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STRUCTURAL CHANGES OF SCOTS PINE WOOD CAUSED BY LOCAL PRESSING IN THE LONGITUDINAL DIRECTION

An indentation can be formed when inserting a punch along wood fibers at the ends of blanks. The aim of this research is to study structural changes during local compression of wood in longitudinal pressing. Punches of prismatic shape were inserted into samples of Scots pine wood with different moisture content. The stages of wood deformation during the process were analyzed. The author then evaluated changes in the macrostructure of the wood and determined the conditions for obtaining a good-quality indentation. This led to a regression model enabling prediction of the depth of the densified zone. Its size is no more than 105% of the depth of penetration. Images of the densified zone were obtained using a scanning electron microscope, and changes in its microstructure were evaluated. The process of forming a "core" causes uncritical structural changes in the boundary undeformed sections. This underlines the possibility of using local pressing technology along the fibers as an alternative to traditional milling or drilling in order to form grooves and blind holes, for example for such joints as tongue and groove or mortise and tenon.

Keywords: compression parallel to grain, densified wood, microstructure, joints

Introduction

Wood is a unique natural material which is used in various industries and spheres of human activity due to its availability, renewability and easy machinability.

The ability of wood to change its shape, as well as its aesthetic, physical and mechanical properties, and its performance under the influence of special processing methods, increase its value and range of use as a structural material [Kollman et al. 1975; Navi and Girardet 2000; Mohebby et al. 2009; Bami and Mohebby 2011; Kwon et al. 2014]. There are various ways of modifying wood, including mechanical, thermal, chemical and radiation methods, as well as combinations of these [Mitsui et al. 2001; Fojutowski et al. 2009; Rautkari et al. 2011; Ahmed et al. 2013; Kutnar et al. 2015; Herrera et al. 2016; Ayata et al.

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2017]. Each method has a different scope, despite some drawbacks – for example, a decline in the mechanical properties of wood during heat treatment [Zawadzki et al. 2016].

A feature of mechanical modification is the ability to impart good mechanical properties to wood due to its densification [Kultikova 1999; Lenth and Kamke 2001; Heger et al. 2004; Kutnar and Sernek 2007] and also to give it the required form [Ito et al. 1998; Kutnar et al. 2015].

As a rule, densification of wood by compression is performed in the transverse direction [Kollmann et al. 1975; Blomberg and Persson 2004]. This kind of pressing and the structure of densified wood are well studied [Schrepfer and Schweingruber 1998; Nairn 2007; Tabarsa and Chui 2007; Benabou 2010]. It has been established that heating and moistening of wood and the use of chemical impregnations provide better conditions for the pressing process and prevent damage to the cell walls [Morsing 2000; Darwis et al. 2017].

Cold pressing of wood is less common. However, there are research results which show that the treatment of cold dry wood also has positive results [Gaff and Gáborík 2014; Kwon et al. 2014].

Uneven pressing to obtain relief indentations in the form of grooves or holes has been less studied [Hesselbach et al. 2007; Gaff and Gáborík 2014; Gaff et al. 2016]; this includes local pressing in the longitudinal direction [Rubleva 2013a, b]. As regards compression along the fibers, research has mainly provided data on the properties and structure of wood subjected to axial compression along the fibers [Kučera and Bariska 1982; Sliker 1985; Poulsen et al. 1997; Reiterer and Stanzl-Tschegg 2001; Benabou 2010].

The purpose of this research is to study structural changes in wood when inserting the punch parallel to the grain without heating the wood or the tool, and to determine the capability of this technology to form grooves and holes.

Materials and methods

Materials

The author studied samples of wood from Scots pine *(Pinus sylvestris* L.), a typical coniferous species widely used in woodworking. The samples came from trees growing in central Russia. Samples were made from the middle zone of the trunk by cutting parallel to the grain direction to form boards. The boards were labeled and cut into small samples of the required dimensions: height H = 60 mm (corresponding to the longitudinal direction of the fibers); dimensions of cross-section 25 × 40 mm in the radial and tangential directions respectively. Samples were cut from pure wood, without knots or cracks, with a slope of fibers no more than 15%, in accordance with the author's preliminary exploratory experiment.

