Research of physical and mechanical properties of plywood based on thermally modified veneer

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Abstract. The article presents the results of a study of the physical and mechanical properties of plywood based on thermally modified birch veneer. The implementation of a full-factor experiment in the temperature range from 160 to 200 ºC with a duration of 120 to 240 min made it possible to establish the nature of the dependence of the change in strength in static bending and strength in shearing along the adhesive layer on the veneer heat treatment mode. The parameters of veneer heat treatment are determined, which do not lead to a decrease in the strength of plywood, but allow to reduce the indicators of water absorption and swelling by an amount from 20.4 to 33.5%. Plywood based on thermally modified veneer acquires higher strength and water resistance, which significantly expands the scope of application of glued wood based on urea-formaldehyde resins.

1. Introduction
The scientific foundations of heat treatment of wood were laid in the 30s – 40s of the twentieth century in Germany and the USA. Further research carried out in Germany in the period from the 50s to the 70s became the basis for more modern research carried out in the 90s in Finland, France and the Netherlands [1]. At the same time, the historical roots of the phenomenon of thermal modification of wood can be traced back to hundreds of years. Our ancestors used fire to increase the durability of wood. For example, even in the days of the Vikings, elements of the enclosing structures were processed over an open fire.

Currently, in many countries, various methods of thermomodification of wood are patented and implemented. The first industrial technology Thermowood was developed in Finland in 1997. In France, the Retification technology is being implemented, developed in the 70s of the last century, and which was commercialized several decades later. The technology involves the use of nitrogen instead of superheated steam. The Westwood method (USA) is based on the "3D heat wave" technology, when the steam in the closed space of the equipment is circulated forcibly by means of fans.

A distinctive feature of the Plato method (Holland) is a two-stage heating and cooling of the stack. The first heating is carried out under high pressure in a steam-water medium to a temperature of 150 to 180 ºC, followed by cooling and drying, then the second stage of heating to 190 ºC is performed.

The analysis of the works of Russian scientists dealing with the thermodification of wood is considered in the works [2-4].

The generalizing element of most technologies for thermal modification of wood raw materials is its heating in various environments in the temperature range from 150 to 280 ºC. The main positive changes acquired by wood are an increase in resistance to the biological effects of fungi and insect larvae, a
decrease in water absorption and moisture absorption, the acquisition of stability of geometric dimensions during operation, and an increase in thermal insulation characteristics. Heat treatment saturates the color of the wood, makes its structure brighter and more effective. Due to this, the wood of low-value species acquires an external resemblance to the wood of valuable hardwood species. [5-6].

As negative aspects of the process of thermal modification, researchers note a decrease in a number of mechanical and operational properties of wood, which limits the scope of its application. In [7], a decrease in the ultimate strength at rupture is noted as a result of a change in the heat treatment temperature, which at the same time has practically no effect on the elastic modulus. In the studies of F. Kollmann, violations in the microstructure of heat-treated spruce wood are described due to a decrease in the volume of wood in the process of heat treatment [8]. Heating wood to 180–200 °C in the presence of moisture leads to a decrease in resistance to shock loads, elastic modulus, tensile strength and compressive strength [9].

In general, the analysis of works devoted to the thermal modification of wood shows a multidirectional change in the properties of the processed material: the strength characteristics of wood decrease, but the characteristics improve, allowing the material to be used in conditions of high humidity.

The positive results of changes in the physical and mechanical properties of wood in the process of its thermal modification have become the basis for further research to study the effect of the thermal modification process on the properties of glued wood materials of various types. Today, plywood based on rotary cut veneer is one of the most widespread and promising glued materials for internal and external use. Significant strength in the longitudinal and transverse directions, high wear resistance and elasticity are the distinctive advantages of this material, which ensure versatility of use.

A number of works of the Kazan National Research Technological University are devoted to the study of the properties of plywood products made on the basis of thermally modified veneer [10-14].

For the manufacture of plywood with increased water resistance and moisture resistance, the veneer sheets were placed in a heat treatment chamber on the press plates, after which the chamber was sealed with a lid, and the press plates were compressed. The high temperature of the press plates up to 280 °C caused thermal modification of the veneer in 10-15 minutes [15]. In the process of processing, the odd rows of plates carried out reciprocating movements and there was a constant "smoothing" of the veneer sheets by the pressure rollers. It is assumed that at such a temperature regime of processing, molecular changes occur in the wood material, in which the wood turns into a completely new material in comparison with what it was before processing. It was found in [15] that high-temperature processing of veneer leads to a decrease in hygroscopicity, a change in color, density, weight and cellular structure of veneer samples. The rational processing temperature is determined in the range from 190 to 210 °C.

