Changes in Temperature and Moisture Content in Beech Wood Plasticized by Microwave Heating

Miroslav Gašparík [a],* and Milan Gaff [b,c]

This paper reports on changes in temperature and moisture content after plasticizing beech wood by microwave heating. There is currently no known use of microwave heating for plasticizing wood. Therefore, a proper procedure was developed to verify the use of microwave heating for the purpose of plasticizing. Moisture content was monitored in beech test samples with dimensions of 25 × 25 × 400 mm and 40 × 40 × 600 mm, while temperature was investigated only on samples 25 × 25 × 400 mm. In all cases, the temperature was suitable for the wood bending process. Microwave heating is quite intense, therefore for this kind of heating, it is better to have higher moisture content in the appropriate power device and minimal plasticizing time. The biggest advantage of microwave heating is the short plasticizing time, a few minutes, while steaming requires tens of minutes or even hours.

Keywords: Microwave heating; Plasticizing; Temperature; Moisture content; Beech wood

*Contact information: a: Department of Elementary Wood Processing, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; b: Department of Furniture and Wood Products, Technical University in Zvolen, T. G. Masaryka 24, Zvolen, 96053 Slovakia; c: Department of Wood Products and Wood Constructions, Czech University of Life Sciences in Prague, Kamýcká 1176, Praha 6 - Suchdol, 16521 Czech Republic; *Corresponding author: gathiss@gmail.com*

INTRODUCTION

The purpose of this work was to contribute to knowledge on the use of microwave heating for wood plasticizing to thus develop and accelerate the process of wood bending. Temperature and moisture are key factors that affect the plasticizing process, therefore their changes needed to be examined during wood plasticizing by microwave heating.

The main aim of the process of plasticizing wood before forming it is the temporary change in its mechanical and physical properties, which achieve optimal conditions for forming. For forming technology, the condition that needs to be met is the point at which the wood reaches the highest level of plasticity and the components of the lignin–saccharide matrix are the least damaged (Melcer 1990; Požgaj *et al.* 1997).

Steaming is one of the oldest and most widely used types of plasticizing, but conditions are not always suitable in the production process. The benefits of this method are the good plasticity of wood and minimal deterioration during the time prolongation of the plasticizing. The drawbacks of steaming are a poor working environment, low technology-readiness, and heat transfer from the surface zones to the inner zones, which with the poor thermal conductivity of wood slows down the plasticizing process (Zemiar *et al.* 1997).

Because of these drawbacks, research has focused on other principles of plasticizing that might suggest improvements or replacements for steaming while maintaining the benefits which it brings. Any new methods are compared with steaming for the widest application and the best results (Gašparík 2008).

Plasticizing by microwave heating brings many important advantages over conventional methods, such as a very short plasticizing time, a small energy requirement, volumetric heating, the ability to easily control the temperature to obtain the best processing conditions, the simple operation of microwave devices, no necessary special requirements for device operation (only an electrical power network is necessary), the mobility of the microwave device, space-saving, and an environmentally friendly process.

This study was intended to test a method by which it is possible to improve and accelerate the process of plasticizing and thus the actual wood bending. The plasticizing of wood (and thus bending) depends on two basic factors: moisture and temperature. The basic principle of microwave radiation heating of wood is based on the polar molecules contained in the wood. If the wood is exposed to an electromagnetic field of high frequency such as is characteristic of microwaves, water molecules which are dipole in character will begin to move to the same frequency as the electromagnetic field (Antti 1999; Antti *et al.* 2001; Hansson and Antti 2003; Klement and Trebula 2004). Moisture is important because water molecules will oscillate with the field and transform the energy into heat. The influence from the moisture bound in the cell walls is somewhat less than the influence from the free moisture in the cell cavities (Lundgren 2007). The dielectric and thermal properties of moisture within wood depend on whether the water is bound in the cell walls or is free in the cavities (Hansson *et al.* 2005). Dielectric properties of wood are also definitely influenced by the basic chemical components of cellulose, hemicellulose, and lignin on the basis of their polar groups (-OH, -CH_2OH, CHOH, -COOH) (Makovíny 2000).

