Microwave modification of wood: determination of mechanical properties of softwood

A A Aksenov and S V Malyukov*
Forestry Mechanization and Machine Design Department, Voronezh State University of Forestry and Technologies named after G.F. Morozov, 8 Timiryazeva street, 394087 Voronezh, Russian Federation

Abstract. Studies of aspen and birch wood interaction with pulsed exposure to microwave energy have been carried out. A method for determining the effect of microwave energy on the temperature inside the test specimen has been developed. It includes experimental setup for studying heat and mass transfer during drying and heat treatment of wood with microwave energy. Moisture content inside wood specimens has been determined by a new method using a laboratory installation for studying the mechanical properties of wood under the influence of microwave energy. This energy influences on the drying speed of the tested wood specimens. The research enables to select the optimal mode of wood heating by pulsed exposure to microwave energy. The results of wood tests for strength and hardness, obtained under the influence of microwave energy, have revealed the effect of wood hardening. The research has shown that microwave treatment of specimens reduces drying time of aspen and birch wood by five times in comparison with convective treatment.

1. Introduction
Wood drying is one of the key stages in timber production. Companies are trying to reduce the cost of drying not forgetting about the quality which should be improved. The required qualitative and quantitative indicators of the final product must be provided [1]. Currently, there are several methods of wood drying [2]. All of them have different effect on the mechanical properties of wood. Drying wood in the air takes a very long time, but drying time must be reduced as much as possible. At the same time, internal stresses often arise in wood [3] causing deformation. This leads to deterioration in the quality of sawn wood.

Traditional convective drying method (European spruce was used) was compared with microwave drying [4]. In the end, it was found that this drying method did not affect the strength of the test specimens in any way. There are also studies on the effect of microwave energy on wood permeability [5]. Depending on the intensity of the microwave energy, wood permeability may increase or decrease [6]. At the same time, increase in wood permeability leads to a deterioration of mechanical wood properties. Therefore, it is better to dry wood materials using low microwaves.

Three-dimensional modeling is often used in the process of wood drying with microwave energy [7]. It is developed on the basis of a mathematical model describing heat exchange process. As a result of mathematical modeling of wood drying process, it is concluded that drying time of different wood species differs from each other [8]. In this case, drying speed first increases and then decreases.
The power of microwave energy has a strong influence on the wood drying process. Beech wood (*Fagus sylvatica* L.) was used for these studies [9]. According to the results of the research, it was concluded that low microwaves reduce drying time. At the same time, the quality of oak wood does not deteriorate in comparison with convective drying method. Increasing power of microwave energy can reduce drying time of Scots pine [10]. Drying speed will increase if wood specimens are thinner. In [11] the authors developed an installation (belt conveyor) that enables continuous wood drying with microwave energy. The device can be used in industrial plants because it has a lot of advantages in front other installations of the same type.

Thus, the problem of wood heat treatment control is very urgent. The use of microwave energy enables to create the desired temperature inside the wood very quickly, thereby accelerating the process of removing moisture from it [6]. The purpose of this work is to study the effect of microwave energy on the strength and hardness of birch and aspen wood, as well as on the duration of its drying.

2. Experimental part

The research on wood drying was carried out on an original experimental installation (figure 1), created by Aksenov A. A. and Malyukov S. V. (Voronezh State University of Forestry and Technologies named after G. F. Morozov, Voronezh, Russia). Magnetron, with the power of 600 watts, was the source of microwave energy. The antenna output of the magnetron was located in a waveguide 8 with a rectangular cross section of 45×90 mm and a length of 295 mm. Through the tunnel 9 microwave energy was supplied to the box 10. The power supply 5 was designed to generate electricity. Structurally, it consisted of a magnetron power supply unit 6 and a power control unit 4. The magnetron power supply unit 6 produced an anode voltage of 4 kV and a filament voltage of the magnetron cathode. The power supply unit consisted of a power transformer with a power of about 1 kW, a rectifier based on a diode, a capacitor for a voltage doubling circuit $1 \, \text{mkF} \times 4 \, \text{kV}$, and a filter based on a 10 MOm resistor.

