Impact of Plasticization by Microwave Heating on the Total Deformation of Beech Wood

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This paper reports on the total deformation and loading force after plasticizing beech wood by microwave heating. There have been few studies devoted to the examination of microwave heating for plasticizing of beech wood. Therefore, a procedure was developed to verify the use of microwave heating for the purpose of plasticizing. Total deformation and loading force were investigated on beech samples immediately after plasticizing by microwave heating. The samples were loaded with pressure applied parallel to the grain. Measured results served the purpose of quantifying total deformation. The investigated factors (wood moisture and plasticizing time) had significant influences on the loading force and total deformation of beech wood plasticized by microwave heating. Increasing initial wood moisture increased total deformation. Increasing plasticizing time decreased the total deformation of wood because of a larger loss of wood moisture. Loading force had contrary behavior: increasing wood moisture decreased the loading force, and increasing plasticizing time increased the loading force.

Keywords: Microwave heating; Plasticizing; Total deformation; Moisture content; Beech wood

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INTRODUCTION

The purpose of this work was to contribute to the knowledge on the use of microwave heating for wood plasticizing to develop and accelerate the process of wood bending. Total deformation is a key characteristic that describes the plasticizing process. This characteristic is represented by the engineering normal strain.

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 plasticizing process. 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 that it brings. Any new methods are compared with steaming for the widest application and the best results (Gašparík 2008; Zemiar *et al.* 1999).

Plasticizing by microwave heating has 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, then water molecules, which are dipolar in character, will begin to move with 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 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, but the influence from the moisture bound in the cell walls is somewhat less than the influence from the free moisture in the cell cavities (Hansson *et al.* 2005; Lundgren 2007). The 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, and -COOH), which can be, like water, heated by microwave radiation (Makovíny 2000).

The basic values of wood dielectric parameters increase with rising moisture. This fact was confirmed by James (1975), who stated that permittivity increases with increasing wood moisture or temperature, but decreases with increasing frequency. The permittivity of water at a temperature of 20 °C and a frequency range of 0 to 106 Hz is 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, the moisture content after plasticizing is important, as the quality of bending depends on it. Because the moisture after heating depends directly on the initial moisture of the wood, 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 absorbs radiation with a 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.

MATERIALS AND METHODS

Materials

Beech trees (*Fagus sylvatica* L.) used in this study were 75 years old and grown in the Javorie mountains in central Slovakia, southeast of Zvolen City. The zones suitable for samples were cut from the trunk at a height of 1.7 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, 100-cm-long sections were cut that contained 1.5-mm-wide annual rings. For the experiments, clear beech samples with dimensions of 25 × 25

× 100 mm were used. All of the samples were air-conditioned in a conditioning room for more than six months before moisture conditioning.

All of the air-conditioned samples were divided into two groups in relation to treatment – samples plasticized by microwave heating and steamed samples. Steamed samples served as a reference standard.

For each combination of heating (initial moisture content x plasticizing time), 25 samples were used, so that the entire study contained 300 samples (225 samples for microwave heating and 75 for steaming). Furthermore, all samples were divided into three groups according to 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. 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 (%)
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

Treatment was carried out in two basic ways: plasticizing and compression. Plasticizing was achieved by microwave heating and steaming.

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

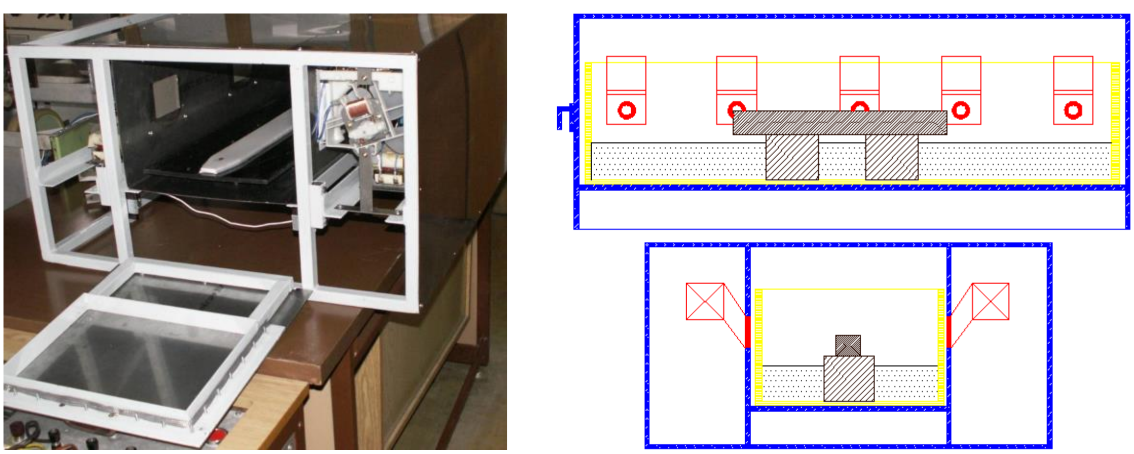

Fig. 1. Microwave plasticizing device, an overview (*left*), side view (*up right*) and front view (*bottom right*)

