diameter of 7 mm, at a speed of 2000 mm/min and transverse steps of 0.1 mm.

After successfully finishing, the ball burnishing workpieces were cut and marked. This is necessary due to the dimensional limitations of the device for determining the mechanical properties of the burnishing

Figure 2. Photograph of control normality surface of the workpiece and the spindle axis vertical milling machine tool.

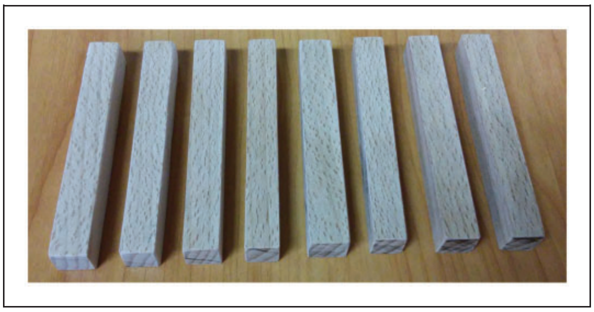

Figure 3. Photograph of samples with different depths of penetration during ball burnishing.

surfaces. In Figure 3, the samples are shown with different penetration depths during ball burnishing.

After ball burnishing of the workpieces, measuring the hardness and microhardness with the Brinell method was carried out. Measurements of microhardness were performed on a nano-hardness tester (Anton Paar NHT2) using a regular trilateral ‘Berkovic diamond pyramid’. These tests were performed in a 3×3 matrix, in the following terms:

- distance between impress: 80 µm;
- normal load: 15 mN;
- speed of loading/unloading: 30 mN/min;
- time of maximum load: 45 s.

When the force acts on the indenter over an area whose characteristics are determined, there are elastic and

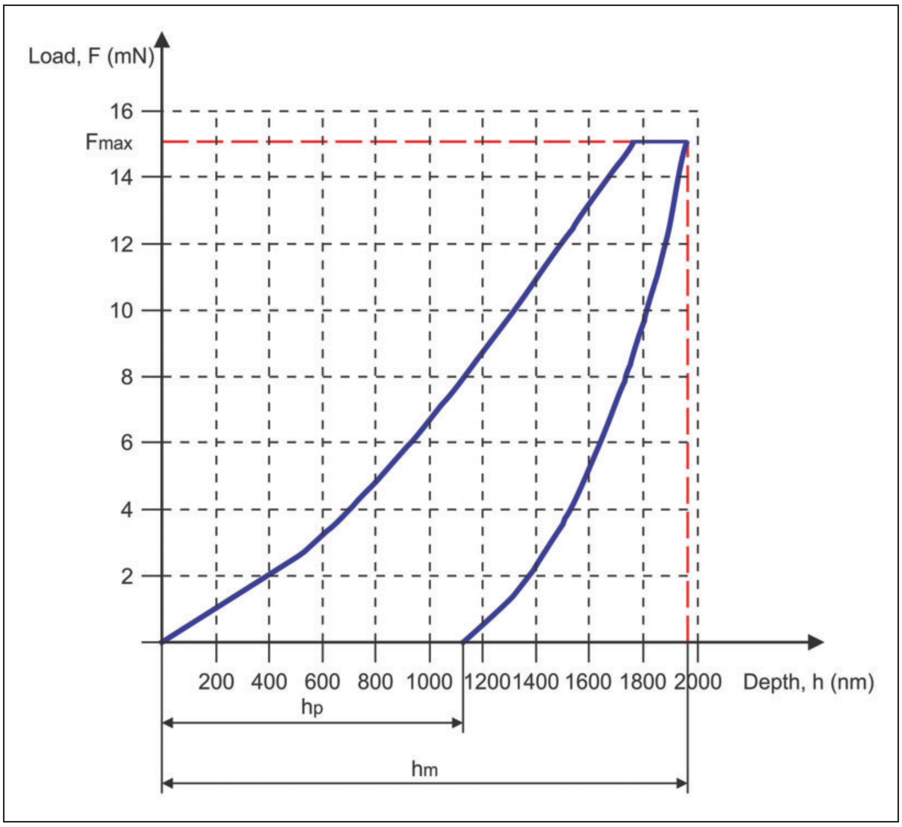

Figure 4. Characteristic curve of the indentation (the dependence of the force on the indentation depth) with the corresponding values.