These components have an important role in wood when heated because they contain polar molecules and can, like water, be heated by microwave radiation. The basic values of wood dielectric parameters increase with rising moisture. This fact was confirmed by James (1975), who states that permittivity increases with increasing wood moisture or temperature, but decreases with increasing frequency. The effect of moisture on the permittivity of wood justifies the high permittivity of water at the temperature of 20 °C and a frequency range of 0 to 106 Hz to be about 81, while the permittivity of absolutely dry wood under the same conditions is 2 to 4 (Zuzula 2002). Wet wood and dry wood are considered polar dielectrics. For the bending process, moisture content after plasticizing is important, as the quality of bending depends on it. On the basis that the higher the initial moisture of the wood, the higher the moisture after heating, more wood moisture will mean better bendability (Zemiar *et al.* 2009). Results confirm that moisture has a significant effect on the heating of wood by microwave energy. Water is an ideal material that most absorbs radiation with the wavelength of 12.25 cm (corresponding to the frequency 2450 MHz) (Merenda 2006). Hansson (2007) also confirmed that the frequency 2450 MHz with wavelengths of approximately 12 cm belongs to the most commonly used frequencies for heating.

EXPERIMENTAL

Materials

The experimental beech trees (*Fagus sylvatica* L.) were 75 years old and grew in the Javorie mountains area in central Slovakia, southeast of Zvolen. Trees were cut and supplied by University Forest Enterprise, also located in this area. The zones suitable for samples were cut from the trunk at a height of 1.5 m from the stump. The zones, which were in the middle distance between the pith and bark, were chosen for sample preparation. From these parts were cut 100-cm long sections which contained 1.5-mm–wide annual rings. For the experiments, clear beech samples with dimensions of 25 × 25 × 400 mm and 40 × 40 × 600 mm were used. All the samples were air-conditioned in the conditioning room for more than six months before moisture conditioning.

All of the air-conditioned samples were divided into two groups for the investigation—samples for temperature investigation (25 × 25 × 400 mm) and samples for moisture content investigation (25 × 25 × 400 mm and 40 × 40 × 600 mm). The samples with initial moisture content less or equal to the fiber saturation point (FSP) (20% and 30%) were conditioned in a conditioning chamber to achieve equilibrium moisture content (EMC). The EMC above FSP (65%) was achieved by water-soaking. The actual EMC of each sample was measured by a weighing method after conditioning. Table 1 shows the average values of equilibrium moisture contents for individual groups.

Table 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 (ºC)
20	20.40	17.95–22.85	87.5	20
30	30.85	27.9–33.8	97	
65	64.55	62.4–66.7	Water-soaking	20

Beech samples with dimensions of 25 × 25 × 400 mm (cross-sectional dimensions equal to the dimensions of standard test samples) for temperature investigation were divided into three groups of initial moisture content 65%, 30%, and 20%. The orientation of samples during microwave heating, with respect to the virtual flow line of opposite magnetrons of the device, was radial (R) and tangential (T). Plasticizing time was set at 2, 4, and 6 min. The device power was constant, *i.e.* a 700 W/cavity magnetron.

Beech test samples, with dimensions 25 × 25 × 400 mm and 40 × 40 × 600 mm (sizes for practical use), for the investigation of moisture content were divided into two groups of initial moisture content of 65% and 30%. Plasticizing time was set, as for the previous type of samples, at 2, 4, and 6 min. The samples during heating were always placed in the middle of a plasticizing space and oriented tangentially. The power device was constant, *i.e.* a 700 W/cavity magnetron for the smaller samples. The power device for the larger samples was a 500 W/cavity magnetron, but they also had a combined heating: for the first 2 min of heating they were set to 700 W/cavity magnetron and for next 2 or 4 min, the power device was lowered to 500 W/cavity magnetron.

For each combination of initial moisture content and plasticizing times, with respect to orientation, 20 samples were used. The temperature investigation contained 360 samples. The investigation on moisture changes contained 180 samples with the dimensions 25 × 25 × 400 mm and 240 samples with dimensions 40 × 40 × 600 mm.

