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THE SUITABILITY OF MICROWAVE HEATING FROM THE PERSPECTIVE OF PRACTICAL USE IN CONSTRUCTION AND BUILDING INDUSTRY

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ABSTRACT

This paper reports on the total deformation and maximum deflection after microwave heating of beech wood. There have been few studies devoted to the examination of microwave heating for of beech wood. The same procedures can be used for structural materials in construction industry. Total deformation and maximum deflection were investigated on beech samples immediately after microwave heating. The samples were loaded parallel to the grain during compression and perpendicular to the grain during bending. Heating time and moisture content are important factors that affect the total deformation as well as maximum deflection. In general, heating time had negative influence to total deformation and maximum deflection. On the other hand the initial moisture content had a positive impact.

KEYWORDS: Microwave heating, total deformation, maximum deflection, moisture content, beech wood.

INTRODUCTION

The aim of this work was to verify the suitability of microwave heating of wood. Total deflection and maximum deflection are key characteristics describing the possibility of formability wood, its bending or densification respectively.

Microwave heating of wood is still among the lesser-used methods for treatment of wood. Although the microwave heating is used, in construction industry, rather for drying of wood or walls, can be used also for production of structural components or products. In the building and constructional industry the microwave heating began to be used in the production of construction materials. The most commonly used in the production of Parallam - parallel strand lumber material or LVL – laminated veneer lumber. Heating of wood construction members need not be performed for the entire volume, but may be performed only locally in at the bend or shaping point. Another option is the realization of only selective or local heating of the material, i.e. for plywood-based materials where is heated only part that can be directly affected by microwaves

Microwave irradiation is carried out in the space of the microwave resonator device. In this space, microwaves reflected from the metal casing, creating locally and temporally variable spatial the field. After inserting or placing the material into this field, the field became deformed depending on its characteristics and volume. The only proven effect on biological materials is the thermal effect. This effect, beyond the power and frequency of microwaves, is affected by the composition of the material, its physical state (free water content), and basically also its structure. Materials containing free water, such as wood and organisms are capable of absorbing microwave energy with a consequent increase in temperature. This phenomenon is called the polar rotation or frictions. Friction is observed just for materials with dielectric active components, in this case water molecules. Water molecules are electrically neutral, while having dipolar character. In the electric field these molecules are therefore oriented according to the polarity if the polarity alternates (Klement and Trebula 2004). At high frequencies of radiation, the high speed rotation of polarity and subsequently the orientation of the water molecules create a thermal energy by friction cavities (Antti et al. 2001; Hansson et al. 2005; Hansson and Antti 2003; Lundgren 2007). Water is an ideal material that absorbs radiation with a wavelength of 12.25 cm (corresponding to the frequency 2.45 GHz) (Merenda 2006). Hansson (2007) and James (1975) also confirmed that the frequency 2.45 MHz with wavelengths of approximately 12 cm belongs to the most commonly used frequencies for heating. Wood also contains basic chemical components which polar groups (-OH, -CH_2OH, CHOH, and -COOH) may be affected as well as water (Makovíny 2000). Other materials, which contain polar molecules, are also adhesives and coating materials. Therefore, microwave heating is also quite frequently used for curing coatings or accelerating hardening of adhesives in structural joints.

MATERIAL AND METHODS

Material

Beech trees (*Fagus sylvatica* L.) used for experiments were harvested from the University Forest Enterprise area, southeast of Zvolen City. The zones, which were in the middle distance between the pith and bark, were chosen for sample preparation. For the experiments, compression samples with dimensions of 25 × 25 × 100 mm and bending samples with dimensions 25 × 25 × 400 mm were used. All of the samples were air-conditioned in a conditioning room for more than six months before testing.

Air-conditioned samples were divided into three groups according to the initial moisture content: 20, 30, and 65 %. The samples with initial moisture content less than or equal to the fiber saturation point (FSP) (20 and 30 %) were conditioned in a conditioning chamber using the principle of equilibrium moisture content (EMC) under different conditions. EMCs above FSP (65 %) were achieved by water soaking. Tab.1 shows the average values of equilibrium moisture contents for individual groups. Entire research contained 450 samples where compression testing as well as bending testing used 225 samples, i.e. 25 samples per combination.

Tab. 1: Moisture contents and conditioning conditions of samples.