Physical and mechanical properties of specimens

The average density of the wood samples was 505 kg/m^3. The static hardness on the end surface of a sample was determined by the Rockwell method and was found to be 37 HRL. The tensile strength of the test specimens under compression in the longitudinal direction was 48.8 MPa, for stretching along the fibers it was 108.9 MPa, and for static bending it was 83.4 MPa (all of these properties are given in terms of a normalized 12% moisture content).

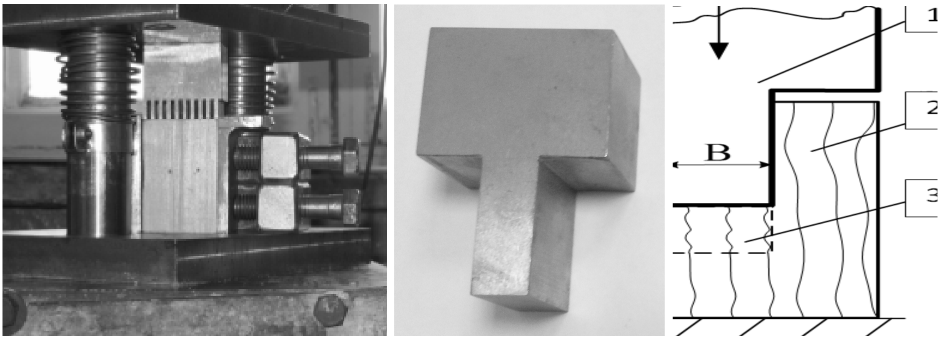
The samples were conditioned in air at a temperature of 20°C and a relative humidity of 50% until they reached equilibrium moisture content. Then, according to the experimental plan, samples with below the required moisture content were moistened to reach the required content, and samples with moisture content higher than required were dried in an SHSP-0.25-60 drying chamber (Teplopribor, Russia) at a temperature of 60°C until the required humidity was reached. The moisture content W in the samples for the second stage of the study, namely investigation of the possibility in principle of forming a groove by pressing, ranged from 8% to 30%. For this stage, eight groups of five samples were prepared, with moisture contents of 8%, 12%, 15%, 18%, 20%, 23%, 26% and 30%, a total of 40 samples. Samples for the third stage of the research – studying the influence of factors on the depth of the densified zone h_d – were obtained with a moisture content W ranging from 8% to 18%. In accordance with the Box-Behnken design, for the third stage of research 15 × 3 = 45 samples were prepared. All of the samples prior to testing were stored in separate sealed vessels.

Humidity was measured using a Hydromette compact (Gann GmbH). For measurement of the moisture content of the samples, the ends of the probes were inserted across the wood fibers, both measuring points being located in the same layer. The moisture value was taken as the arithmetic mean of four measurements, one made on each longitudinal side of the sample.

Pressure treatment

The treatment was carried out on a P-10 laboratory test hydraulic press (ZIM Tochmashpribor, Russia). Studies were conducted at an ambient temperature of 20°C.

During the first stage of work, the samples were first subjected to free compression along the fibers to establish the patterns of cracking. Then, at the second stage, the author investigated the possibility in principle of forming a groove by the method of pressing along the fibers in samples with different moisture contents, and determined the conditions for obtaining high-quality indentations. During the forming of grooves, the workpieces were fixed in a special tool (fig. 1a), which provided the base, fixation and four-sided crimping across the section with a force up to 300 N. It served to minimize the risk of cracking during the embossing process.



a b c

Fig. 1. Tooling and tools for pressing along the fibers: a – device for fixing the workpiece and tool; b – example of punch; c – scheme of groove formation, 1 – punch, 2 – sample, 3 – densified zone, H – sample's height, B – width of groove, h_n – depth of groove, h_d – depth of the densified zone, arrow indicates the direction of the compression force F

Grooves on the end surface of the samples were formed by punches of prismatic shape (fig. 1b), with cross-sections of 25 × 4, 25 × 8 and 25 × 20 mm. The displacement speed of the punch was set based on preliminary research at 50 mm/min.

As a result, on the end surfaces of the blanks, grooves were obtained (fig. 1c) with width B equal to 4, 12 and 20 mm. During the second stage of the study, the depth h_n of the grooves was varied from 1 to 30 mm to investigate the stages of wood deformation and to define the limiting criteria for shaping a good-quality groove. The samples for the third stage of the research (to estimate the depth of the densified zone) were prepared in the same way as for the second stage, but h_n was varied from 5 to 11 mm based on the results of previous stage, with the aim of excluding possible defects and obtaining a good-quality groove.