Procedure

Investigation of changes of moisture content and temperature was followed by plasticizing by microwave heating which was carried out in a plasticizing device (Fig. 1). During this heating the samples were placed in the center of the plasticizing space on wooden trestles 5 mm above the water. At the bottom of the polypropylene case, water was added to moisturize the environment, limit the loss of moisture (drying) of test samples, and provide an environment with higher water content with respect to the relative moisture of the environment.

Fig. 1. Microwave plasticizing device, an overview (*left*) and placement of cavity magnetrons (*right*)

The temperature of plasticized samples was measured in four holes on the tangential face of each sample (Fig. 2) using a thermocouple thermometer, and immediately after microwave heating. These holes were drilled 100 mm from the end of the test sample on the tangential surface and were remote from each other by 5 mm. The depth of the holes reached to mid-thickness of the test sample.

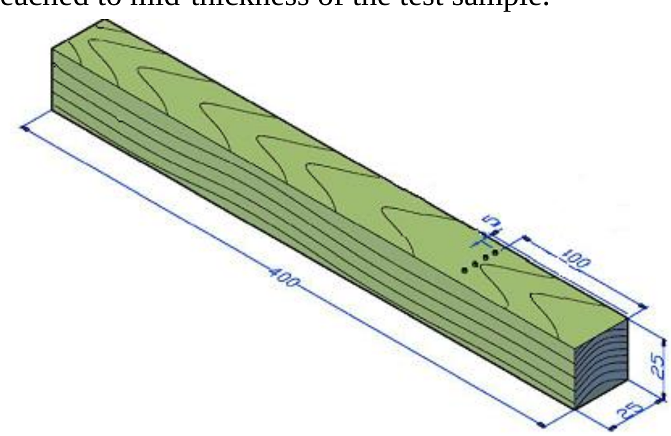

Fig. 2. Testing sample with holes for temperature measurement

Moisture content of samples was determined and verified before and after microwave plasticizing. These calculations were carried out according to ISO 3130 (1975) and Equation 1,

$$w = \frac{m_w - m_0}{m_0} * 100 \quad (1)$$

where w is the moisture content of the samples [%], m_w is the mass (weight) of the test sample at a certain moisture w [kg], and m_0 is 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).

During the examination of changes in temperature, selected factors such as initial moisture content of wood, plasticizing time, and orientation of plasticizing samples during microwave heating were monitored. The examinations of moisture changes were monitored only with the factors of initial moisture content and plasticizing time. The influence of these factors on temperature and moisture content after plasticizing, which were obtained from measurements and calculated to average values, was evaluated by STATISTICA 7 software (analysis of variance (ANOVA)).

RESULTS AND DISCUSSION

Temperature

Temperature together with moisture, are the most important factors that influence wood during plasticizing. Their mutual interaction influences the final result for the bending of wood. Temperature was determined on samples with radial and tangential orientation, with the placement in the middle of the plasticizing device.

A temperature within the range 95 to 100 °C is generally considered to be the most suitable temperature for wood bending process. At this temperature in conjunction with suitable moisture content, the wood becomes plastic and therefore suitable for forming. While the water in the wood acts as a lubricant, *i.e.* reduces friction and weakens the cohesion between the molecules of basic compounds of wood for their mechanical stress, heating leads to an increased mechanical oscillating motion of the molecules of basic compounds of wood, leading to a weakening of the cohesion forces between the macromolecules and apparently softening (transition to the plastic state) and consequently reducing the mechanical properties of wood. Regarding the basic components of wood, the most essential for the process of bending the lignin is the lignin–saccharide complex. With the water loss and temperature drop of the wood, the lignin loses plasticity, hardens, and creates new bonds in the neighborhood (Zemiar *et al.* 1999).

Table 2 shows the results from statistical analysis of variance (ANOVA), obtained from STATISTICA 7 software, which presents the influence of individual factors and their interactions on temperature.