Power control unit 4 was designed for contactless connection of the power transformer. In addition, power control unit generated the voltage needed to power the control unit 3. The primary power supply was provided from AC network with a voltage of 220 V and a frequency of 50 Hz. The control unit 3 controlled the operation of the power supply unit and the microwave power source and set the required microwave power. It was equipped with a sensor 1 and a power meter 2.
The microwave energy from the magnetron (through the waveguide and tunnel) penetrated into the wood and heated the water contained in it. The water passed into a vaporous state and was removed through specially drilled holes in the tunnels. When water was converted into steam inside the wood cells, a sharp increase in volume occurred, which caused the instantaneous formation of a large pressure. The pressure accelerated the transfer of moisture and steam from the wood to the outside. The total pressure was the sum of steam and air pressures contained in the macro- and micropores and capillaries of heated wood. The intensity of drying \( V_i \) (the volume of removed moisture) depended on the total pressure in the wood, as well as on the initial moisture content \( W \) of the bars and wood density. The presence of total pressure was determined by hydrodynamic resistance of capillary-porous wood structure. At the same time, the rate of vapor formation exceeded the rate of air transport inside the wood.

In order to measure the temperature inside the specimens, it was necessary to measure the temperature simultaneously at 5-10 points. This is a rather difficult process. Therefore, a thermocouple was used to determine the temperature inside the test specimens. At the beginning of the experiments, the thermocouples made serious errors in the measurements which happened due to the fact that large metal wires were inserted in the wood specimens. These wires affected the electric field of the thermocouple.

The second factor in the appearance of measurement errors was capacitive currents which also appeared due to the large length of the thermocouple wires. Two short wires with a cross section of \( \varnothing 0.2 \) mm and a length of 40 mm were used in order to eliminate the influence of capacitive currents on the instrument readings. These two wires were inserted into the test specimen of wood to a depth of 30 mm. At the same time, two holes were made in the test specimens in advance using a needle. Then one wire was connected to the thermocouple, which was placed in the Dewar vessel, the second wire was connected to the potentiometer.

The tests were conducted in the form of pulses. Processing time of the test wood specimens with microwave energy was 60 seconds. After that, the microwave energy was turned off and temperature was measured. Two thermocouples were used during the tests. One thermocouple was permanently inserted into the wood specimen under test, and a second thermo-pair was inserted into the wood when the microwave power was turned off. The thermocouple, permanently inserted into the wood, overestimated the temperature of the test specimen. More accurate readings of the temperature of the test specimen were at the removable thermocouple. However, their readings were somewhat underestimated, due to a decrease in temperature during the introduction of removable thermocouples in the bar. Also the readings were affected by poor contact inside the bar of wood when it moved freely in the hole.

Determination of vapor-air mixture pressure inside the test specimen was performed at the original installation (figure 2). Using U-shaped pressure gauges (700 mm long), the pressure of water vapor inside the tested wood specimens was measured. The gauges were filled with 300 mm of mercury. Before the experiment began, the zero of the scale of each pressure gauge was combined with the initial readings. The pressure gauges were connected to paired pressure sensors. The end of one pressure sensor was sealed tight. This sensor was used to correct the pressure readings of the expanding air. Pressure sensors had the following geometric dimensions: external diameter was \( \varnothing 1 \) mm, internal diameter was \( \varnothing 0.6 \) mm, and length was 263 mm. The paired pressure sensors were inserted into the test specimens. Then the pressure change was registered (readings were recorded every second). At the same moment, stopwatch and thermometer readings were recorded. While exposing to microwave energy, the temperature inside the test specimens increased rapidly with the speed equal to \( 2^6 \) C/s. The pressure inside the specimens also increased rapidly and the results were recorded.

The determination of moisture content \( W \) inside the cylindrical specimen was performed according to the scheme (figure 3) by layer-by-layer measurement. The layers were positioned parallel to the surface on which the microwave energy was directed. The width of the specimen was 120 mm; the ends (10 mm thick) were cut off from each edge of the specimen with a saw. Trimming from the ends
was performed to reduce the measurement error. Upper layers of the end surfaces had zero moisture content after treatment with microwave energy. The remaining part of the wood was divided into 12 plates with a thickness of 10 mm. Further, these specimens were placed in containers for moisture measuring.

**Figure 3.** Scheme of cutting a bar into specimens for moisture determining \(W, \%: 1 – \) discarded end cuts with minimal moisture; 2 – plates by which the moisture content is determined by the weight method; 3 – plate numbers; 4 – moisture curve across the width of the bar.