In some samples, the process of groove shaping was carried out step by step, to obtain images of intermediate stages of the change in the wood structure. Each step was performed under constant pressure for identical samples (for example, the pressure force was approximately 17.8 kN for samples with groove width 12 mm and 18% moisture content). After each stage, the punch was removed from the sample. Further, the studied surface was sanded to reveal the structure better and to take photographs. The results obtained for the step-by-step samples and the final samples were not combined, because of the differences of procedure, and are presented in different sections of the paper.

Estimation of the densified zone depth

At the third stage of the study, a second-order non-compositional plan (known as the Box–Behnken design) was realized in order to obtain a regression model that predicts the depth h_d of the densified zone. In this three-level factorial experiment, each of three independent factors (W, h_n and B) was varied between three levels: –1, 0, +1 (high, average and low). The ranges of variation were: W from 8% to 18%, h_n from 5 to 11 mm, and B from 4 to 20 mm. The experiments, presented in table 1 at numbers 1-15, were performed in random order with three replications.

After pressing, the samples were dried in an SHSP-0.25-60 chamber (Teplopribor, Russia) at a temperature of 40°C until 8% humidity was reached.

Next, digital photos of the samples were obtained using an HP ScanJet 2380 scanner with a resolution of 600 × 600 dpi. In the Microsoft Visio application, a scale dimension grid was applied to the images, by which means the depth of the groove h_n and the size of the densified zone h_d under the groove (fig. 1c) were measured. The lower limit of h_d was identified by drawing a line parallel to the bottom of the groove, through the furthest protruding parts of the visible changes in the wood structure, in particular the deformation of the rings. The term "relative depth of the densified zone", h_3, was introduced, given by the ratio (1):

$$h_3 = \frac{h_d}{h_n} \times 100 \quad (1)$$

where h_n is the depth of the groove and h_d is the depth of the densified area under the groove.

The data obtained were processed using statistical analysis methods according to the technique described by Spiridonov [1981]. The calculations were carried out manually for training purposes. Then graphical images of the obtained polynomial model were built using the program Microsoft Excel.

Scanning electron microscopy

At the fourth stage of the study, the anatomical structure of the deformed parts of the wood was observed with the use of a JEOL JSM-6510 LV (Japan) scanning electron microscope (SEM). For this, the pressed samples were further processed. First, cut and split surfaces (respectively tangential and radial) were obtained in the densified zone (fig. 2). The cut surface was obtained on the pressed sample using circular sawing, and the split surface was obtained using a knife by splitting parallel to the grain at the boundary of the pressed and undeformed zones (fig. 2a).

Next, a small sample was taken with a cross-section of approximately 3 × 3 mm (indicated by an arrow in fig. 2a, b). Vacuum deposition of platinum was then performed using a JEE-420 apparatus, and images of the wood structure in the form of microphotographs were obtained. The images were examined and analyzed, taking account of their scale.

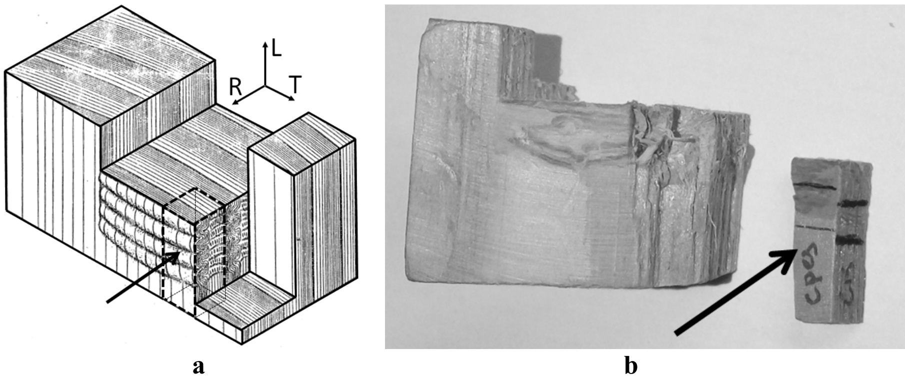


Fig. 2. Scheme for obtaining a sample for SEM: a – location of the small sample with a cross-section of approximately 3 × 3 mm in the pressed sample with cross--section 25 × 40 mm; b – photo of samples; arrows indicate the small sample for SEM