Chimiris Yu. V. in his work [16] found that to refine (obtain a light-yellow color) wood veneer with a thickness of 1 mm, it is necessary to heat up to a temperature of 190 °C for 10 minutes and hold at the same temperature for 90 minutes. The test results showed that the color of the workpiece depends on the thickness of its cross-section and the holding temperature. With an increase in the thickness of the workpiece, an increase in the heating duration to the required temperature and an increase in the holding time are required. In this case, the color of the workpiece is in direct proportion to the holding temperature: the higher the temperature, the darker the color.

In [17], the thermal modification of veneer was carried out by the method in a rarefied environment in the temperature range from 413 to 533 K. The change in the color gamut was most noted at temperatures above 473 K. Considering that in the process of thermal modification, many properties of the veneer change from color to cellular structure, an indicator of the degree of thermal modification was applied - the change in the density of veneer in the process of heat treatment at different temperatures and duration of exposure relative to its initial density. It has been established that the swelling pressure of modified veneer samples decreases according to an increase in the processing temperature of the wood material, with the main effect on the degree of processing of the wood material is exerted by temperature and duration.
2. Methods
At the Department of Woodworking Technology, Siberian State University M.F. Reshetnev, an experimental installation for thermal modification of wood was mounted and tested. In the course of preliminary experiments, a heat-shielding structure was developed and constructed, designed to ensure a uniform and stable arrangement of samples and their protection from thermal radiation from the surface of the cabinet walls. For the experiment, the temperature range was used, which is considered the most optimal for the thermal modification of wood from 150 to 230 °C [4]. Preliminary experiments have shown that for birch veneer with a thickness of 2.0 mm, the temperature range can be taken from 160 to 200 °C, since an increase in temperature above 200 °C leads to a significant change in the appearance and color of the veneer. Thermal modification of veneer consisted of the following stages: heating, heat treatment for a given duration, cooling-conditioning. After the end of the thermomodification mode, the veneer was removed, placed in bundles in batches, and kept for 24 h under a slight surcharge to equalize possible stresses. At the end of the aging process, the veneer was formed into plywood packages according to the standard general-purpose plywood assembly method and pressed according to the mode shown in table 1. The pressing value for all plywood samples corresponded to that adopted for birch plywood and ranged from 9.8 to 10.6%.

An experiment to study the influence of the parameters of thermal modification of veneer on the physical and mechanical properties of plywood products was carried out in accordance with the B3 plan. The required accuracy was ensured by 5-fold duplication of measurements. Factors and levels of their variation are given in table 2. The output parameters were static bending strength and shear strength along the adhesive layer. The results of the experiment are presented in table 3.

### Table 1. Pressing mode of plywood based on thermally modified veneer.

| Factor name                        | Designation | Parameter value |
|------------------------------------|-------------|-----------------|
| Pressing pressure, MPa             | P           | 1.8             |
| Specific pressing time, min / mm   | τ<sub>slid</sub> | 0.52           |
| Pressing temperature, °C           | T           | 130             |

### Table 2. Factors and levels of variation.

| Factor name                        | Designation | Variation levels |
|------------------------------------|-------------|-----------------|
| Duration of heat treatment, min    | τ/Factor_A  | +1 240          |
| Heat treatment temperature, °C     | T/ Factor_B | 0 160           |
|                                    |             | -1 120          |
|                                    |             | upper  main     |
|                                    |             | lower           |

### Table 3. Experiment planning matrix.

| Duration of heat treatment, min | Heat treatment temperature, °C | Static bending strength, MPa | Shearing strength along the adhesive layer, MPa |
|---------------------------------|--------------------------------|-----------------------------|-----------------------------------------------|
| Factor_A                        | Factor_B                      | Var_1                       | Var_2                                        |
| 1                               | 1                              | 67                          | 0.99                                         |
| -1                              | 1                              | 110                         | 2.05                                         |
| 1                               | -1                             | 91                          | 1.75                                         |
| -1                              | -1                             | 123                         | 1.71                                         |
| 0                               | 1                              | 80.5                        | 2.12                                         |
| 0                               | -1                             | 115                         | 1.93                                         |
| 1                               | 0                              | 86.5                        | 1.97                                         |
The influence of the investigated factors (temperature and duration of heat treatment) on the strength of plywood under static bending (figure 1) and when chipping along the adhesive layer (figure 2) was assessed by graphic interpretation of the regression equation and graphs of the effects of factors and the effects of their interactions.