Table 2. Influence of Individual Factors and Their Interactions on Temperature

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level P
Intercept	6,998,430.8	1	6,998,430.8	3,983,041.5	0.000000
Plasticizing time (min)	3,192.15	2	1,596.07	908.38	0.000000
Initial moisture content (%)	3,300.09	2	1,650.04	939.1	0.000000
Orientation	169.75	1	169.75	96.61	0.000000
Plasticizing time * Initial moisture content	368.33	4	92.08	52.41	0.000000
Plasticizing time * Orientation	32.11	2	16.06	9.14	0.000121
Initial moisture content * Orientation	1,845.14	2	922.57	525.06	0.000000
Plasticizing time * Initial moisture content * Orientation	17.03	4	4.26	2.42	0.046908
Error	1,233	702	2		

Figure 3 shows the combination of all factors together. The plasticizing time had a positive effect, *i.e.* with the increase of plasticizing time there were also increases in the temperature of the samples. Temperature growth was directly proportional to plasticizing time. The highest temperature values were at the plasticizing time of 6 min. This behavior can be explained by the classical approach. The longer the wood was heated, the more microwave energy was absorbed and then converted into heat.

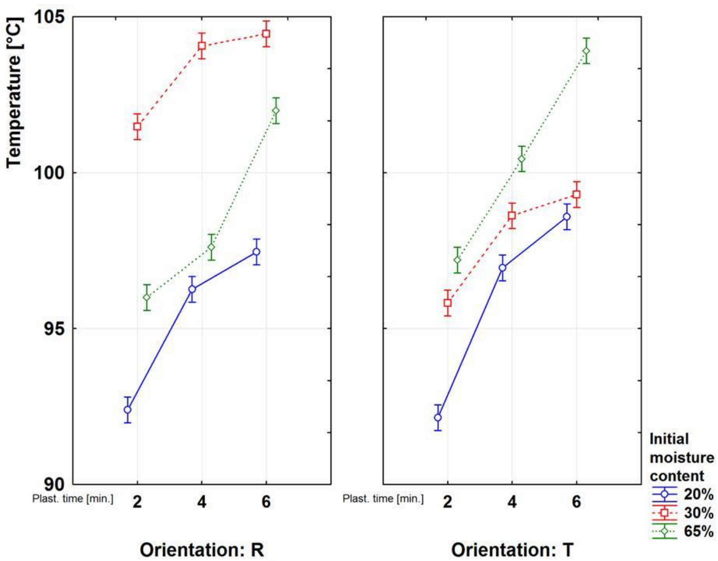

Fig. 3. Temperature dependence on plasticizing time, initial moisture content, and orientation

The impact of initial moisture content did not have a uniform character. While in a radial orientation, the wood reached a maximum temperature of 104.3 °C at 30% initial moisture content; wood oriented tangentially had a maximum temperature of 103.2 ºC at 65% initial moisture content. On the other hand, differences were not large.

There was no significant effect of different orientations on the temperature of the samples. Although the higher temperature was found in the radial orientation, differences between individual orientations were small. Differences between the individual orientations were probably caused by better penetration of microwaves into the wood, which is oriented radially, *i.e.* its tangential surface is directly exposed in the direction of the orifice of the waveguide connected to the cavity magnetrons. It was very difficult to determine from which direction the microwave radiation penetrated into the wood, inasmuch as the plasticizing device has a metal outer casing, from which the microwaves were reflected in all directions.

Comparing the values shows that the optimum temperature was achieved in all the cases tested. The influence of moisture content on the temperature reached during heating was confirmed, and this effect was not directly proportional. The clear effect of plasticizing time was confirmed, where with increasing plasticizing time temperature also rose.

Comparison of our values of temperature here with other studies shows that they achieved similar results. As mentioned above, the most suitable temperature for bending wood is in the range 95 to 100 °C, which is also confirmed by Sundqvist (2004) and Košíková *et al.* (1999) in their research. Studhalter *et al.* (2009) examined the temperature profiles in the wood of Mountain ash with different initial moisture contents (20%, 35%, and green 85–120%). Wood was heated by microwave heating at two selected temperatures (85 ºC and 105 ºC) in microwave devices. The highest temperatures 86 to 90 ºC (for a heating temperature of 85 ºC) and 101 to 105 ºC (for heating temperature of 105 ºC) were found in the middle of the wood and the temperature was slightly higher with higher moisture content. Wood was heated by microwave heating for a very short time (12 and 24 sec). Mori *et al.* (1984) as well as Norimoto and Gril (1989) also state that in their research, the internal temperature of the wood reached a value from 100 to 130 ºC during microwave heating at plasticizing times of 1 to 3 min. They found that in general a plasticizing time of 1 min is sufficient for small and medium-sized elements, and for larger elements up to a few minutes.