plastic deformations, which will ultimately lead to the formation of the indent in material, which corresponds to the geometry of the indenter. During unloading and subsequent withdrawl of the indenter, elastic deformation disappears. Figure 4 represents typical relationship curves between the intending force of penetration depth and a characteristic view of elastic and plastic deformation during and after the process. In Figure 4, h_{max} represents the depth of indentation at the maximum value of intending force F_{max} and h_p is the depth of the indentations upon release.

Measuring the hardness is defined as the ratio of the intending force and the surface of the resulting impression (contact materials indenter). This value, in effect, represents the average value of the pressure to which the material may be submitted under the influence of a load, and is given by:

$$H = F_{max}/A \quad (1)$$

where A is surface of impression and F_{max} is the maximum value of the load applied to the indenter during the test.

Results

Results of measuring microhardness

In order to obtain the most accurate results, microhardness was measured at six points on each sample (Table 1). The force with which the intender was loaded on the workpiece material is 15 mN, and the rate of force increase is 30 mN/min. Due to very strong material relaxation during the termination of the force, the time at the maximum force value is 45 s. The measurement process is shown in Figure 5. A diagrammatic representation of the mean value of microhardness in relation to the depth of penetration is shown in Figure 6.

Brinell hardness measurement method

The measurement of hardness was performed by applying the Brinell method. The indenter used a steel ball, diameter 2.5 mm, and an applied load of 156.25 N. Time effects at the maximum load is 30 s. The indentation of the steel balls in the material of the workpiece produced resulting imprints in the form of spherical sections. For the determination of hardness by the Brinell method, it is possible to measure the diameter of the imprint, obtained indentation, or the depth of the imprint from:

$$\mathrm{HB} = \frac{F}{D \bullet \pi \bullet h} = \frac{0.102 \bullet 2 \bullet F}{D \bullet \pi \bullet (D - \sqrt{D^2 - d^2})} \quad (2)$$

where F is applied load (N), D is diameter of indenter (mm), and d is diameter of indentation (mm).

Due to the greater accuracy, the hardness measurement was based on the depth of the imprint using the

Table 1. Surface microhardness measured for the nanoindenter.

Penetration depth (mm)	Microhardness HV 1	2	3	4	5	6	Mean microhardness HV
0	10.251	23.075	14.264	11.686	14.908	8.878	13.844
0.05	37.640	97.545	43.183	78.040	33.537	38.711	54.776
0.15	15.769	46.872	26.638	53.813	36.461	61.487	40.173
0.25	71.456	62.906	71.367	68.436	51.767	58.489	64.070
0.35	20.866	20.866	38.609	60.206	73.114	77.610	48.545
0.45	56.937	43.680	59.135	38.848	81.189	48.439	54.705
0.55	45.438	57.652	53.617	79.285	71.291	90.724	66.335
0.65	69.335	73.091	80.052	64.113	66.851	66.773	70.036
0.75	91.439	76.120	81.354	87.026	95.884	103.390	89.202

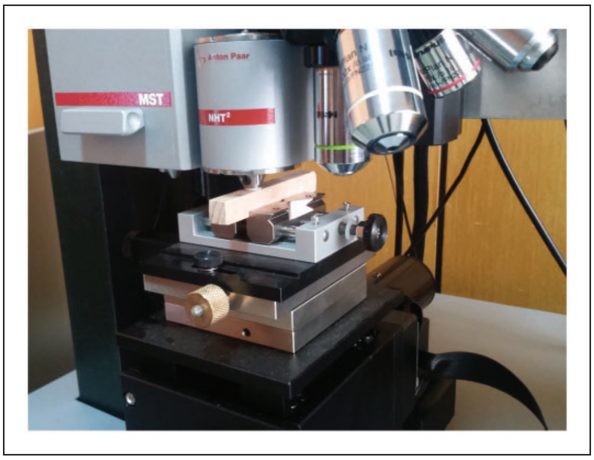

Figure 5. Measurement of microhardness on nano-hardness tester.