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. Plasticizing time was set at 2, 4, and 6 min. The device power was constant, *i.e.*, a 700-W/cavity magnetron. Steaming was carried out in a homemade steaming device that contained water at the bottom. Before testing, the water was heated to the boiling point; the samples were then inserted into the steaming device. Samples were placed on a metal grate over the water. During heating, the temperature in the device was kept at about 95 ºC. Plasticizing of samples took 20 min. Steamed samples and samples plasticized by microwave heating were loaded and tested.

Immediately after plasticizing, the plasticized samples were cut to test samples with dimensions of 25 x 25 x 30 mm using a special circular saw. This procedure was chosen based on the preliminary tests. During plasticizing of microwave heating the ends parts of wood have a greater loss of moisture, therefore should be cuts off. Even though it happens only when microwave heating, the ends parts of wood were cut off also at samples plasticized by steam because of equal conditions for all samples.

Pressing (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. Because the research was focused more on practical use, plasticized wood went directly to bending, and therefore only the maximum deformation was investigated. Samples were placed on the compression plate and pressed to reach the ultimate compression strength.

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.

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.

Values of loading forces were directly gathered from the data logger (connected to the tensile-pressing machine) on a personal computer.

Calculations and Evaluation

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 Equation 1,

$$\varepsilon_c = \frac{l_0 - l_{\min.}}{l_0} * 100 \tag{1}$$

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

The influence of factors on the total deformation and force, which were obtained by measuring and sensing during the test, was further evaluated using STATISTICA 7 software.

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

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

where w is the moisture content of the samples (%), m_w is the mass (weight) of the test sample at 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) using the following procedure: The samples were placed in a drying oven at a temperature of 103 ± 2 ºC until constant mass was reached. Constant mass is considered to be reached if the loss between two successive weight records carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, the samples were weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy at weighing was at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Total Deformation

The results revealed that the influence of plasticizing time and moisture on the total deformation was statistically very significant (Table 2). Figure 2 *left* shows the total deformation dependence on the plasticizing time. The plasticizing time had a negative influence, *i.e.* with increasing plasticizing time, there were decreases in the temperature of the samples. The decrease in total deformation was directly proportional to the time of plasticizing. The lowest values of total deformation 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, leading to the highest loss of moisture. The total deformation dependence on moisture content for samples plasticized by microwave heating is shown in Fig. 2 *right*. In this case, the total deformation was highest at a moisture content of 65%.

Table 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
Plasticizing 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
Plasticizing time * initial moisture content	436.7	4	109.2	58.7	0.000
Error	150.6	81	1.9		

Samples with an initial moisture content of 65% plasticized by microwave heating achieved the highest value of total deformation (Fig. 2 *right*). In this case, the total deformation (37.2%) increased with increasing plasticizing time and approached the total deformation of samples plasticized by steam (39.7%) (Table 3). This finding is attributed to a sufficiently high moisture content and plasticity of wood after heating, which led to the achievement of high values of distortion.