Results and discussion

Determining the conditions for obtaining good-quality indentations

With free compression of the samples, both across and along the fibers, there are three main phases of wood deformation [Moran et al. 1995; Poulsen et al. 1997; Nairn 2007; Tabarsa and Chui 2007; Benabou 2008, 2010]. The first, linear compression phase is the region of elastic deformations. The second phase, the onset of plastic deformation, occurs when the peak tension is reached. At this moment, the cell walls of stronger late wood lose stability. This phase continues in the case of compression along the fibers prior to the beginning of the destruction of the wood (the third phase) [Reiterer and Stanzl-Tschegg 2001]. This is manifested in the shifting of the wood [Benabou 2008, 2010] with the formation of folds and cracks [Brabec et al. 2015]. In the case of loading in the longitudinal direction, the destruction of the wood with the formation of folds and cracks occurs without its densification [Reiterer and Stanzl-Tschegg 2001].

With compression along the fibers, a part of the late wood loses stability and curves in the radial plane, and a part of it in the tangential plane. As a result, with free compression, the shift occurs in both planes [Reiterer and Stanzl--Tschegg 2001]. A typical pattern of fracture on the specimens under study consisted of oblique folds with longitudinal splitting (fig. 3a). For different breeds, the kink band orientation with respect to the cross-section of the blanks is different [Benabou 2010]. For the observed samples (fig. 3a), the angle ranged from –7° up to 55°.

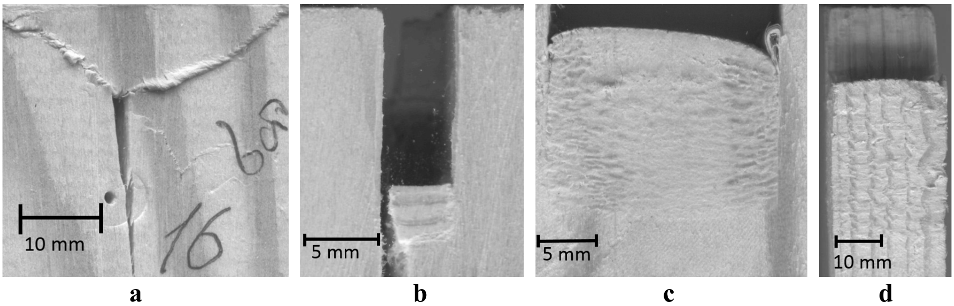


Fig. 3. Possible defects in the compression of wood parallel to grain: a – destruction with free compression; b – crack in a sample of Scots pine under a groove of width B = 4 mm, depth h_n = 13 mm, W = 8% as a result of pressing without crimping; c, d – low accuracy of the indentation at 30% moisture content, respectively tangential and radial incision

The formation of an advanced longitudinal crack on local insertion of the punch without compression of the sample is also inevitable (fig. 3b). It is established that a crack of considerable size is formed with an increase in the depth of penetration of the punch h_n to one-and-a-half groove widths B: $h_n \leq 1.5B$.

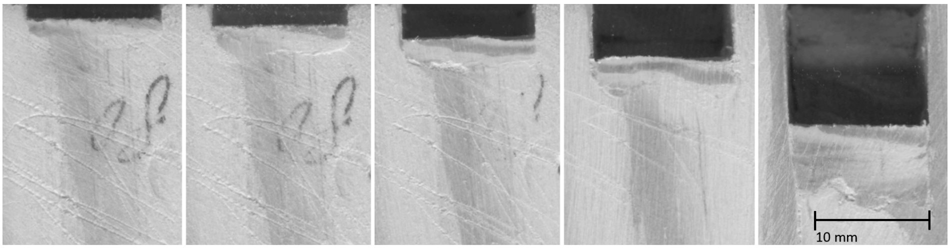
Crimping the workpiece in planes parallel to the side faces of the grooves (fig. 1a) reduces the likelihood of cracks. It also allows an increase in the depth of insertion of the punch h_n to two-and-a-half groove widths B: $h_n \leq 2.5B$. The value of the crimping force for the range of values is determined experimentally and is no more than 300 N for Scots pine wood.

