Effect of Plasticizing by Microwave Heating on Bending Characteristics of Beech Wood

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This paper reports the bending strength and maximum deflection after plasticizing beech wood by microwave heating. Previous work by the authors confirmed that microwave heating resulted in plasticizing of beech wood, which greatly affected its deformation when loaded by compression. This work complements the overall analysis of the behavior of microwave-plasticized wood during its bending. Bending strength and maximum deflection were investigated on beech samples immediately after plasticizing by microwave heating. Static bending test with three-point flexural test was used. While plasticizing time and moisture content had an important influence on the bending strength, the device power had no appreciable effect. Plasticizing time had a significant influence on the maximum deflection, while the moisture content and device power had no substantial influence.

Keywords: Microwave heating; Plasticizing; Steaming; Bending strength; Maximum deflection; Moisture content; Beech wood

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INTRODUCTION

Plasticizing is a process through which the temperature and moisture content or the addition of chemical substances increases the plasticity of wood. The main aim of plasticizing is therefore a temporary change in the mechanical and physical properties of wood. It is desirable to maximize the degree of plasticity with the lowest possible degradation of components of the lignin-cellulose matrix (Gáborík and Zemiar 1997). The degree of plasticity depends mainly on softening of the middle lamella, whose main component is lignin, since the plastic properties of wood are determined primarily by lignin properties. Lignin is one of the main components of wood responsible for its dimensional change upon heating, but not the only one. In the dry state, the glass transition temperature (T_g) of the lignin is about 205 °C (Back and Salmén 1982). Some investigators alleged a different glass transition temperature for lignin that is dependent on various temperature conditions, *e.g.*, 60 °C (Kelley *et al.* 1987), 50 to 100 °C (Furuta *et al.* 1997), and 170 °C (Ibach 2010). Increasing the moisture content or using the plasticizers helps reduce the glass transition temperature for all components of wood (Ibach 2010). Under these conditions, lignin has a glass transition temperature around 100 °C. For this reason, water-saturated wood as a whole has a softening temperature of about 100 °C (Salmén 1984). Even though lignin is the most important, increasing the moisture content lowers the glass transition temperature of all components of wood. Goring (1963) found that the glass transition temperature of the cellulose, hemicellulose, and lignin in wet conditions range from 222 to 250 °C, 54 to 142 °C, and 77 to 128 °C, respectively.

Steaming is a fundamental method of plasticizing, in which the wood is exposed to the effects of moisture and temperature. Temperature and moisture changes the physical and mechanical properties of wood. These changes in properties are temporary in nature during a time when it causes a necessary reduction in the strength of wood. With the decrease in strength, the plastic deformability increases (Zemiar *et al.* 1997). This principle is used during the bending of wood and the production of veneers. In addition to these beneficial results, steaming has several disadvantages to include a long interval of plasticizing (30 to 120 min, depending on the cross-section dimensions). Based on this fact, new methods are being developed that will keep the results of steaming while achieving a shorter plasticizing time and thus a shorter production time. Therefore, all new plasticizing methods are almost always compared with steaming (Gašparík and Gaff 2013; Zemiar *et al.* 1999).

Microwave energy is a seldom used method for plasticizing. In most cases, it is utilized primarily for wood drying, controlling pests or fungi in wood, and for the hardening of bonded joints. The principle of microwave heating is based on the conversion of radiation energy into thermal energy due to oscillations of molecules and other charged wood particles by an electromagnetic field. These molecules and particles tend to turn in the direction of the field, but because the polarity of the microwave field is constantly changing, this is not possible. In the course of the oscillating movements, the molecules collide with each other, and these repeated collisions cause frictional heating of the material (Chang and Chang 2003). It is therefore evident that microwave heating causes heating in the entire volume of the wood matter, not from the surface mass inward, as is the case with conventional methods of heating. For the drying and heating of wood, radiation with a frequency of 2450 MHz is used, which corresponds to a wavelength of 12.5 cm. This frequency is chosen such that the microwave energy affects most of the water molecules (Klement and Trebula 2004; Makovíny 2000). Plasticizing using microwave heating does not require more complex equipment, and control of the process is quite simple. However, optimum device performance, monitoring of temperature during heating, and sufficiently high moisture content of wood must be maintained.