All the above-mentioned operations for specimen preparation, including the time for closing containers with lids, were as quick as possible. The speed of specimen preparation made it possible to exclude the influence of the environment on the bar's moisture plot across the width of the bar. Thus, it provided the necessary accuracy of measurements. Further, each container with a plate of wood was weighed on a scale with an accuracy of 0.001. Then it was placed in the drying chamber and wood plates were dried to a completely dry state. This state was determined by the termination of weight reduction of the wood plate.

The method for calculating the moisture content of the plates was the difference in the masses of wet and dry wood [2]:

\[
W = \frac{m - m_0}{m_0} \times 100\%,
\]

where, \(W\) is the wood moisture content, \(\%\); \(m\) – weight of wet wood specimen, g; and \(m_0\) – weight of an absolutely dry wood specimen, g.

On the basis of these data, a moisture content graph was constructed for the width of the bar (figure 3). The mechanical properties of wood under the influence of microwave energy were measured on a laboratory installation (figure 4), created by Aksenov A. A. and Malyukov S. V., Voronezh State University of Forestry and Technologies named after G. F. Morozov (Voronezh, Russia). This installation enabled to track changes in wood deformations and stresses when it is processed with microwave energy. The test rig generated a force of up to 30 tons. The microwave energy was generated by a magnetron (manufactured by Magratep, Russia), which emitted microwave energy at a frequency of 2450 MHz with a power of 520 to 600 W. It was located on a rectangular waveguide.

Birch and aspen wood with a density of 450 to 600 kg/m\(^3\) and moisture content of 30-60% was tested to study the mechanical wood properties under the influence of microwave energy. Bars with dimensions of 120×120×260 mm were made of wood and compacted to a maximum density of 1200 kg/m\(^3\). The end surfaces of the bar were exposed to microwave energy.

The tests to study the mechanical properties of wood under the influence of microwave energy were carried out as follows. A weighted block of wood measuring 120×120×260 mm, heated to a temperature of +105°C with microwave energy, was pressed by a hydraulic cylinder to a given density. Time and initial deformation were noted and after that, the first pulse of microwave energy was applied with duration of 20-30 s. Then the deformation of the bar was measured. After two minutes, the impulse was repeated and measurements and loads were read and time was recorded. The total microwave energy treatment time was set in the range from 1.5 to 2.5 hours. Optimal processing time was determined by comparison with control tests without microwave energy.
Figure 4. Laboratory setup for studying the mechanical properties of wood under the influence of microwave energy: 1 – frame; 2 – waveguide; 3 – microwave energy generator; 4 – test specimen; 5 – large displacement meter; 6 – hydraulic cylinder; 7 – manometer; 8 – small displacement meters; 9 – box; 10 – microwave energy absorber meter.

The next series of experiments was carried out in the drying mode. Microwave energy was supplied in the same mode and at the same cross-sectional dimensions of the processed wood end surface. Specific power of microwave energy was set in the range from 0.005 to 0.5 W/cm³ at a flux density of 3 W/cm².

Next, we compared the indicators α (stress relaxation coefficient) and a (creep relaxation form indicator), which were obtained in the mode of heat treatment, drying and without treatment. Then we recorded information on reducing the voltage and temperature inside the wood in the cooling mode.

After drying the pressed wood to a moisture content of 6 ± 2 %, the modified wood was obtained. It was analyzed for hardness and strength and “hardening” effect was highlighted. It consisted in the fact that hardness on the wood surface was greater than hardness in the core of the bar.

3. Results and discussion
Experimental studies have shown that wood heating is a decisive factor [11]. The specific density of microwave energy was 0.25 W/cm². The temperature in the center of the specimen after 4 pulses (12 min) exceeded 100°C and significant overpressure developed inside the bar. The same results of wood processing by microwave energy were obtained by the authors in the article [12]. Heat treatment and drying process was completed efficiently without burnouts if the temperature inside the bar did not exceed 105±2°C for a density of 1000 kg/m³. Wood with low density dries much faster than wood with high density.

For aspen wood with a density of 500 kg/m³, the intensity of moisture reduction from 80 to 60% was from 0.60 to 0.48% per second, i.e. it decreased by 0.12 % per second; from 60 to 40 % it was from 0.48 to 0.40% per second, i.e. it decreased by 0.08 % per second, and for moisture content below 20% it decreased by only 0.01 % per second (figure 5). These data are consistent with the results obtained by the authors in their research [2, 8].