Required initial moisture content (%)	Average values of EMC after conditioning (%)	Scattering of EMC values after conditioning (%)	Conditions during conditioning	
			Relative humidity of air (%)	Temperature (%)
20	20.72	18.23–23.21	87.5	20
30	30.25	28.31–32.19	97	
65	64.85	62.7–67.0	Water-soaking	20

Procedures

Microwave heating was carried out in a microwave heating device (Fig. 1). During this heating, the samples were placed in the center of the heating space and oriented tangentially on wooden trestles 5 mm above the water.

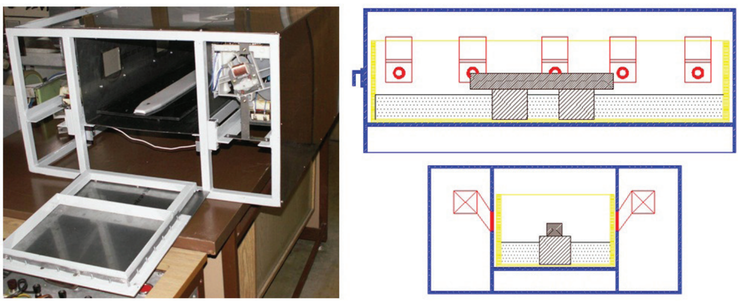

Fig. 1: Microwave device, an overview (left), side view (up right) and front view (bottom right) (Gašparík and Barcík 2013).

At the bottom of the polypropylene case, water was added to moisturize the environment. Heating time was set at 2, 4, and 6 min. The device power was constant, i.e., a 700-W/cavity magnetron. The temperature in wood was controlled by a thermal teflon-coated sensor and kept at 95°C during heating.

Immediately after heating, the samples for compression were cut to clear samples with dimensions of 25x25x30 mm using a special circular saw. This procedure was chosen based on the preliminary tests. During microwave heating the ends parts of wood have a greater loss of moisture, therefore should be cuts off. After heating the samples intended for bending were weighed and tested immediately.

Compression parallel to grain was carried out in a tensile-pressing machine ZD 10/90, manufacturer VEB TIR Rauenstein (Germany). The longitudinal direction (length) of wood samples was parallel (vertical) with the compression direction. Samples were placed on the compression plate and pressed to reach the ultimate compression strength. Also bending was carried out in a tensile-pressing machine ZD 10/90, which contained a special jig for flexural tests. Testing samples were placed on supporting pins (l=360 mm) so that loading force affected in radial direction considering to longitudinal direction of sample (three-point flexure test). Samples were loaded until breaking.

The tensile-pressing machine also incorporated a data logger for recording the loading forces during compression.

Measurements

The lengths necessary for the calculation of total deformations were those that were measured after compression. Every length necessary for the calculation of total deformation was measured at 5 different places (4 corners and 1 center of the sample), but for the calculation, only the average value of them was used.

Maximum deflection was measured in midpoint of testing sample (mid-span deflection) with accuracy 0.01 mm by digital indicator (gauge).

All dimensions and dimensional changes, for calculating the total deformations as well as moisture content, were measured with a precision of 0.1 mm using a digital caliper from the Mitutoyo company.

Calculations and evaluation

The influence of factors on the total deformation and maximum deflection was further evaluated using ANOVA analysis in STATISTICA 12 software.

Wood deformations, which are indicators of bendability, were investigated after compression parallel to the grain. Total deformations were represented by the engineering normal strain (in percentages), which was calculated according to Eq. 1,

$$\varepsilon_c = \frac{l_0 - l_{min.}}{l_0} * 100 \quad (1)$$

where: εc - the engineering normal strain (%),
l_0 - the original dimension (length) of the sample in the pressing direction (mm),
$l_{min.}$ - the minimum dimension (length) of the sample in the pressing direction after loading (mm).

The moisture content of the samples was determined and verified before and after microwave heating. These calculations were carried out according to ISO 3130 (1975) and Eq. 2,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (2)$$

where: w - the moisture content of the samples (%),
m_w - the mass (weight) of the test sample at certain moisture w (kg),
m_0 - the mass (weight) of the oven-dry test sample (kg).

Drying to an oven-dry state was also carried out according to ISO 3130 (1975).

RESULTS AND DISCUSSION

Total deformation

The results show that the influence of heating time as well as moisture on the total deformation was statistically very significant (Tab. 2).

Tab. 2: Influence of individual factors and their interactions on total deformations.