The aim of this work was to verify and evaluate the impact of microwave plasticizing on bending characteristics of beech wood with a method that can improve and accelerate the process of plasticizing while maintaining a degree of plasticity. The bending strength and maximum deflection are important factors for practical use because they describe the flexural properties of wood affected by plasticizing.

MATERIALS AND METHODS

Materials

Seventy-five-year-old beech trees (*Fagus sylvatica* L.) were harvested from the area of the Javorie Mountains, in the center of Slovakia, by the University Forest Enterprise. Sections suitable for the test samples were cut from the trunk at a height of 1.5 m in the middle distance between the pith and the bark. These sections were subsequently sawn into 1-m lengths with annual width rings 1.5 mm wide. For the experiments, clear beech samples with dimensions of 40 mm × 40 mm × 600 mm were used.

The samples were divided into two groups (160 samples per group) according to the initial moisture content: 30% and 78% (Table 1). The samples with an initial moisture content equal to the fiber saturation point (FSP), approximately 30%, were conditioned in a chamber using the principle of equilibrium moisture content (EMC). The samples were conditioned for more than six months before testing. The EMC above FSP were achieved by water soaking which lasted two weeks. The actual EMC of each sample was measured by a weighing method after conditioning.

The testing included three groups of conditioned samples - samples for non-plasticized controls, samples for microwave heating, and samples for steaming. The steamed samples were intended for comparison of plasticizing methods, while the non-plasticized samples were used for comparison of changes in wood properties. The entire study consisted of 320 samples (240 for microwave heating, 40 for steaming, and 40 non-plasticized wood controls), 20 samples per each combination of moisture content, plasticizing time, and device power.

Table 1. Moisture Contents and Conditioning Conditions of Samples

Required Initial Moisture Content (%)	Average Values of EMC after Conditioning (%)	Range of EMC Values after Conditioning (%)	Conditions During Conditioning	
			Relative Humidity of Air (%)	Temperature (°C)
30	30.18	28.3 to 32.2	97	20
78	78.22	74.0 to 82.7	Water-soaking	20

Methods

The samples were treated with two procedures. The first procedure was plasticizing by microwave heating or steaming, and the second procedure was bending of the plasticized samples. A microwave device with a frequency of 2.45 GHz was designed and constructed specifically for a technical project that included this research. The plasticizing space was created in a polypropylene case, the bottom of which was filled with water to reduce moisture loss in the surface layers of wood. The water was heated to a temperature of 95 °C prior to the heating of wood. The samples were placed on wooden supports 5 mm above the water in the center of the plasticizing space and were oriented tangentially in relation to the direction of microwave radiation (Gašparík and Barcík 2013). The specific conditions are shown in Table 2.

Table 2. Plasticizing Conditions of Samples

Initial Moisture Content (%)	Microwave Heating				Steaming	
	Plasticizing Time (min)		Device Power (W)	Temperature (°C)	Plasticizing Time (min)	Temperature (°C)
30	2	2+0*	500	95	20	95
	4	2+2*				
78	6	2+4*	700+500*			

Note: *After heating for 2 min, the device power was reduced from 700 to 500 W

Steaming was carried out in a device designed for this research. Before steaming of the wood, water in the bottom of the device was heated to 100 °C. Subsequently, the sample was placed on a metal grate and plasticized for 20 min (Table 2). During heating, the temperature in the device was kept at about 95 ºC. Microwave heating was carried out at constant as well as a combined device power (Table 2), in contrast to previous work (Gašparík and Barcík 2013). Combined power device has been proposed to allow optimization of the amount of microwave radiation emitted into plasticizing space because of the heat control for sample of different sizes. Immediately after plasticizing, all samples were quickly weighed and immediately tested for bending to avoid possible undesirable cooling of wood.