Defects in the form of low accuracy of dimensions and shape were observed when pressing wood with moisture content increased to 18-30% (fig. 3c, d). The indentation obtained in moist wood has tears and scuffing of fibers on the side surfaces, a convex bottom shape due to elastic recovery after removal of the load, and microcracks caused by the movement of a significant amount of moisture through the capillaries of the wood.

Thus, the necessary conditions for obtaining a good-quality indentation of depth $h_n \leq 2.5B$ are crimping of the workpiece with a force of up to 300 N, and a wood moisture content W in the range from 8% to 18%.

Study of wood deformation stages when inserting a punch along the fibers

An initial evaluation of structural changes was made by observing the densified zone directly on the samples and on their images (fig. 4) with a small magnification of between 2 and 5. This technique is fully applicable at the initial stages of the evaluation of the wood structure, since the samples have visible changes in their macrostructure [Kučera and Bariska 1982].



a b c d e

Fig. 4. Stages of formation of a groove 12 mm wide in a sample of Scots pine wood, W = 8%: a-e – stages of the deformation process, the scale on image e is valid for all of the images

Fig. 4 shows photographs of the stages of deformation of Scots pine wood with 8% moisture content during insertion of a prismatic punch with cross--section 25 × 8 mm.

Inserting the punch along the wood fibers is a process of local compression and has some similarity to the process of free compression along the fibers. The nature of the wood deformation is also determined by the rigidity of the structural timber frame, and in the first stage of the deformation process under the groove there is an elastic deformation less than or equal to 8%.

At the peak stress (for dry Scots pine wood this is no more than 60 MPa) we observe a loss of stability of the anatomical elements of the wood. At this point in the process, the wood platform under the working plane of the punch cleaves. There is a shift of wood along the fibers, and the formation of sliding surfaces coinciding with the groove sides begins. The process of plastic deformation – local crushing of the wood along the fiber – begins. Figure 4a shows the initial stage of the formation of the groove.

When the punch moves into the workpiece, the depth of the densified zone increases. The next stages of the process (fig. 4b-e) are characterized by the pressing and moving of a compressed layer of wood along the slip planes. The height of the "core" of densified wood (as it was named by Hesselbach [2010]) increases as the punch moves deeper into the bar. The densified zone somewhat widens in the tangential plane due to the bending of the late wood layers, which agrees with the data given by Kučera and Bariska [1982]. Similar observations are described by Brabec et al. [2015], who showed that when the wood is pressed along the fibers, there is an expansion of the middle zone of the deformed sample. In our case, the expansion in the tangential direction is confined to neighboring cells of strong late wood. It leads to the appearance of frictional forces in the slip planes of the "core" made of pressed wood. As a result, the initial force necessary to start the local plastic deformation increases by, at a rough estimate, 8-12% in total during movement deep into the sample. For example, when forming grooves with width 12 mm in samples with 18% moisture content, the initial observed force was equal to about 16,226 N, and it then increased to about 17,848 N. A similar pattern was observed for all test samples, but this phenomenon is not considered in detail in this paper, since our goal was to determine the final pressing force of the groove.

At the end of the pressing process (fig. 4e), under the base of the punch, there was formed a "core" of pressed wood with height h_d usually smaller than h_n. The elastic recovery of the "core" is not more than 2%.

Thus, when inserting the punch, we observe three processes: chipping, local crushing, and friction of the tool faces against the wall of the resulting hole. The data obtained are consistent with the results given by Hesselbach [2010].

Influence of the moisture content and width and depth of the groove on the depth of the densified zone

Assessment of the macrostructure using photographs of the type shown in figure 4, with a scaled mesh, makes it possible to obtain enough data to determine the size of the densified zone h_3 [Kučera and Bariska 1982]. The results of estimation of h_3 are presented in table 1.

Table 1. Results of estimation of h_3

Number of experiment	W (%)	h_n (mm)	B (mm)	Average for three estimates of h_3 (%)
1	18	11	12	70.59
2	18	5	12	85.71
3	8	11	12	62.50
4	8	5	12	100.11
5	13	8	12	94.12
6	18	8	20	80.06
7	18	8	4	70.59
8	8	8	20	114.29
9	8	8	4	53.33
10	13	8	12	99.87
11	13	11	20	100.03
12	13	11	4	55.56
13	13	5	20	64.29
14	13	5	4	92.86
15	13	8	12	98.95