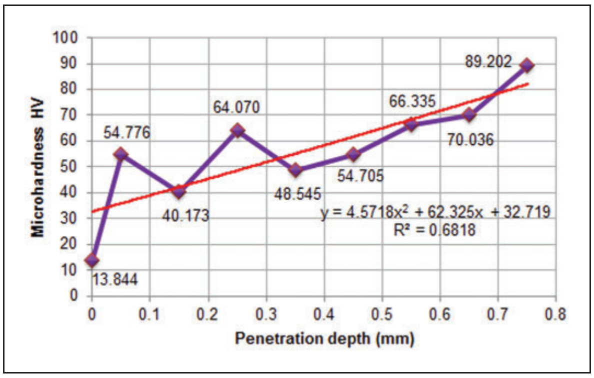

Figure 6. Mean value of microhardness, measured on the nanointender, depending on the depth of penetration.

coordinate measuring machine DEA GLOBAL Silver Performance 07:10:07 accuracy of $1.9 + L/333\,\text{m}$, where L is the measured size.

During the measurements, the sensor LSP-X1c with an extension length of 10 mm and ball diameter of 1 mm was used. The software used is PC-DMIS 2015.1. The measurements were made using scanning, with the requested lowest point of the profile that represents the depth of the impressions. The depth of the imprint, formed by indentation, obtained by measuring the distance between the surface (reference plane) and the lowest point. A photographic display of the measurement process is shown in Figure 7. The depth of the imprints and the calculated hardness are shown in Table 2. Figure 8 shows the dependence of hardness testing samples from a depth of penetration balls during the execution of the ball burnishing process.

Discussion

According to the literature, it can be concluded that the ball burnishing process have very positive effects in terms of reducing surface roughness and increasing the hardness of the surface layer. A large number of workers have examined the effects of workpieces made of metal materials. We examined the effects of ball burnishing from the aspect of a possible increase in hardness as the processing of wood.

According to the results of micro-hardness measurements (Figure 6), the trend of microhardness increase with increasing depth of penetration balls is clearly distinguishable. We can also notice that there are some microhardness decreases with increasing depth of penetration. It is very likely these are a consequence of the inhomogeneity of the wood, and thus they depend on the location and the indentation hardness variation, especially if one takes into account that the size of the pyramid, which is indented in the measurement in wood and reverse pyramid, is extremely small. In this regard it is realistic to expect that the top of the pyramid sometimes makes direct contact with the wood fibres, which causes more resistance: the device identifies more microhardness. Otherwise, the diamond pyramid penetrates between two wood fibres, whereby it splits apart and makes less resistance penetration of the pyramid, leading to the identification of less microhardness.

Irrespective of the deviations, an upward trend with the increase in hardness penetration depth is obvious. In fact, all the measured values of

Figure 7. Scanning the surface in the coordinate measuring machine.

Table 2. Hardness of wood, depending on the penetration depth.

Penetration depth (mm)	Depth of imprint (mm)	Hardness HBS
0	0.229	8.687 HBS 2.5/15.625/30
0.05	0.212	9.384 HBS 2.5/15.625/30
0.15	0.138	14.416 HBS 2.5/15.625/30
0.25	0.134	14.846 HBS 2.5/15.625/30
0.35	0.094	21.164 HBS 2.5/15.625/30
0.45	0.090	22.105 HBS 2.5/15.625/30
0.55	0.078	25.505 HBS 2.5/15.625/30
0.65	0.091	21.862 HBS 2.5/15.625/30
0.75	0.098	20.300 HBS 2.5/15.625/30

microhardness were several times higher than the microhardness of the sample that was not treated by ball burnishing.