Convective method of wood heating was the longest process of removing moisture from 15 to 8% (pressed bars with a density of 1200 kg/m³). Practice has shown that the duration of convective heat treatment of wood with hot air in order to reduce moisture content from 15 to 8% reaches 480 minutes.

The results of microwave drying of pressed wood are presented in table 1. As an optimal one, you can take the 4-th mode of heat treatment using microwave energy. This mode produces wood of high-quality. In this mode the duration of the pulsed action of microwave energy is 60 seconds, and the breaks between pulses are 120 seconds (table 1). Overheating of the inner layers of wood until the core is burned out occurs when the duration of microwave energy pulses increases to 120 seconds, as well
as when the break time between the pulses decreases to 30-60 seconds. The decrease in the duration of microwave energy pulses to 30 seconds with 120 seconds breaks between pulses leads to the fact that wood does not dry well (mode 5, table 1). During the tests, it was repeatedly noted that smell of steam was clearly felt at a moisture content of 12-17%. When overheating of the middle of the bar took place, its surface remained intact. Information on the speed of compressed wood drying with microwave energy can be used for practical purposes.

**Table 1.** Results of microwave drying of compressed wood.

| Mode | Pulse duration, s | Interval between pulses, s | Result                          |
|------|-------------------|---------------------------|--------------------------------|
| 1    | 120               | 60                        | Mid-wood burnout                |
| 2    | 60                | 30                        | Wood darkening                  |
| 3    | 60                | 60                        | Wood overheating                |
| 4    | 60                | 120                       | High quality wood               |
| 5    | 30                | 120                       | Wood does not dry well, up to 17% |

The results of compressed wood testing for strength and hardness obtained as a result of microwave drying are presented in table 2 and table 3. As it can be seen from table 2, the final density of wood after exposure to microwave energy was in the range of 920-1000 kg/m³. During the tests, it was found that variation in quality indicators is insignificant. Moisture content of the specimens ranged from 4.17 to 4.7%, and the highest strength of 160.2 MPa was seen in wood specimen with a density of 920 kg/m³ and moisture content of 4.7%. A specimen with a density of 930 kg/m³ and moisture content of 4.43 had the lowest strength of 118.7 MPa.

**Table 2.** Strength indicators of pressed wood dried under the influence of microwave energy.

| Mode | Density, kg / m³ | Moisture content, % | Strength, MPa |
|------|------------------|---------------------|----------------|
| 1    | 930              | 4.17                | 120.45         |
| 2    | 920              | 4.70                | 160.20         |
| 3    | 940              | 4.57                | 126.01         |
| 4    | 930              | 4.43                | 118.70         |
| 5    | 1000             | 4.29                | 140.78         |
| 6    | 1000             | 4.36                | 123.92         |
Table 3. Indicators of hardness and deformation of pressed wood after convective heat treatment and while exposing to microwave energy.

| #  | Hardness, MPa | Moisture content, % | Deformation, % |
|----|---------------|---------------------|---------------|
|    |               |                     | Elastic | Residual           |
| 1  | 116           | 4.40                | 56      | 44                 |
| 2  | 166           | 4.43                | 63      | 37                 |

Table 3 shows the average values of five different wood hardness measurements. In the first case, the indicators of wood after convective heat treatment are presented. In the second case we show the indicators of wood after exposure to microwave energy.

The comparative analysis of the results of wood processing by microwave energy with the results of wood processing by convective drying was also carried out by the authors in the article [4]. Hansson L and Antti A divided wood specimens into four groups. In two groups, wood was dried at a temperature of 60°C; in the other two groups, the drying temperature was 100°C. At the same time, the final wood moisture content in all the groups was 8 and 12%. Our tests differed in that wood drying temperature was 105±2°C, and final wood moisture content was within 4-5% (table 2). As a result of research, they obtained the strength of experimental wood specimens in the range of 66-84 MPa [4]. According to the results of our tests, wood strength was 118.7-160.2 MPa (table 2). We see that wood strength decreased twice. As a result, we can conclude that both methods of drying do not affect the strength of spruce wood.

As it can be seen from table 3, the resulting material fully meets the technical requirements for hardness (100-180 MPa). Variation in quality indicators is insignificant and moisture indicators are uniform. The temporary elastic deformations under the influence of microwave energy increase from 56 to 63%, and residual deformations decrease from 44 to 37% (table 3). End wood hardness while exposing to microwave energy increases from 116 to 166 MPa (30%) compared to convective heat treatment.

