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Prediction model for the pressing process in an innovative forming joints technology for woodworking

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Abstract. To improve the efficiency of the joints formation, a new method of pressing in the longitudinal direction is proposed. This paper presents a predictive model for the pressing force depending on the state of the wood and the parameters of the pressed mortise. The most significant factors are the width of the mortise and the moisture content of the wood. Interestingly, the depth of the mortise formation is a less significant factor, which means that the pressing technology will allow to form a long glue line and accordingly high joint strength due to sufficient profile length. In the test range of factors, the best results in terms of energy costs are shown by a minimum mortise width of 4 mm. Further research should be devoted to the study of the formation of small width mortises (4 mm or less) and the investigation of their quality.

1. Introduction

Wood is one of the most demanded construction materials due to the availability and renewability of forest resources. Solid and glued wood is used for manufacturing such construction details as beams and arches, for carpentry (windows, doors), furniture and mechanical engineering parts. The quality and strength of these products depend on the quality of joints to a large degree. Glued joints, and in particular, finger joints, are most widely used due to a complex of necessary strength properties [1].

Milling is the most studied and commonly used process of forming a profile of joints [1]. This cutting process has some drawbacks as waste in the form of chips, expensive tools, and high energy costs. The local pressing technique applied in longitudinal direction allows to eliminate these disadvantages and to obtain high quality mortises [2]. Uneven pressing in order to obtain relief indentations in the form of grooves or holes has been insufficiently studied [3-5]. The purpose of this research is to describe the parameters of mortise forming process by developing a regression model.

2. Materials and methods

2.1. Materials

The wood material used was Scots pine (*Pinus sylvestris L.*) wood obtained from the middle Russia, due to the fact that it is one of the most common coniferous species for the manufacture of finger-jointed wood products. Specimens were selected from the sapwood boards with tangential plane of the grain orientation. Samples were cut from pure wood free from such defects as knots and cracks, with a slope of fibers no more than 15% in accordance with author's preliminary search experiment [6]. To achieve this, the boards were marked and cut into small samples of the required dimensions. Samples had height H=60 mm (corresponds to the longitudinal direction of the fibers), dimensions of the cross-section were 25×40 mm in radial and tangential direction respectively.

2.2. Physical and mechanical properties of specimens

Specimens were kiln-dried in drying chamber SHSP-0.25-60 produced by "Teplopribor" (Russia), at a temperature of 60 °C, in order to reach 8, 13 and 18 % moisture content according to the plan of the experiment. Total numbers of specimens were 3×15=45 (with three replicates for each combination of main factors). The moisture content of the samples was measured by a Hydromette compact manufactured by Gann GmbH. The moisture value was taken as the arithmetic average of four measurements: one measurement on each longitudinal side of the sample.

The average original density of wood was approximately 505 kg/m^3, the static hardness on the end grain surface of the sample, determined by the Rockwell method, was 37 HRL and the tensile strength of the test specimens under compression in longitudinal direction was 48.8 MPa (all these properties in terms of the normalized 12% moisture content).

2.3. Pressure treatment

The treatment was carried out on a laboratory test hydraulic press P-10 manufactured by ZIM Tochmashpribor, Russia. Pressing was conducted at 20°C ambient temperature and relative humidity 65%. Before forming the open mortise, the workpiece was fixed and crimped in a special tool with the force up to 300 N, to minimize the risk of cracking during the embossing process. Open mortises on the end surface of the samples were formed by inserting the punches of prismatic shape (figure 1), with three types of cross-section dimensions: 25×4, 25×8, 25×20 mm. The depth h_n of mortises was varied from 5 to 11 mm based on results of author's previous stage [6].

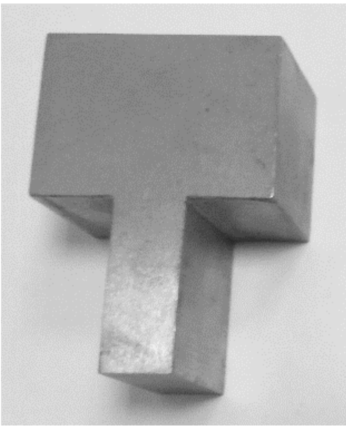


Figure 1. The form of punch for embossing the mortises along the fibers.