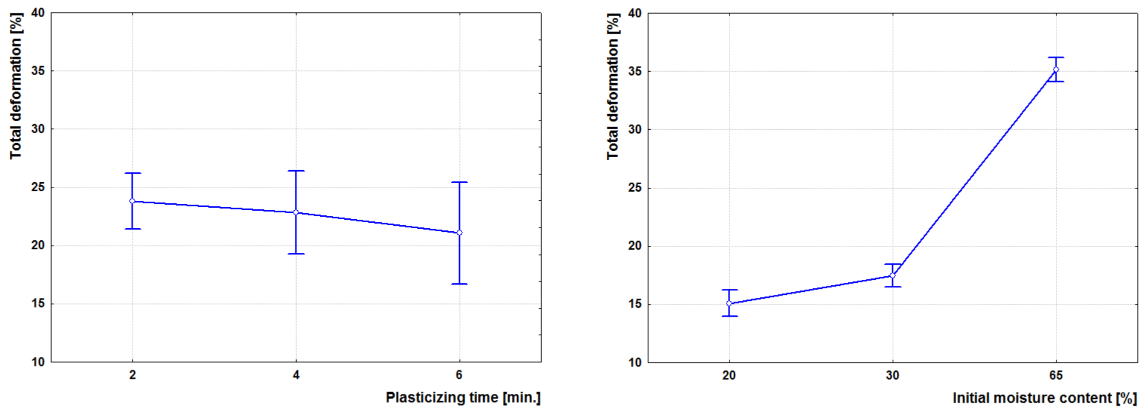

Fig. 2. 95% confidence interval shows the influence of plasticizing time (*left*) and initial moisture content (*right*) on total deformation

At a moisture content of 30%, the total deformation of plasticized wood by steam was 36.9%, while the wood plasticized by microwave heating only had a total deformation of 20.1% at a plasticizing time of 2 min. The biggest difference was found for 20% moisture content, where the total deformation of the steamed wood reached an average value 32.0%, while wood plasticized by microwave heating reached only 40% of the this value, *i.e.*, 11.7%, at a plasticizing time of 6 min.

For both lower initial moisture contents, the total deformation was two to three times lower compared to the values that were found for the wood with initial moisture contents of 65%. The comparison of total deformation reached for different plasticizing methods (microwave and steam plasticizing) shows the following: with decreasing of initial moisture content, greater differences were reached between the values of total deformation at microwave plasticizing. The values of deformation upon plasticizing by steam, depending on the initial moisture content, changed with a much smaller difference.

Table 3. Comparison of the Total Deformations at Different Methods of Plasticizing

Plasticizing						
Microwave heating					**Steaming**	
Initial moisture content	**Plasticizing time**				**Plasticizing time**	**Initial moisture content**
	2 min.	4 min.	6 min.		20 min.	
20%	18.9	14.7	11.7	**Total**	32.0	20%
30%	20.1	18.0	14.3	<= **deformation** ε_c =>	36.9	30%
65%	32.4	35.8	37.2	(%)	39.7	65%

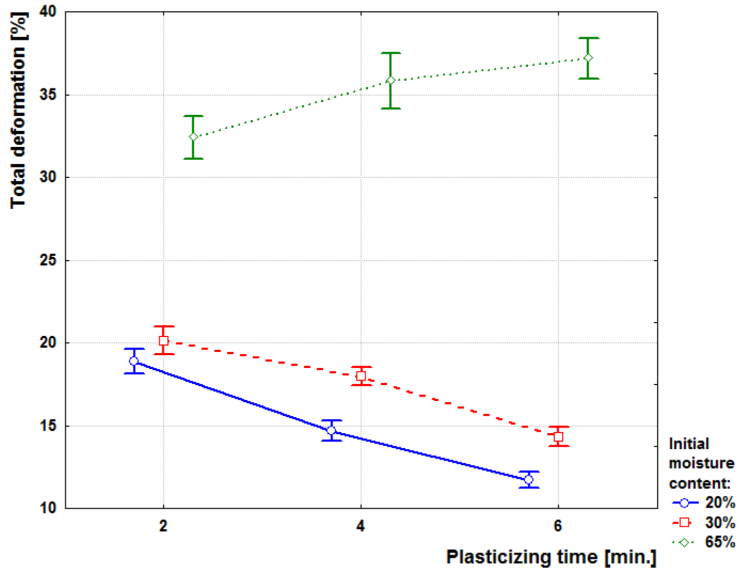

Fig. 3. 95% confidence interval shows the influence of plasticizing time and initial moisture content on total deformation

Based on the above information, it can be concluded that moisture decreased with increasing plasticizing time and with rising initial moisture content (Table 4). This fact is also confirmed by Mori *et al.* (1984) as well as Norimoto and Gril (1989). They stated 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.

Table 4. Moisture Contents of Wood Before and After Microwave Plasticizing

Required Initial Moisture Content (%)	Plasticizing Time (min.)	Average Values of EMC Before Plasticizing (%)	Average Values of MC After Plasticizing (%)
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

The plasticizing times employed in the present work were up to 2 times longer (6 min. in one case) so it is possible that plasticizing time has been too long (at the border to the thermal destruction) (Table 5) for samples of these dimensions. A significant decrease in moisture can be explained by a large amount of microwave energy, which affects a small volume of wood, causing a reduction in moisture. 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, while at a moisture content of 20% and

35%, the drop in moisture was very small. This fact was also confirmed in the present case. With the decrease in moisture, the plasticity of wood also decreased, which had a negative impact on the total deformation (Fig. 3). With increasing moisture of wood, the amount of heat converted from microwave energy also increased. Conventional steaming of wood is characterized by a gradual penetration of heat from the surface to the central zones, while microwave heating heats the material throughout its cross section and the water is pushed out, under the influence of created pressure, from the center to the surface because the vapor pressure inside the wood is higher than the vapor pressure in its surroundings.