**Figure 1.** Results of the study of strength in static bending.
Figure 2. Results of a study of the shear strength along the adhesive layer.

The given graphical dependencies show the presence of directly proportional relationships between the duration and temperature of heat treatment and the strength of plywood under static bending. With an increase in the duration of heat treatment, the strength of plywood decreases more significantly compared with a decrease with an increase in the heat treatment temperature. At the same time, an increase in the duration at the maximum temperature of heat treatment (200 °C) leads to a more significant decrease in strength than when processing at the minimum temperature.

Analysis of the data when testing plywood for the index of shear strength along the adhesive layer shows a decrease in strength similar to that discussed above with an increase in the duration of heat
treatment. In the case of a change in the heat treatment temperature, a different dependence is observed. An increase in the heat treatment temperature to 180 ºC leads to an increase in the strength of plywood when chipping along the glue layer. This is probably due to a certain loss of veneer density during heat treatment, which contributes to a deeper penetration of the adhesive into the veneer and the formation of a single monolithic veneer and glue structure, which, as a consequence, leads to an increase in chipping strength. A further increase in the heat treatment temperature reduces the strength of the plywood when chipping due to a more significant loss of its weight by the wood veneer. In addition, a denser layer is formed on the veneer surface, which prevents the surface from wetting with glue, leading to a decrease in the adhesive contact between the glue and the wood.

These assumptions are confirmed by the appearance of the fracture surfaces of plywood samples during chipping. The destruction of samples from veneer, processed at temperatures up to 180 ºC, is of a mixed nature, subsequent samples have a cohesive nature of destruction along the adhesive layer or along the wood. It should also be noted that an increase in the duration of heat treatment at the minimum temperature has practically no effect on the strength characteristics of plywood samples, and at the maximum temperature, an increase in the duration of heat treatment leads to a significant decrease in strength.

As a result of mathematical processing of experimental data, regression equations were obtained that adequately describe the dependence of the ultimate strength of plywood on the heat treatment mode:

- with static bending:
  \[
  \text{Var}_1 = 93.222 - 19.416 \times \text{Factor}_A - 11.918 \times \text{Factor}_B + 8.417 \times \text{Factor}_A^2 - 1.083 \times \text{Factor}_B^2 - 2.75 \times \text{Factor}_A \times \text{Factor}_B;
  \]

- when chipping along the adhesive layer:
  \[
  \text{Var}_2 = 2.202 - 0.257 \times \text{Factor}_A - 0.038 \times \text{Factor}_B - 0.143 \times \text{Factor}_A^2 - 0.348 \times \text{Factor}_B^2 - 0.275 \times \text{Factor}_A \times \text{Factor}_B
  \]

A certain number of works on thermal modification of wood is devoted to reducing the values of water absorption and swelling of wood [10, 12, 13]. Therefore, water absorption and swelling values were also determined for the manufactured plywood samples.

The water absorption of thermally modified samples in comparison with general-purpose plywood is reduced by 5.4 to 26.6%. The swelling is reduced by an amount from 8.8 to 43.4%. The maximum value of water absorption and swelling is observed in samples made of veneer, thermally modified for 120 minutes at a temperature of 160 ºC (62.1 and 16.6%, respectively). The minimum value for samples made of modified veneer at a temperature of 240 ºC for a duration of 120 minutes (40.2 and 9.9, respectively). It should be noted that water absorption and swelling are more pronouncedly reduced when using higher heat treatment temperatures.

Thus, plywood based on thermally modified veneer acquires higher water resistance, which significantly expands the scope of plywood based on urea-formaldehyde resins.

3. Conclusion
The use of thermally modified veneer for gluing plywood is one of the methods of directionally changing its physical and mechanical properties.

The implementation of the PFE in the work made it possible to establish that the strength characteristics of plywood are to a greater extent determined by the temperature of the heat treatment of the peeled veneer. The duration of heat treatment more significantly reduces the strength characteristics of plywood at maximum temperatures and practically does not affect the strength at minimum temperatures.

It has been established that heat treatment of veneer, which does not lead to a decrease in the strength of plywood, makes it possible to reduce water absorption and swelling by an amount from 20.4 to 33.5%.

Thus, plywood based on thermally modified veneer acquires higher strength and water resistance, which significantly expands the scope of application of glued materials based on urea-formaldehyde resins.
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