The samples were bent by the free-bending principle without a bending (tension) strap (*i.e.*, three-point bending test) according to ISO 3133 (1975). The bending was carried out in a standard tensile-pressing machine ZD 10/90 (VEB TIR Rauenstein; Germany) that contained a special jig for flexural tests and a data logger for recording the maximum loading forces at the breaking point. Test samples were placed on supporting pins (l = 560 mm) so that loading force acted in the radial direction considering the length of the sample (three-point flexure test), and a load was applied until they broke.

Measurements

The values of maximum loading forces were directly downloaded from the data logger on a personal computer, and the bending strength (*i.e.*, modulus of rupture) was calculated. The maximum deflection, measured at the midpoint of the test sample (mid-span deflection), had an accuracy to 0.01 mm by a digital indicator gauge.

The dimensions of the samples, used for calculating the moisture content, were measured with a digital caliper 500-150-20 device (Mitutoyo; Japan) to a precision of 0.1 mm.

Calculations and evaluation

The influence of factors on the bending strength and maximum deflection was statistically evaluated using ANOVA analysis, mainly by Fisher's F-test, in STATISTICA 12 software (Statsoft Inc.; USA).

The bending strength (MOR) of the samples was calculated after bending. These calculations were carried out according to ISO 3133 (1975) and Eq. 1,

$$\sigma_b = \frac{3 F_{max} l}{2 b h^2} \tag{1}$$

where σ_b is the (ultimate) bending strength of wood (MPa), F_{max} is the maximum (breaking) force (N), l is the distance between supporting pins (mm), b is the width of the test sample (mm), and h is the height (thickness) of the test sample (mm).

The bending strength values were also converted for 12% moisture content. The conversion was carried out according to ISO 3133 (1975) and Eq. 3,

$$\sigma_{b12} = \sigma_b \left[1 + \alpha \left(w - 12\right)\right] \tag{2}$$

where σ_{b12} is the bending strength of wood at 12% moisture content (MPa), σ_b is the bending strength of wood at a set moisture content (MPa), α is the correction coefficient of bending strength dependent on moisture content with the value of 0.04 for all wood species, and w is the moisture content of the samples during testing (%). This equation is applicable up to a moisture content of 30% (FSP).

When the wood moisture content is higher than the FSB, then the bending strength must be recalculated according to Požgaj *et al.* (1997) and Eq. 3,

$$\sigma_{b12}* = \sigma_{b30}.k_{30} \tag{3}$$

where σ_{b12}* is the bending strength of wood at 12% moisture content (for MC higher than FSP, above 30%) (MPa), σ_{b12} is the bending strength of wood at 30% (FSP) moisture content (MPa), and k_{30} is the correction coefficient for moisture content above 30%, with a value of 1.72 for beech wood.

The moisture content of the samples was determined before and after treatments. These calculations were carried out according to ISO 3130 (1975) and Eq. 4,

$$w = \frac{m_w - m_0}{m_0} * 100 \tag{4}$$

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 performed according to standard ISO 3130 (1975). Samples were weighed and then dried at a temperature of 103 ± 2 ºC. Samples reached constant moisture content when the weight change between two weightings at intervals of 6 h did not exceed 0.5% of the mass of the sample. After drying, the samples were cooled in a desiccator and subsequently rapidly weighed to insure the moisture content did not increase more than 0.1% under the influence of humidity in the air. Weighing was carried out with an accuracy of 0.5%.

RESULTS AND DISCUSSION

Bending Strength

Table 3 shows results from the statistical analysis, which presents the influence of factors and their interaction on the bending strength of wood. The results revealed that only the plasticizing time and moisture content were statistically significant ($p < 0.05$).