Table 5. Temperature of Wood After Microwave Plasticizing and Compression

Required Initial Moisture Content (%)	Plasticizing Time (min.)	Average Values of Temperature After Plasticizing (°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

Force

Table 6 shows individual factors that affect the loading forces; the table shows that these factors have a significant influence.

Table 6. Influence of Individual Factors and Their Interactions on Loading Force

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance Level P
Intercept	41,528.2	1	41,528.2	22,342.2	0.000
Plasticizing time	120.6	2	60.3	32.4	0.000
Initial moisture content	6,673.5	2	3,336.8	1,795.2	0.000
Plasticizing time * initial moisture content	428.1	4	107.0	57.6	0.000
Error	148.1	78	1.9		

Individual curves of the force and its dependence on plasticizing time and initial moisture content can be seen in Fig. 4 *left* and *right*. In contrast to the total deformation, loading (compression) force rose steadily with increasing plasticizing time. Lower initial moisture content and longer plasticizing time led to greater compression force (Fig. 4 *left*).

The initial moisture content of the wood has the opposite effect on the loading force (Fig. 4 *right*). The higher the moisture content of wood, the lower the resistance against deformation or pressure. A value of the force describes the behavior of wood during deformation, *i.e.* the greater is the force, the lower is the deformation.

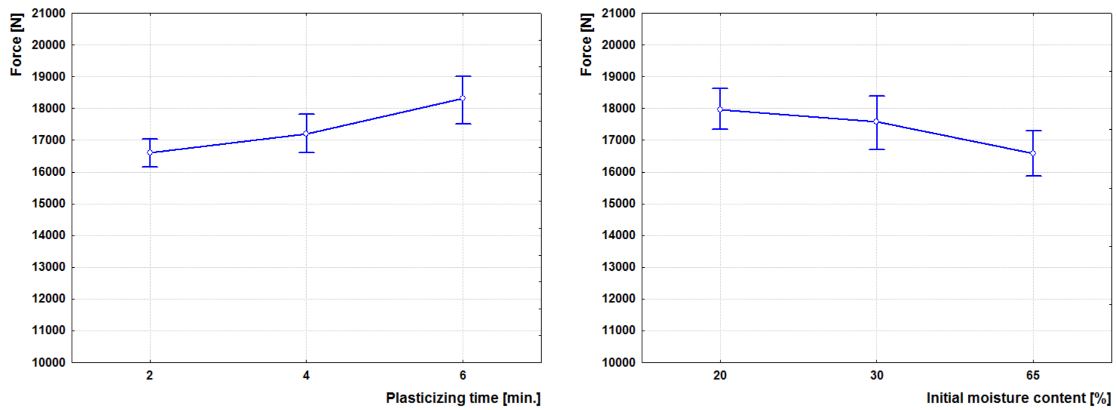

Fig. 4. 95% confidence interval shows the influence of plasticizing time (*left*) and initial moisture content (*right*) on force

When comparing methods of plasticizing by microwave heating and by steam (Table 7), one can see that values of force in compression for plasticized wood by microwave heating were almost the same (samples with an initial moisture content of 20% at 6 min plasticizing time; samples with an initial moisture content of 65% for 2 min plasticizing time) and even in some cases were higher (samples with an initial moisture of 65% at 4 and 6 min plasticizing time) than for plasticizing by steam.

Table 7. Comparison of Loading Forces with Different Methods of Plasticizing

Plasticizing						
Microwave heating					**Steaming**	
Initial moisture content	**Plasticizing time**				**Plasticizing time**	**Initial moisture content**
	2 min.	4 min.	6 min.		20 min.	
20%	17,040	17,620	19,230	**Loading** <= **force** F => (N)	20,330	20%
30%	16,810	17,200	18,700		18,010	30%
65%	15,960	16,800	17,020		16,020	65%

In other cases, however, loading (compression) force was lower. These results point to the fact that increasing force is caused by the growing strength of wood, which is affected by lower initial moisture content (Fig. 5) or a decrease of moisture in the wood during plasticizing.