Wood Moisture

The movement of the moisture field (bound water) by the heating of wood is a practical application of molecular flow, which is described by diffusion. Diffusion describes the movement of bound water in wood. If the wood contains moisture that is unevenly distributed, the movement of water is triggered: Diffusion leads to the leveling of the differences (Merenda 2006).

The decreased moisture during microwave heating is caused by the movement of water in the wood during heating. Moisture loss is greater with higher initial moisture and gradually decreases with the reducing moisture, which is confirmed by the diffusion of water, which itself increases with the rising of wood moisture. The wood has higher moisture and thereby increases the number of polar particles with accepted water molecules which can absorb more microwave energy that is subsequently converted into heat. Water is not only significant in the development of heat, but also in the transfer of heat through the volume of wood. Kotlík (2005) concludes by saying that the heat in the microwave heating inside the material leads to the formation of an internal pressure gradient (warmer water and rising water vapor have a larger volume than the original cold water) and causes the extrusion of water to the surface.

Our research is first dealt with the change of moisture in the smaller samples with dimensions 25 × 25 × 400 mm. Table 3 shows factors that significantly influenced the final moisture content after microwave plasticizing of these samples.

Table 3. Influence of Individual Factors and Their Interactions on Moisture Content

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level P
Intercept	85,416.9	1	85,416.9	8,015.67	0.000000
Plasticizing time (min)	1,119.66	2	559.83	52.535	0.000000
Initial moisture content (%)	31,340.3	2	15,670.1	1,470.51	0.000000
Plasticizing time * Initial moisture content	171.30	4	42.83	4.019	0.005042
Error	863.16	81	10.66		

Although wood with the highest initial moisture (65%) had the most significant decrease in moisture, not in one case did the moisture drop below the fiber saturation point. Wood with an initial moisture content of 30% had moisture content, at all the plasticizing times, less than the fiber saturation point, and in one case it even dropped below 20% (Fig. 4). If the initial moisture of samples was too low, and therefore unsuitable for bending, then this caused even more heat reduction. Samples with moisture content of 20% were used to verify the extent to which moisture affects wood properties after plasticizing by microwave heating.

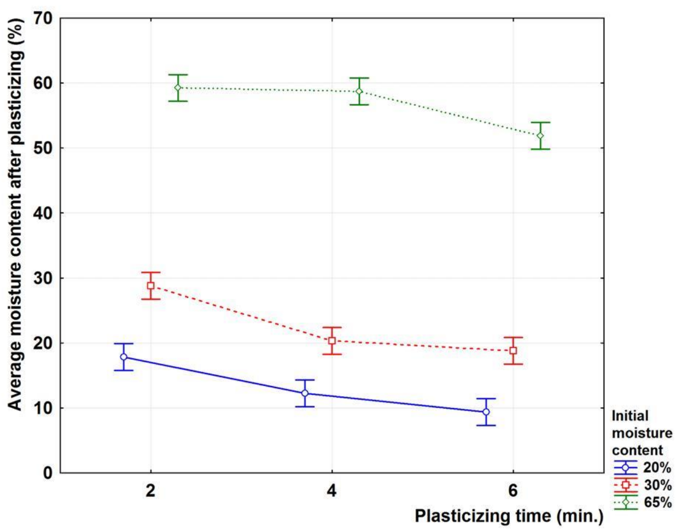

Fig. 4. Change in moisture content after plasticizing, and dependence on plasticizing time and initial moisture content at constant power with a 700 W/cavity magnetron device

Based on these data, in the case of samples with dimensions 25 × 25 × 400 mm, a drop in moisture increased with increasing plasticizing time and also with increasing the initial moisture content. A significant decrease in moisture can be explained by a higher volume of energy which is absorbed by the higher water content in the wood or by a large amount of energy relative to the small volume of wood.