Table 3. Influence of Factors and Their Interactions on Bending Strength

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	231,540.2	1	231,540.2	16900.49	0.000
Plasticizing time	2,134.58	2	1,067.29	77.90	0.000
Initial moisture content	1,318.83	1	1,318.83	96.26	0.000
Device power	13.00	1	13.00	0.95	0.332
Plasticizing time * initial moisture content	602.40	2	301.20	21.98	0.000
Plasticizing time * device power	19.57	2	9.78	0.71	0.491
Initial moisture content * device power	10.54	1	10.54	0.77	0.382
Plasticizing time * initial moisture content * device power	0.069	2	0.035	0.002	0.997
Error	1,479.62	108	13.70		

Statistical significance was evaluated at the 95% confidence interval

Figure 1a shows the dependence of bending strength on plasticizing time. The effect of plasticizing time is depicted as a negative, as bending strength decreases with an increase in plasticizing time. The role of plasticizing is to induce a temporarily reduction of the strength of the wood; ultimately, this is proof of the good plasticizing ability of microwave heating.

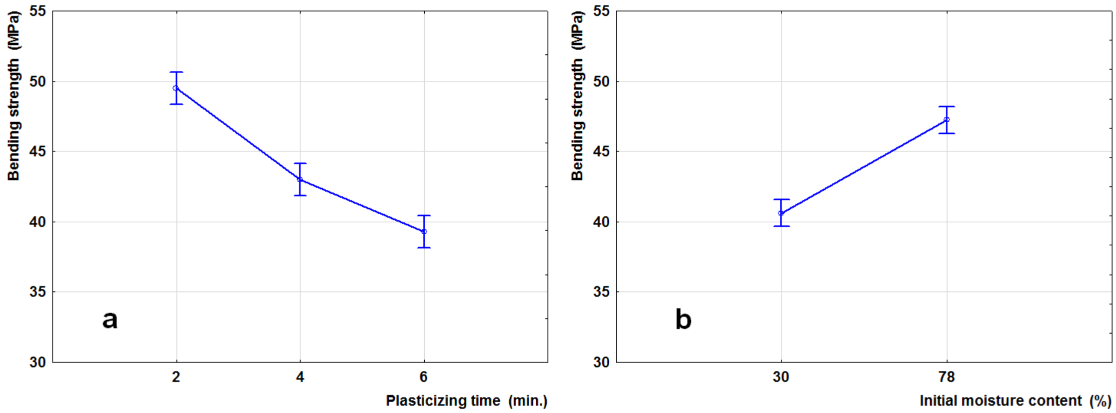

Fig. 1. Influence of (a) plasticizing time and (b) initial moisture content on bending strength

Figure 1b shows the dependence of bending strength on initial moisture content. A higher bending strength was found in wood with a moisture content of 78%. This difference probably arises because microwave heating causes a certain decrease in the moisture content, so wood with lower initial moisture content is most affected.

Figure 2 shows the influence of device power on the bending strength. A change in device power had no substantial impact on the bending strength, as the differences in values of bending strength *versus* device power were negligible.

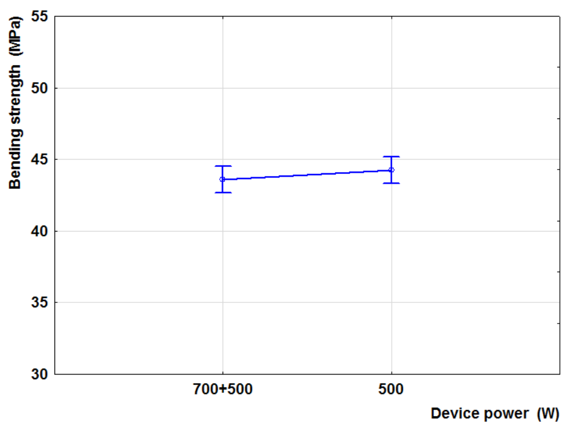

Fig. 2. Influence of device power on bending strength

Figure 3 compares the bending strength and the plasticizing time of each power source relative to the moisture content of the samples. This graph confirms that plasticizing time and moisture content had the greatest influence on the bending strength of wood. However, these effects were different in nature. The largest changes occurred at a moisture content of 30%, where increasing of plasticizing time caused a sharp decline in bending strength. With a moisture content of 78%, the decline was more moderate.