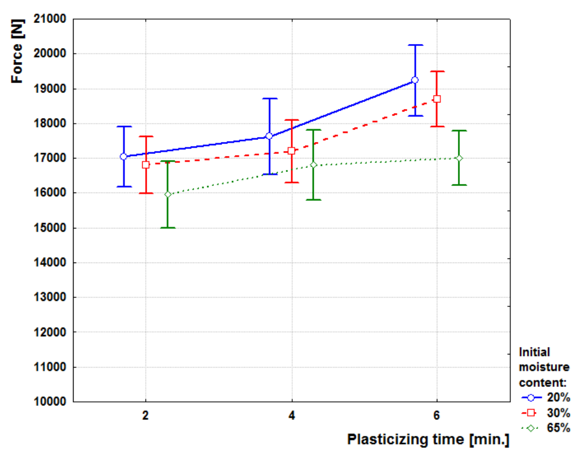

Fig. 5. 95% confidence interval for effect of plasticizing time and initial moisture content on force

CONCLUSIONS

1. For bending processes, it is important to know what the moisture content will be after plasticizing because this moisture affects the bending quality. Therefore, if the initial wood moisture will be higher, then the moisture after plasticizing must also be higher so wood can achieve better deformation. This fact is also confirmed by the measured values of total deformation, where the highest total deformation was reached at 65% moisture content. With decreasing moisture, the total deformation is reduced.
2. Plasticizing time is an important factor that has a significant influence on the total deformation. This fact was confirmed by statistical results. Increasing the plasticizing time also raises the amount of microwave energy, but moisture loss becomes larger during heating, *i.e.*, the increasing the plasticizing time decreases the total deformation in general. An exception was wood with 65% moisture content, which had moisture content high enough after plasticizing by microwave heating.
3. The behavior of the wood during loading can be described not only by the total deformation, but also by the force that acts during compression. This force shows behavior opposed to that of total deformation, where the higher initial wood moisture content means lower values of strength. Therefore, it is important for plasticizing by microwave heating wood to choose a higher moisture content or shorter plasticizing time. Improvements can also be achieved by changing the device power or additional moistening of the internal environment.

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 the 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."

REFERENCES

Antti, L. (1999). "Heating and drying wood using microwave power," PhD Thesis, Luleå University of Technology, Division of Wood Physics, Skellefteå, 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]," PhD Thesis, Technical University in Zvolen, Slovakia, 115 p. (in Slovak).

Hansson, L. (2007). “Microwave treatment of wood,” PhD 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 pp.
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).
Lundgren, N. (2007). “Microwave sensors for scanning of sawn-timber,” PhD Thesis, Luleå University of Technology, Division of Wood Science and Technology, Skellefteå, Sweden, 115 p.
Makovíny, I. (2000). “Dielectric and electromagnetic characteristics of beech wood,” *Drevársky výskum* 45(3), Štátny drevársky výskumný ústav, Bratislava, Slovakia, 23-34.
Melcer, I. (1990). *Chemizmus Hydrotermickej Úpravy Listnatých Drevín* [*Chemism of hydrothermal treatment for broadleaved wood species*], 2nd Ed., Zvolen, Slovakia, 217 pp. (in Slovak).
Merenda, L. (2006). “Varianty využití multifunkčního experimentálního autoklávu [Utilization variants of multifunctional experimental autoclave],” MS Thesis, Mendel University, Brno, Czech Republic, 94 pp. (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.
Požgaj, A., Chovanec, D., Kurjatko, S., and Babiak, M. (1997). *Štruktúra a Vlastnosti Dreva* [*Structure and Properties of Wood*], Príroda a. s., Bratislava, 485 pp. (in Slovak).
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.
Zemiar, J., Gáborík, J., 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 pp. (in Slovak).

Zemiar, J., Gáborík, J., Solár, M., Kotrady M. (1999). *Tvárnenie Dreva Ohýbaním* [*Wood Forming by Bending*], Scientific Studies, Technical University in Zvolen, Slovakia, 69 pp. (in Slovak).

Zemiar, J., Palko, M., Makovíny, I., 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(1), 283-288.

Zuzula, S. (2002). "Plastifikácia nábytkových hranolčekov mikrovlnovým ohrevom [Plasticizing of furniture semi-products by microwave heating]," MS Thesis, Technical University in Zvolen, Slovakia, 85 pp. (in Slovak).

Article submitted: July 29, 2013; Peer review completed: October 1, 2013; Revised version received and accepted: October 17, 2013; Published: October 22, 2013.