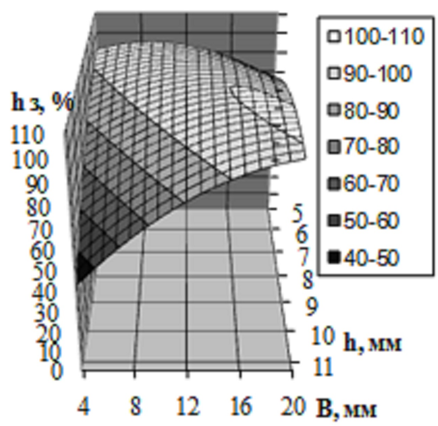
By processing the experimental data using the technique of Spiridonov [1981], we obtain a regression model for Scots pine wood (2):

$$h_3 = -27.28 + 12.69\,W + 6.14\,h_n + 3.21\,B - 0.34\,W^2 - 1.10\,h^2 - 0.16\,B^2 - \\ -0.32\,WB + 0.76\,h_n B \qquad (2)$$

where h_3 is the relative depth of the densified zone (%), W is the moisture content of the wood (%), h_n is the depth of the groove (mm), and B is the width of the groove (mm).

Following the method of Spiridonof [1981], the variances of the regression coefficients were calculated, confidence intervals were determined, and the significance of the regression coefficients was checked. Insignificant coefficients were excluded from the polynomial model. All variables in model (2) are statistically significant. Verification of the adequacy of the model was carried out by the F-test. The estimated value of the Fisher criterion was 15.68 against the table value of 19.3; therefore the resulting model is adequate. A more detailed statistical analysis might be of interest, but this is not the main goal of the study, and is not possible here because of the limited length of this paper. Consequently, the represented regression model (2) can be used to approximate (estimate) the degree of influence of variable factors on h_3, and requires further discussion.

Some graphic representations of the model are shown in figure 5. In the studied range of factors, the depth of the groove and its width most strongly influence the depth of the deformed zone. The depth of the densified zone, depending on the pressing conditions, ranges from about 41% (if h_n = 11 mm, W = 13%, B = 4 mm) up to 105% (for example, if h_n = 8 mm, W = 8%, B = 20 mm).



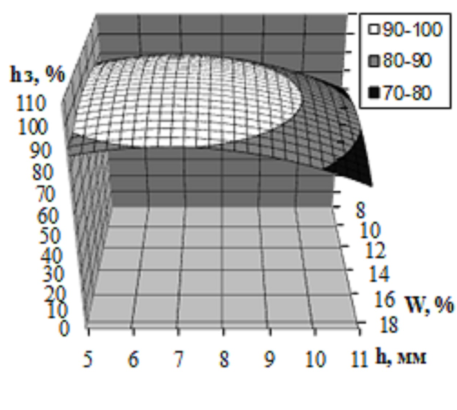


Fig. 5. Dependence of the depth of the densified zone h_3 for Scots pine wood: a – on the width *B* and the depth of the groove h_n at a humidity of *W* = 13%; b – on the depth of the groove h_n and the moisture content *W* at a width of *B* = 12 mm

Study of the structure of the densified zone

To study the structure of the densified zone under the groove, tangential and radial sections of the samples were obtained. Enlarged images of the deformation zones are shown in figures 6 and 7.

When inserting the punch, shearing and bending of the layers are observed mainly in the radial direction (fig. 2a; fig. 7). The stronger late wood acts as a "reinforcing" element, and so a loss of stability, in the radial direction, is more likely due to pressing of the looser and easily deformed early wood [Kučera and Bariska 1982]. The magnitude of the bend is limited by the core rays.

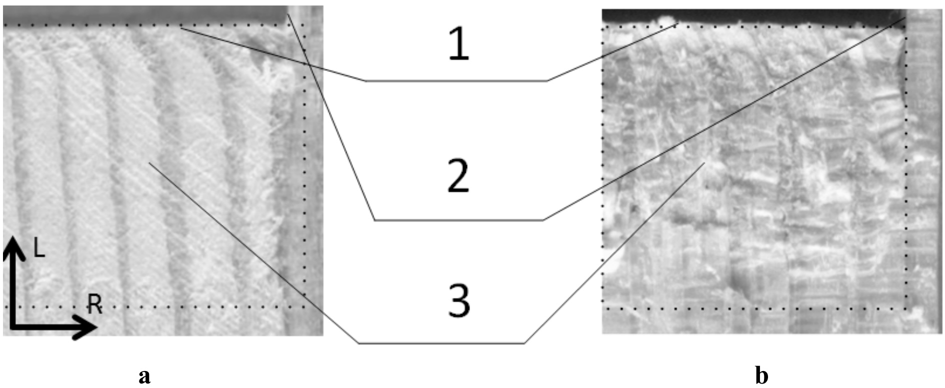


Fig. 6. Radial surface of the densified zone in a Scots pine wood sample, *W* = 8%: a – cut surface; b – split surface; 1 – bottom of the groove; 2 – side face of the groove; 3 – area of the densified zone