Table 4 shows the bending strength of the non-plasticized wood as well as plasticized wood. In comparing the bending strength of the plasticized wood, it is clear that the microwave method properly softens the wood in a manner similar to steaming. Wood with a moisture content of 30% that was plasticized for 4 and 6 min achieved results similar to steamed wood. At a moisture content of 78%, the bending strength was higher by about 8%. However, the bending strength of wood plasticized by microwave was about 27 to 47% lower, and steamed wood about 39 to 46% lower, than that of non-plasticized wood. Very similar results were found by Gáborík and Zemiar (1996), who examined the flexural strength of steamed beech with a moisture content of 30%.

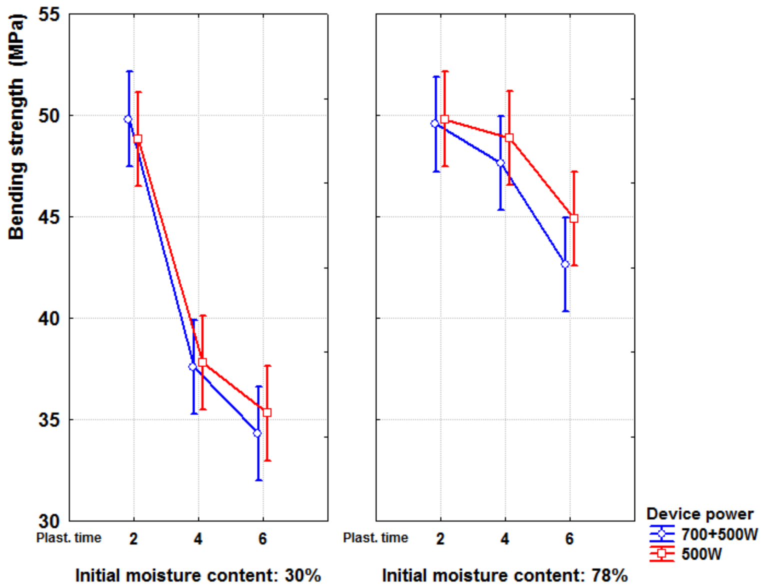

Fig. 3. Influence of moisture content, device power, and plasticizing time on bending strength

Table 4. Comparison of the Bending Strength with Different Methods of Plasticizing

<table>
<tr><th colspan="6">Plasticizing</th><th colspan="2" rowspan="3">Non-plasticized (control)</th><th rowspan="4">Initial moisture content</th></tr>
<tr><th colspan="4">Microwave heating</th><th rowspan="8">Bending <= strength => σ_b (MPa)</th><th>Steaming</th></tr>
<tr><th rowspan="2">Initial moisture content</th><th colspan="3">Plasticizing time</th><th>Plasticizing time</th></tr>
<tr><td>2 min</td><td>4 min</td><td>6 min</td><td>20 min</td><td>σ_b</td><td>σ_{b12}*</td></tr>
<tr><td>30%</td><td>49 (3.7)</td><td>38 (4.4)</td><td>35 (6.1)</td><td rowspan="3">40 (2.9)</td><td rowspan="3">68 (1.8)</td><td rowspan="3">117</td><td rowspan="3">30%</td></tr>
<tr><td>78%</td><td>50 (5.7)</td><td>49 (3.9)</td><td>45 (1.7)</td></tr>
<tr><td colspan="4">Device power 500W ↑</td></tr>
<tr><td>30%</td><td>50 (6.1)</td><td>38 (3.8)</td><td>34 (1.7)</td><td rowspan="3">35 (3.9)</td><td rowspan="3">65 (0.5)</td><td rowspan="3">193</td><td rowspan="3">78%</td></tr>
<tr><td>78%</td><td>50 (3.3)</td><td>48 (4.9)</td><td>43 (1.9)</td></tr>
<tr><td colspan="4">Device power 700W+500W ↑</td></tr>
</table>