Monitored factor	**Sum of squares**	**Degree of freedom**	**Variance**	**Fisher's F - Test**	**Significance level P**
Intercept	45.821.2	1	45.821.2	24,646.4	0.000
Heating time	115.0	2	57.5	30.9	0.000
Initial moisture content	7.199.5	2	3.599.7	1.936.2	0.000
Heating time * initial moisture content	436.7	4	109.2	58.7	0.000
Error	150.6	81	1.9		

Fig. 2 left shows the total deformation dependence on the heating time. Heating time did not have a positive impact on the total deformation, i.e. with the increase of heating time, the total deformation gradually decreased. At the heating time of 6 min the lowest values of total deformation were found. The longer the wood exposed to heating, the more energy can be converted to heat which results in a greater decrease in moisture.

Fig. 2 right show dependence of total deformation on moisture content. The total deformation was highest at wood with initial moisture content of 65 %. This fact is connected with sufficiently high moisture as well as the plasticity of wood which leads to higher values of deformation. This is also confirmed by Zemiar et al. (2009) who claim that the final moisture content of wood is directly linked to the initial moisture of wood, therefore it can be stated that the higher the moisture content, the better bendability.

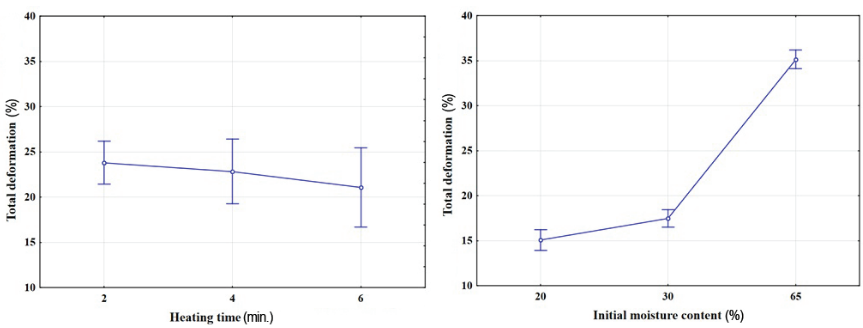

Fig. 2: 95 % confidence interval shows the influence of heating time (left) and initial moisture content (right) on total deformation.

As shown in Fig. 3, the total deformation obtained at a moisture content of 65 % is significantly higher than that at lower moisture contents. Also the curve has an opposite character at this moisture than the others. At both lower initial moisture contents, the total deformation was 2-3 times lower in comparison to the values which were found at initial moisture contents of 65 %.

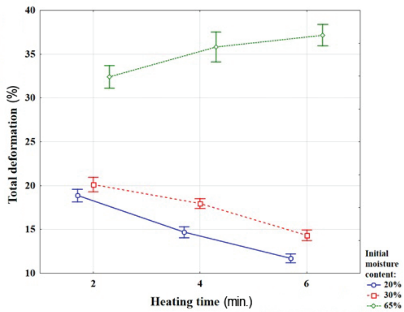

Fig. 3: 95 % confidence interval shows the influence of heating time and initial moisture content on total deformation.

On this basis it is clear that the final moisture content of wood decreases with increasing heating time as well as a higher initial moisture (Tab. 3). The same dependence is also confirmed by Mori et al. (1984) as well as Norimoto and Gril (1989) who stated that internal temperature of the wood reached a value from 100 to 130°C during microwave heating at heating times of 1 to 3 min. This research had heating times twice longer (6 min.) therefore it is possible that heating time has been very long (limit of structure destruction) (Tab. 4) for samples of these dimensions. The large amount of microwave energy when affects a small volume of wood can cause reduction in moisture.

Tab. 3: Moisture contents of wood before and after microwave heating.

Initial moisture content (%)	Heating time (min.)	Average values of EMC before heating (%)	Average values of MC after heating (%)
65 %	2	65.10	37.91
	4	65.25	37.92
	6	64.20	36.50
30 %	2	29.18	27.73
	4	29.58	22.70
	6	31.99	19.51
20 %	2	19.25	17.02
	4	20.77	13.13
	6	22.14	11.95

Also Studhalter et al. (2009) stated that the highest moisture change was achieved in green wood, while at a moisture content of 20 % as well as 35 % had very small decrease in moisture. When wood moisture content begins to decrease, there is also a decrease of plasticity, resulting in a reduction of the total deformation (Fig. 3). Microwave heating heats the whole volume of the material, but is bound to the water concentration in the cross section. The water is pushed out, from the center to the surface because the vapor pressure inside the wood is higher than the vapor pressure in its surroundings.

Tab. 4: Temperature of wood after microwave heating and compression.