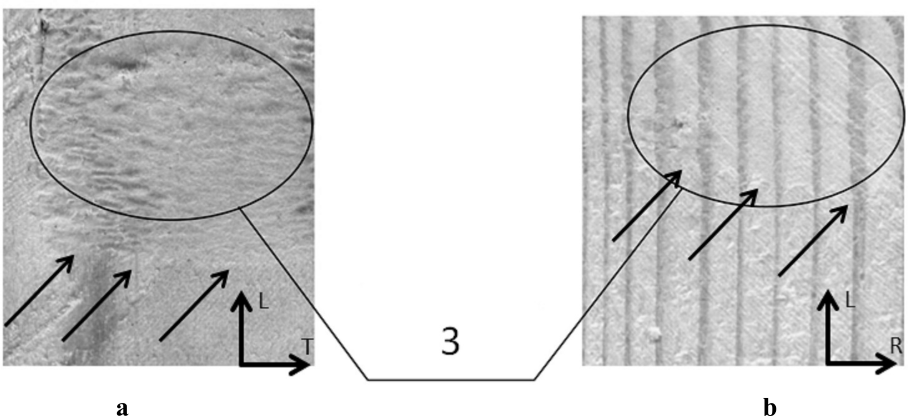


Fig. 7. Macrostructure of the densified zone in Scots pine wood, *W* = 8%: a – tangential cut, b – radial cut; 3 – section of the densified zone; arrows indicate the lower boundaries of the densified zone

Accordingly, there is a thickening of the zones of late wood on the radial surface of the specimen (figs. 6a, 6b, 7b), and on the tangential section there are folds of the deformation of the late zone shift in the radial direction (fig. 7a). It can be seen that the volume fraction of early wood decreases, and consequently, the degree of densification of the early zone will be somewhat higher than that of the late zone. The data obtained are consistent with the results given by Kučera and Bariska [1982].

The images (figs. 6, 7) show a clearly discernable boundary between the pressed wood and the undeformed wood. It is quite clearly seen that the areas of undeformed wood adjacent to the "core" retain their original structure.

The structure and dimensions of the folds of wood fibers in the densified zone were studied in more detail from micrographs of the split surface in the tangential plane (fig. 8) and the split surface in the radial plane (fig. 9).

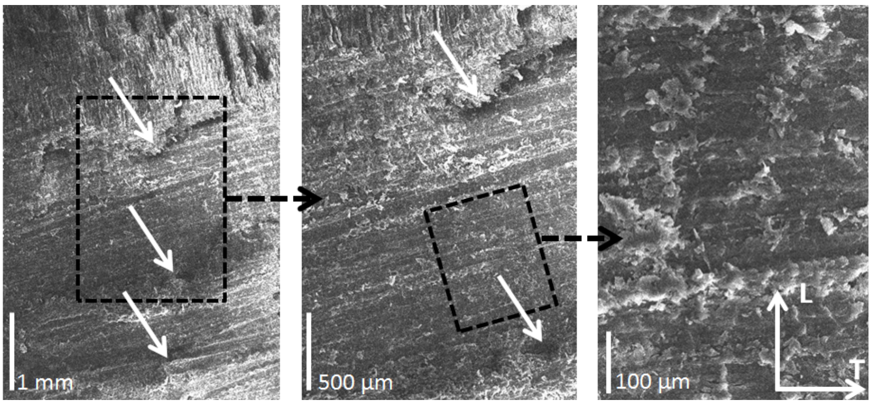
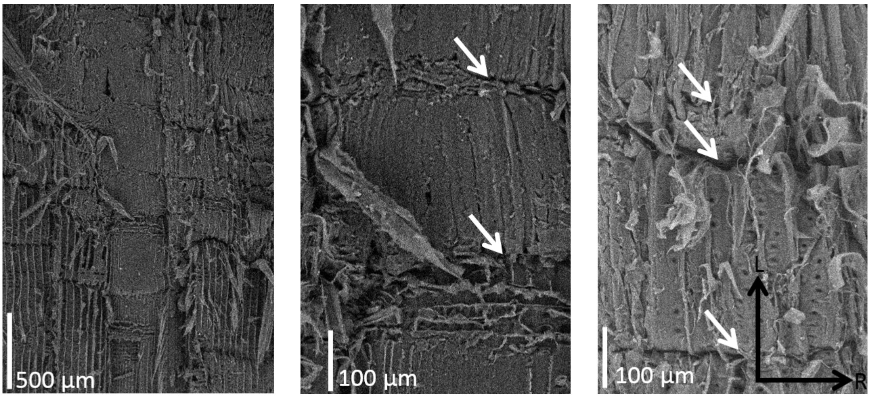