Change of moisture content, for samples with dimensions of 40 × 40 × 600 mm, was also associated with a decrease of moisture dependent on plasticizing time (Fig. 5). In this case, the loss of moisture during heating was much smaller in comparison with a decrease in the moisture content of smaller samples. Table 4 shows factors which significantly influence the final moisture content after microwave plasticizing.

Table 4. Influence of Individual Factors and Their Interactions on Moisture Content

Monitored Factor	Sum of Squares	Degree of Freedom	Variance	Fisher's F-test	Significance Level P
Intercept	237,390.5	1	237,390.5	61,896.96	0.000000
Plasticizing time (min)	1306.1	2	653.0	170.27	0.000000
Initial moisture content (%)	22,523.4	1	22,523.4	5,872.72	0.000000
Power device (W)	210.5	1	210.5	54.88	0.000000
Plasticizing time * Initial moisture content	163.5	2	81.7	21.31	0.000000
Plasticizing time * Power device	9.8	2	4.9	1.28	0.281464
Initial moisture content * Power device	2.4	1	2.4	0.63	0.429378
Plasticizing time * Initial moisture content * Power device	19.0	2	9.5	2.47	0.089232
Error	414.2	108	3.8		

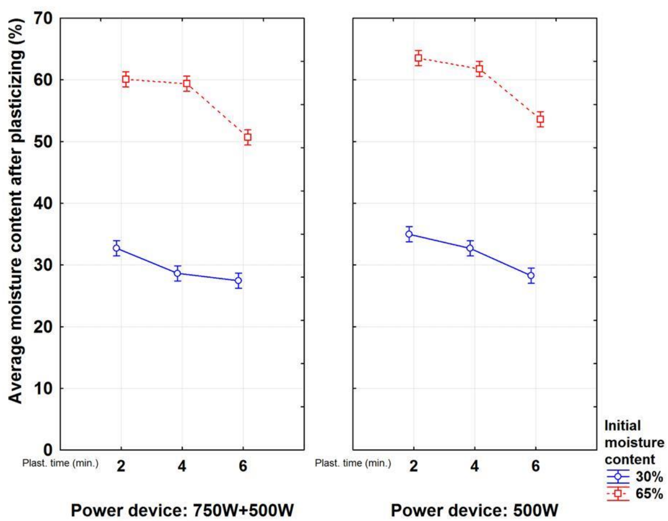

Fig. 5. Change of moisture content after plasticizing, and dependence on plasticizing time, power device, and initial moisture content

Comparing the final moisture of samples shows that moisture was high even after microwave heating. It cannot be clearly determined which variants in relation to the device power (constant power or a combination of powers) have more or less influence on the moisture content of wood. On the other hand, the slightly higher moisture content was reached at the lower power device of 500 W for both initial moisture contents. The assumption is that the same positive effect had also increased the dimensions of test samples, which also increased the volume of the wood.

In addition to temperature, moisture content is also an important factor that affects the plasticity of wood. Therefore, the influence of moisture has often been investigated. Palko (2008) is among the authors who have examined the effect of moisture in wood after microwave heating. Palko confirmed the same moisture behavior during microwave heating of smaller samples, *i.e*. the higher the initial moisture content of wood, the greater the decrease in moisture. He examined moisture profiles in wood with different initial moisture content (green about 100%, and 30%), which was heated 2, 4, and 6 min. Studhalter *et al.* (2009) investigated the moisture profile in wood during microwave heating and found that the highest moisture change was achieved in green wood (down 7%), while at a moisture content of 20% and 35%, the drop in moisture was very small. These small reductions of moisture were probably caused by very short heating times of 12 and 24 sec. Salmén *et al.* (1984) analyzed the influence of moisture on the behavior of lignin, cellulose, and hemicelluloses. They confirmed the fact that the water has a positive effect on the plasticity of wood. The softening temperature, *i.e*. the glass transition of the lignin, in wood samples which were immersed in water occurred at about 80 ºC. Drastic reductions were found in the glass transition temperature of various lignins, which were caused by small amounts of water *e.g*. for a thio-lignin from 174 ºC down to 115 ºC by a moisture content of 5%. Further addition of water has comparatively little effect, *i.e*. a limiting softening temperature is reached.