The hardness of the polished specimen before ball burnishing processing as measured by the Brinell method is 8.687 HB. From Figure 8 it can be seen that the hardness of wood increases with depth of penetration of the steel ball, to a depth of 0.55 mm. When the depth increases to values greater than 0.55 mm, it leads to a certain decrease in hardness, which may be due to the large contact pressures and material destruction. Based on Figure 7 it can be concluded that the optimum depth of penetration of the balls is close to 0.55 mm, wherein the hardness is about three times higher than the hardness of the sample that was not treated with ball burnishing. Also, based on that diagram, it can be concluded that at any depth of penetration, a significant increase of the material hardness was achieved.

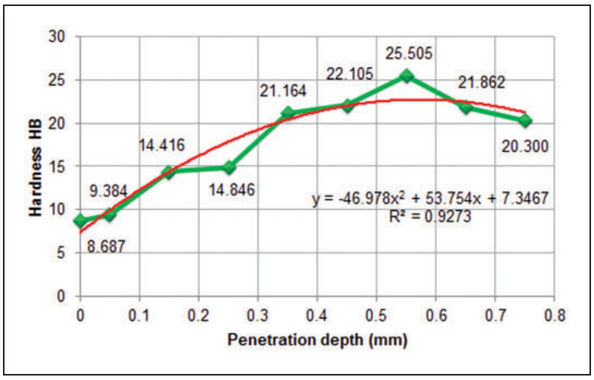

Figure 8. Dependence of hardness on penetration depth during ball burnishing.

By analysing and comparing the results of microhardness and measurements of hardness, very useful information can be provided. The microhardness of the surface layer with a maximum depth of penetration is 89.202 HV, which is relative to the initial value of microhardness of 13.844 HV, i.e. an increase of more than seven times. The hardness measured by the Brinell method at the maximum depth of penetration is 20.3 HB, which is relative to the initial hardness value of 8.687 HB: a hardness increase of approximately 2.3 times. The effects of the surface treatment method of ball burnishing are obviously significantly higher in the surface layer. This is generally understood as a consequence of the distribution of the stress field, i.e. decreasing the hardness from the surface of materials with depth of the material. The effect of surface treatment of workpieces made of metallic materials by ball burnishing is limited to a very thin surface layer. Considering the small thickness of the hardened layer, the effects of the treatment expressed by the Brinell test in metal materials are very small (negligible).

Our investigation indicates that, when the workpiece is made of wood, the effects of processing by the ball burnishing method can be seen through the Brinell hardness test. The effects of the increase in the hardness measured by the Brinell method are logically smaller relative to the effects expressed through a method of measuring microhardness, but the Brinell hardness test method significantly increases with increasing depth of penetration balls. The thickness of the hardened layer, in the case of treatment of the workpiece made of wood by ball burnishing, is obviously significantly higher relative to the workpiece made of metal, which exactly shows the results of the Brinell hardness measurement. The final treatment of the workpiece made of wood by ball burnishing, in fact, indicates a significant increase not only in microhardness, but also in the overall hardness of the workpiece.

Based on these results that indicate the possibility of a significant increase in hardness, it is realistic to assume that the treated surface layer shows a significant increase in density, which has positive effects in terms of protecting the wood from putrefaction.

Conclusions

Our investigation has indicated the evident increase of hardness during the wood finishing process called ball burnishing. It is shown that, with this method of finishing, it is possible to achieve multiple increases in hardness, which can have extremely positive effects in terms of increasing the level of mechanical and exploitation characteristics of objects made of wood. The results were compared to literature data: the process of ball burnishing on wood as the workpiece can achieve a significant increase in hardness compared to metallic materials. It should also be noted that this method of processing increases the density of the surface layer and thus reduces the risk of ingress of moisture and oxygen into the interior of the tree. We believe that future research should focus on testing the effects of ball burnishing on the resistance of wood to atmospheric conditions. Then, these methods could be compared to existing procedures.

Declaration of conflicting interests

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