2.4. Modelling method

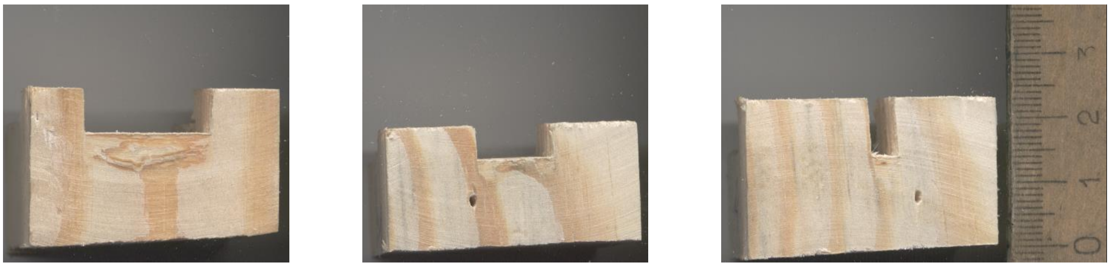
Regression analysis is still widely used in woodworking researches with satisfactory results. It allows to predict the relationship between explanatory variables and a response variable with sufficient accuracy. To receive such regression model for predicting the pressing force, using the minimum possible number of experiments, the authors realized the Box–Behnken design with 3 factors: moisture content W (8−13%), width B (4−20 mm) and depth h_n of the mortise (5−11 mm). These three factors were identified as the most important as a result of a series of preliminary exploratory experiments. The Box–Behnken design represents a combination of a two-level fractional factorial design with an incomplete block design including centre points. Each independent variable was varied thus at three levels, coded as −1, 0, +1.

The obtained data were statistically processed using the methodology described in Spiridonof [7] at 95 % confidence interval.

3. Results and discussion

3.1. Regression model

Some samples obtained as a result of the experiment are shown in figure 2.



(a) (b) (c)

Figure 2. Some examples of mortises obtained by inserting the punch parallel to grain: (a) width of mortise B=20 mm, depth of mortise h_n=8 mm; (b) B=12 mm, h_n=5 mm; (c) B=4 mm, h_n=11 mm; the scale of figure (c) is valid for the rest of figures.

The results of experiment, factor and response values are presented in table 1. The order of realization of the experiments was random.

Table 1. Mean pressing force value.

Number of experiment	W (%)	h_n (mm)	B (mm)	Average for three estimation of F (N)
1	18	11	12	12356.32
2	18	5	12	10787.26
3	8	11	12	17848.01
4	8	5	12	19024.80
5	13	8	12	13533.11
6	18	8	20	19122.87
7	18	8	4	4903.30
8	8	8	20	30204.33
9	8	8	4	5099.43
10	13	8	12	13925.37
11	13	11	20	25006.83
12	13	11	4	5883.96
13	13	5	20	22555.18
14	13	5	4	5197.50
15	13	8	12	13533.11

As a result of processing the experimental data, following by Spiridonof technique [7], we get a regression model for pressing force in Scots pine wood in coded (1) and uncoded form (2);

$$y = 13663,86 - 3125,85x_1 + 441,30x_2 + 9475,63x_3 + 755,92x_1^2 + 584,31x_2^2 + \\ + 686,46x_1x_2 - 2721,33x_1x_3 \quad (1)$$

$$P = 9812{,}21 - 961{,}04W - 1486{,}61h_n + 2068{,}88B + 30{,}24W^2 + 64{,}92h_n^2 + \\ + 45{,}76Wh_n - 68{,}03WB \quad (2)$$

In the process of calculations, the variance of the regression coefficients were calculated, confidence intervals were determined, and the significance of the regression coefficients was checked. The variance s^2 was calculated and amounted to s^2=51289.3. The significance of the regression coefficients was checked and insignificant coefficients were excluded from the polynomial model. All variables in model (1) are statistically significant.