CONCLUSIONS

1. From the perspective of temperature, the procedure of microwave heating is suitable for plasticizing wood, because the required temperature for softening lignin can be reached. Plasticizing time as well as moisture content had a positive effect on temperature. In most cases, the optimum temperature was reached at plasticizing times from 2 to 4 min, but with 6-min heating the values sometimes exceeded 100 ºC. There was no significant impact due to the orientation of samples during microwave heating.
2. The moisture content of wood is the second but no less important factor which has a fundamental impact during the plasticizing of wood. The power device had an impact only in relation to the volume of plasticized wood. Smaller pieces of wood had a significant decrease in moisture content, and in many cases the wood did not have sufficient moisture for bending. The larger pieces of wood meant that the microwave energy was absorbed by the higher volume of wood, and thus the moisture loss was less and therefore did not reduce the bendability of the wood. For different individual device powers, the differences in the values of moisture content were not important.
3. Based on these findings, this microwave heating procedure of plasticizing for achieving the proper temperature is recommended. For optimum softening of beech wood with similar dimensions, it is appropriate to use wood with an initial moisture content at least 40% or higher and a plasticizing time up to 4 min. Orientation during heating is not decisive. A substantial difference between the examined powers was not found, but on the other hand higher power than a 700 W/magnetron may cause

undesired moisture loss and deterioration of flexural properties for beech wood with similar dimensions.

ACKNOWLEDGMENTS

The authors are grateful for the support of VEGA grant No. 1/3512/06 "Thermo-mechanical treatment of wood and wood-based materials—changes of surface and structure and its relation to shaping, gluing, and surface finishing by coating substances," and also for the support from Slovak Research and Development Agency scientific–technical project AV/4911/2004 "Application research of microwave heating and microwave techniques for wood-working technology a realization of microwave device for wood plasticizing." Both projects were undertaken at the Technical University in Zvolen.

REFERENCES CITED

Antti, L. (1999). "Heating and drying wood using microwave power," Doctoral Thesis, Luleå University of Technology, Division of Wood Physics, Skellefteå Campus, Sweden.

Antti, L., Jönsson, A., and Nilsson, M. (2001). "The effect of drying method on the mechanical properties of wood: Comparison between conventional kiln and microwave dried Scots pine," in *Third European COST E15 Workshop on Wood Drying*, Helsinki, Finland, 1-9.

Gašparík, M. (2008). "Plastifikácia dreva mikrovlnným ohrevom pre účely ohýbania. [Wood plasticizing by microwave heating for bending purposes]," Ph.D. Thesis, Technical University in Zvolen, Slovakia, 115 p. (in Slovak).

Hansson, L. (2007). "Microwave treatment of wood," Doctoral Thesis, Luleå University of Technology, Department of Wood Physics, Skellefteå, Sweden, 137 p.

Hansson, L., and Antti L. (2003). "The effect of microwave drying on Norway spruce woods: A comparison with conventional drying," *Journal of Materials Processing Technology* 141(1), 41-50.

Hansson, L., Lundgren, N., Antti, L., and Hagman, O. (2005). "FEM simulation of heating wood in an industrial microwave applicator," in *10th International Conference on Microwave and High Frequency Heating*, 12–15 September, Modena, Italy, 415-418.

ISO 3130 (1975). "Wood—Determination of moisture content for physical and mechanical tests," International Organization for Standardization.

James, W. L. (1975). "Dielectric properties of wood and hardboard: Variation with temperature, frequency, moisture content, and grain orientation," U.S. Department of Agriculture, Forest Service Research Paper, University of Madison, Wisconsin, USA, 32 p.