Initial moisture content (%)	Heating time (min.)	Average values of temperature after heating (°C)	Average values of temperature after compression (°C)
65 %	2	97.25	93.14
	4	98.81	92.52
	6	104.22	95.74
30 %	2	96.44	92.84
	4	97.29	93.02
	6	101.86	94.50
20 %	2	93.11	90.11
	4	96.84	91.47
	6	97.62	92.24

Maximum deflection

Tab. 6 contains the values which reflect the statistical significance of individual factors and their mutual combinations. Based on these values, it may be stated that all factors were statistically significant, except the placement of samples.

Tab. 5: Influence of individual factors and their interactions on maximum deflection.

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	227.533.6	1	227.533.6	30.887.6	0.000
Heating time	3.764.0	2	1.882.0	255.5	0.000
Initial moisture content	8.021.8	2	4.010.9	544.5	0.000
Heating time * initial moisture content	243.0	4	60.7	8.3	0.000
Error	2386.8	324	7.4	2386.8	324

Fig. 4 left shows the impact of heating time on the maximum deflection of wood. The results show that the highest maximum deflection was achieved at a heating time of 2 minutes, while the lowest values were found for a heating time of 6 minutes. The increase in heating time leads to a decrease in maximum deflection, which is probably caused by the higher moisture loss (Dubovský et al. 1998).

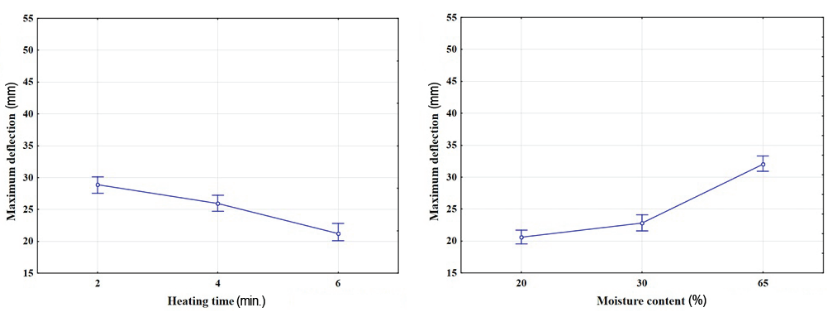

Fig. 4: 95 % confidence interval shows the influence of heating time (left) and initial moisture content (right) on maximum deflection.

Fig. 4 right shows the impact of initial moisture content. On the contrary moisture content had a positive impact on the maximum deflection, i.e. the higher the moisture content, the higher the maximum deflection reached. This fact is also confirmed by the results of which can be seen that the highest values of maximum deflection reached the wood with a moisture content of 65 %. On the other hand, the lowest values of maximum deflection were reached at 20 % moisture content.

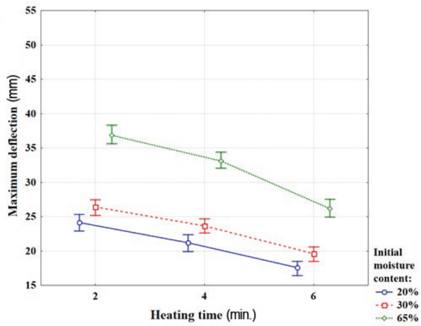

Fig. 5: 95 % confidence interval shows the influence of heating time and initial moisture content on maximum deflection.

The combined effect of heating time and moisture of time is shown in Fig.5. The negative impact of heating time on maximum deflection was also confirmed in this case. The maximum deflection increased with increasing moisture content, but not uniformly and not in all cases.

Zuzula (2002) reported higher results as those in our study. He heated beech wood with cross-sectional dimensions 40 × 40 mm with a moisture content of 30 %, at heating time 4.5 min with a similar device power. The author presents the average maximum deflection of 31.7 mm, while our values were 23.6 mm at 30.2 % moisture and heating time for 4 min. Probably greater wood volume for a given device power, which the author used, resulting in better results.

In general, maximum deflection decreases with increasing heating time. This fact can be explained by that if wood adsorbed a lot of energy, thereby increasing the temperature inside it. This increased temperature causes the extrusion of water from the center to the surface. Reduction of moisture during heating affects the plasticity of wood, thus also its formability. A suitable final moisture content of wood is an important and necessary condition for good and qualitative bending (Nemec et al. 1986, Palko 2008, Požgaj et al. 1997).

CONCLUSIONS

The total deformation of wood heated by microwave heating is affected differently. In general, heating time has a negative effect, although the decline in values is not so large. Only at 65 % moisture content, the total deformation of wood increased with increasing heating time. On the contrary moisture content has a positive effect, which is confirmed by the results.

A similar effect of heating time and moisture content can be observed at maximum deflection. However, in this case, the maximum deflection decreased in all cases. Differences in values of maximum deflection at different moisture contents were smaller than those of the total deformation.

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