4. Conclusion

Processing of blocks with microwave energy can reduce drying time of soft-wooded broadleaved species by 5 times compared to convective processing. Scientific novelty is the identification of the “hardening” effect, i.e. increasing the strength and hardness of the surface of the processed specimens in comparison with the strength and hardness of its core. For example, you can get parquet by processing birch and aspen with microwave energy that is not inferior in quality to oak or beech parquet. The scientific originality lies in the fact that wood was dried with the pulsed action of microwave energy. Birch and aspen are low-quality wood species and it is very rarely used as raw materials. At the same time, the area of forests where birch and aspen grow in the world increases from year to year. Manufacturing of wood products from soft-wooded broadleaved species using our proposed method (instead of scarce hardwood species) is of great social and economic interest for the whole world from the point of view of energy saving. Introduction of pulsed microwave processing of soft-wooded broadleaved species into manufacturing will significantly increase the economic effect and reduce costs.

References

[1] Vermaas H F 1995 Drying eucalypts for quality: material characteristics, pre-drying treatments, drying methods, schedules and optimisation of drying quality. South African Forestry Journal 174(1) 41 doi: 10.1080/00382167.1995.9629877
[2] Oloyede A and Groombridge P 2000 The influence of microwave heating on the mechanical properties of wood. *J. Mater. Process. Tech.* **100**(1-3) 67 doi: 10.1016/s0924-0136(99)00454-9

[3] Couceiro J, Hansson L, Sehlstedt-Persson M, Vikberg T and Sandberg D 2020 The conditioning regime in industrial drying of Scots pine sawn timber studied by X-ray computed tomography: a case-study. *Eur. J. Wood Wood Prod.* **78**(4) 673 doi: 10.1007/s00107-020-01549-2

[4] Hansson L and Antti A 2003 The effect of microwave drying on Norway spruce woods strength: a comparison with conventional drying. *J. Mater. Process. Tech.* **141**(1) 41 doi: 10.1016/s0924-0136(02)01102-0

[5] Torgovnikov G and Vinden P 2010 Microwave wood modification technology and its applications. *Forest Prod. J.* **60**(2) 173 doi: 10.13073/0015-7473-60.2.173

[6] Balboni B M, Ozarska B, Garcia J N and Torgovnikov G 2017 Microwave treatment of Eucalyptus macrorhyncha timber for reducing drying defects and its impact on physical and mechanical wood properties. *Eur. J. Wood Wood Prod.* **76**(3) 861 doi: 10.1007/s00107-017-1260-1

[7] Dedic A D, Svrzic S V, Janevski J N, Stojanovic B and Milenkovic M D 2018 Three-dimensional model for heat and mass transfer during convective drying of wood with microwave heating. *J. Porous Media* **21**(10) 877 doi: 10.1615/jpormedia.2018018908

[8] Kostoreva A A, Kostoreva Z A, Rogovaya L V and Loginov V S 2017 Research of heat and mass transfer processes in conditions of microwave heating of wet wood. *MATEC Web Conf.* **110** 01043 doi: 10.1051/matecconf/201711001043

[9] Rajewska K, Smoczkiewicz-Wojciechowska A and Majka J 2019 Intensification of beech wood drying process using microwaves. *Chem. Process Eng.* **40**(2) 179 doi: 10.24425/cpe.2019.126110

[10] Ouertani S, Koubaa A, Azzouz S, Bahar R, Hassini L and Belgith A 2018 Microwave drying kinetics of jack pine wood: determination of phytosanitary efficacy, energy consumption, and mechanical properties. *Eur. J. Wood Wood Prod.* **76**(4) 1101 doi: 10.1007/s00107-018-1316-x

[11] Vongpradubchai S and Rattanadecho P 2009 The microwave processing of wood using a continuous microwave belt drier. *Chem. Eng. Process.* **48**(5) 997 doi: 10.1016/j.cep.2009.01.008

[12] He X, Xiong X, Xie J, Li Y, Wei Y, Quan P, Mou Q and Li X 2017 Effect of microwave pretreatment on permeability and drying properties of wood. *BioResources* **12**(2) doi: 10.15376/biores.12.2.3850-3863