Fig. 8. SEM images of wood samples *(Pinus sylvestris* L.) subjected to local pressing in the longitudinal direction, showing structure of wood in tangential section; light arrows indicate the folds of wood fibers

The light arrows in figures 8-9 indicate the lines through which the folds of wood fibers pass. At the tangential cut, these are the lines of cutting of the folds. It may be noted that the wood remains practically intact between the fold lines (fig. 8).

In the early wood layers of the studied region, there are uneven small and large folds from 67 to 333 µm in height and from 138 to 650 µm in width (fig. 9). The folds in the late zone are more even: their height ranges from 277 to 500 µm, and their width from 290 to 330 µm. The structural elements of the wood outside the folding zones remain virtually intact.



a b c

Fig. 9. SEM images of wood samples (*Pinus sylvestris* L.) subjected to local pressing in the longitudinal direction, showing structure of wood in radial section: a – folds in deformed zone; b – zone of deformed late wood; c – zone of deformed early wood; light arrows indicate the folds of wood fibers

Studying the image of the bottom of the groove (the face surface of the indentation) (fig. 10), it may be noted that the surface has low roughness, with maximum profile peaks no more than 86 µm in height. The pores are “closed” by tilting and squeezing of the surface fiber. The surface is considerably densified, as confirmed by the Rockwell test [Rubleva 2011]. Closing of the pores and densification of the wood can mitigate one of the problems in gluing the end surfaces: the high absorbance of glue. This is consistent with the data obtained by Džinčić and Živanić [2014] and is important for the development of processing modes for innovative gluing along the grains with rectangular tenons. Figure 1a in the tooling set shows a punch for implementing this method of gluing.

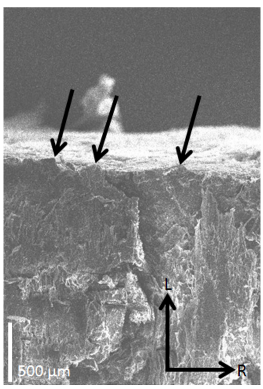


Fig. 10. A micrograph of the end surface of an indentation formed in the process of local pressing in the longitudinal direction; the arrows indicate some profile peaks on the bottom of the groove

Conclusions

When inserting a prismatic punch along the grains in a Scots pine wood sample, it is possible to form a good-quality indentation in the form of a groove with the relative height of the densified "core" no more than 105% of the depth of the groove. The conditions for this are: moisture content of wood up to 18%, crimping of the workpiece in the tooling, and penetration depth of the punch not more than two-and-a-half groove widths ($h_n \leq 2.5B$).

The densified zone contains folds from deformed layers of early and late wood, with heights of 67 to 333 μm and 277 to 500 μm respectively. The roughness of the bottom of the indentation is no more than 86 μm. The wood of neighboring undeformed areas retains its original structure. The "core" can be considered as a denser inclusion in the wood, similar to a knot. Therefore, insertion of a punch along the fibers can be used as a new technology for forming grooves and blind holes, as an alternative to drilling and milling. To support this assertion, it is necessary to study the effect of the "core" on the mechanical strength of the wood and the quality of joints obtained using the described method.

The data obtained as a result of this research may be used to develop technological systems for compressive molding of the elements of glued joints, such as tongue and groove or mortise and tenon, by the method of cold local pressing in the longitudinal direction.

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