Klement, I., and Trebula, P. (2004). “Dielektrické sušenie: Špeciálne spôsoby sušenia [Dielectric drying: Special drying methods],” *Stolársky magazín* 5(4), Banská Bystrica, Slovakia, 6-7 (in Slovak).
Košíková, B., Hricovíni, M., and Cosetino, C. (1999). “Interaction of lignin and polysaccharides in beech wood (Fagus sylvatica) during drying process,” *Wood Science and Technology* 33(5), 373-380.
Kotlík, P. (2005). “Využití mikrovlnného záření při vysoušení zdiva a likvidaci živých organismů ve stavebních materiálech [The use of microwave energy for drying walls and destruction of living organisms in building materials],” *Materiály pro stavbu* 2(1), 24-26 (in Czech).
Lundgren, N. (2007). “Microwave sensors for scanning of sawn-timber,” Doctoral Thesis, Luleå University of Technology, Division of Wood Science and Technology, Skellefteå Campus, Sweden, 115 p.
Makovíny, I. (2000). “Dielectric and electromagnetic characteristics of beech wood,” *Wood Research* 45(3), 23-34.
Melcer, I. (1990). *Chemizmus hydrotermickej úpravy listnatých drevín* [*Chemism of hydrothermal treatment for broadleaved wood species*], 2nd ed., Zvolen, Slovakia, 217 p. (in Slovak).
Merenda, L. (2006). “Varianty využití multifunkčního experimentálního autoklávu [Utilization variants of multifunctional experimental autoclave],” Master’s Thesis, Mendel University, Brno, Czech Republic, 94 p. (in Czech).
Mori, M., Nakazawa, S., Norimoto, M., Yamada, T., Hirano, M., Takaoka, M., and Muranaka, T. (1984). “Measurement of internal temperature of wood piece during microwave irradiation by fiber-optical temperature sensor,” *Wood Industry* 39(1), 600-603.
Norimoto, M., and Gril, J. (1989). “Wood bending using microwave heating,” *Journal of Microwave Power and Electromagnetic Energy* 24(4), 203-212.
Palko, M. (2008). “Vlhkostné a teplotné profily pri mikrovlnnom ohreve [Moisture and temperature profiles in wood during microwave heating],” Master’s Thesis, Technical University in Zvolen, Slovakia, 82 p. (in Slovak).
Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva* [*Structure and Properties of Wood*], Príroda a. s., Bratislava, 485 p. (in Slovak).
Salmén, L., Back, E., and Alwarsdotter, Y. (1984). “Effect of non-aqueous plasticizers on the thermal softening of paper,” *Journal of Wood Chemistry and Technology* 4(3), 347-365.
Studhalter, B., Ozarska, B., and Graeme, S. (2009). “Temperature and moisture content behaviour in microwave heated wood prior to bending—Mountain ash (Eucalyptus regnans),” *European Journal of Wood and Wood Products* 67(2), 237-239.
Sundqvist, B. (2004). “Colour changes and acid formation in wood during heating,” Doctoral Thesis, Luleå University of Technology, Division of Wood Material Science, Skellefteå Campus, Sweden, 154 p.
Zemiar, J., Gáborík, J., and Solár, M. (1997). “Plastifikácia dreva a metódy jeho ohýbania [Plasticizing of wood and bending methods],” *Elektrické teplo v drevárskej praxi:*

Plastifikácia, ohýbanie a lamelovanie dreva 18-19, June, Technical University in Zvolen, Slovakia, 110 p. (in Slovak).
Zemiar, J., Gáborík, J., Solár, M., and Kotrady M. (1999). *Tvárnenie Dreva Ohýbaním* [*Wood Forming by Bending*], Scientific Studies, Technical University in Zvolen, Slovakia, 69 p. (in Slovak).
Zemiar, J., Palko, M., Makovíny, I., and Gašparík, M. (2009). "Temperature and moisture profiles at microwave heating of wood," *Annals of Warsaw University of Life Sciences—SGGW, Forestry and Wood Technology* 67, 283-288.
Zuzula, S. (2002). "Plastifikácia nábytkových hranolčekov mikrovlnovým ohrevom [Plasticizing of furniture semi-products by microwave heating]," Master's Thesis, Technical University in Zvolen, Slovakia, 85 p. (in Slovak).

Article submitted: March 15, 2013; Peer review completed: April 9, 2013; Revised version accepted: April 28, 2013; Published: May 10, 2013.