Verification of the model adequacy was carried out by F-test. The estimated value of the Fisher criterion was F=18.90 against the table value of F_t=19.3, therefore, the resulting model is adequate. The represented regression equation (1), (2) can be used to estimate the degree of influence of variable factors to pressing force.

3.2. The effect of variables on the pressing force

The analysis of the obtained regression models shows that the width of the mortise has the greatest influence on the pressing force in the test range (figure 3). This is consistent with the results of the previous research in the field of wood pressing [8–11]. In fact, the width of the mortise is the area of the pressed section of wood and, just like in similar studies, with increasing the area of pressing, the pressing force increases. Thus, the wider the mortise, the greater the energy costs of its formation.

Moisture content is the second most influential factor. An increase in moisture content causes a decrease in pressing force. This is consistent with the data obtained by other researchers [12–14]. Moistening the cell walls plasticizes the wood and reduces the force of their deformation. Based on these data, it would be possible to recommend pressing the mortise at the maximum moisture content of test range. However, with an increase in the moisture content of the sample, the quality of the mortise decreases dramatically, as shown in [6]. Therefore, the humidity needs to be stabilized at the level of operating moisture content of the finished product (8–12%). In this case, the quality of compressive moulding the mortise will be high, and the workpiece will not require subsequent drying.

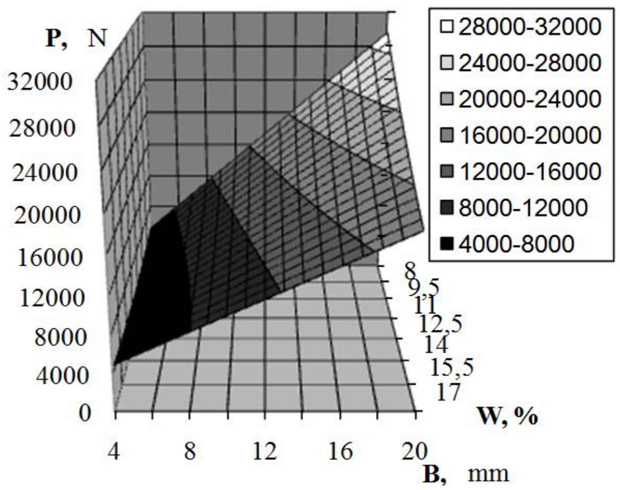


Figure 3. Dependence of the pressing force for Scots pine wood on the width B and the moisture content W at a depth of the groove h_n=8 mm.

The depth of the mortise is the least significant factor. This phenomenon could be explained by the conditions of wood deformation in a closed volume. After the wood platform under the working plane of the punch has chipped, the process of plastic deformation of earlywood zones begins. The process continues with a nearly constant compression force with some slight increase caused by friction of a growing "core" of pressed wood when moving along the slip planes. Hesselbach [3] noted a similar process of the occurrence of a compacted core when forming a hole by punching the blind holes in timber workpieces. Kučera and Bariska [15], Brabec [9] described the observations of an expansion of the deformed wood during pressing along the fibers which leads, in our case, to the appearance of frictional forces.

It is widely known, that increasing the length of the tenon (and the depth of mortise accordingly) noticeably increases the strength of the joint both for end joints in splicing and for mortise-and-tenon joints [1, 16]. In traditional milling method, it is technologically difficult to get a long finger profile [6, 17]. Therefore, the small effect of increasing the depth of the mortise on the pressing force is an undoubted advantage of pressing technology. The method will allow the manufacturer to form the required depth of the mortises in order to achieve a long length of glue line without unnecessary energy costs.

4. Conclusions

With forming the open mortises in wooden workpieces by local pressing in the longitudinal direction a new process for industrial wood machining was developed. Pressing could be an effective alternative technique to milling, which is the most common method to form a profile of a finger joint.

Experiments carried out have shown that in the test range of factors, the best results in terms of energy costs are shown by a minimum mortise width of 4 mm. From the point of view of assessing the strength of glued joints, the smaller the pitch and the longer the length of the tenon profile, the higher the strength of the joint. Bearing in mind these results, further research should be devoted to the study of the formation of mortises of minimum width (4 mm or less) and the investigation of their quality.

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