*Bending strength values recalculated for 12% moisture content
Each mean (±SD) of bending strength represents 20 wood samples per combination of factors for each plasticizing method or control.

Native beech wood had an average bending strength of 117 MPa, which is very similar to values reported by other authors; for example, Wagenfuhr (2000) stated that the average value of bending strength was 123 MPa (range 74 to 210 MPa), and Pöhler *et al.* (2006) found an average value of 127 MPa. Alternatively, Naylor *et al.* (2012) found a bending strength of only 95.04 MPa for beech wood with a moisture content of 10%, while Badescu and Dumitrascu (2013) found a bending strength of 97 MPa.

Bending strength is defined as a material's ability to resist deformation under load. Therefore, the role of plasticizing is to reduce this resistance in wood without damaging the structure so that the wood can be formed with the minimum load. The bending principle is based on this fact.

In general, the nature of the plasticizing is based on the two most important factors, moisture content and temperature. The influence of each of these factors is weaker than their mutual effect on the wood. Treatment with a suitable temperature and moisture content will ensure the reduction of bending strength of the wood and thereby allow better and easier formability in bending. This is confirmed by Gerhards (1982), who stated that an increase in moisture content from 12 to 20% as well as an increase in temperature from 20 to 50 °C reduces the bending strength of wood by 25%. This describes a reduction of the bending strength of the wood immediately after plasticizing, followed by bending.

But in general, the bending strength decreases with increasing moisture content up to the fiber saturation point (FSP). With further rising of moisture, the bending strength varies only slightly. In our case, this rule would be valid if wood with different moisture contents was plasticized and bent at the same radius. However, in our case, the moisture content of 78% was so high that the wood was much more extensively plasticized, since the converted microwave energy depends on the moisture content in wood. For this reason, the wood could be theoretically loaded longer, and hence the force was higher.

On the basis of a higher force, a higher bending strength was calculated. On the other hand, it is necessary to consider why the high moisture content of wood did not have a greater effect on the maximum deflection. The maximum deflection of wood is investigated for the point where a breach of the sample occurs, although this may not be a breach of the whole cross-section (the maximum is achieved even with partial damage of the surface layers of the sample). Because water is incompressible, a higher moisture content disrupts layers of wood, which is most pronounced at the surface. Therefore, the maximum deflection was not quite as high as would have been expected based on the bending strength.

Maximum Deflection

Table 5 shows the influence of factors and their interaction on the maximum deflection of wood. The results show that the influence of plasticizing time on the maximum deflection was statistically significant ($p<0.05$), while initial moisture content and device power were not significant. Figure 4a shows the maximum deflection dependence on plasticizing time. The graph shows that maximum deflection increased as plasticizing time increased. The highest increase in maximum deflection was found between 2 and 4 min. Figure 4b shows that the device power does not significantly affect the maximum deflection. Higher maximum deflection was achieved at 500 W, but these differences were not significant.

Table 5. Influence of Factors and Their Interactions on Maximum Deflection

Monitored factor	Sum of squares	Degree of freedom	Variance	Fisher's F - Test	Significance level P
Intercept	25,4045.1	1	25,4045.1	23,161.5	0.000
Plasticizing time	285.9	2	142.9	13.03	0.000
Initial moisture content	1.8	1	1.8	0.16	0.690
Device power	9.5	1	9.5	0.87	0.353
Plasticizing time * initial moisture content	30.0	2	15.0	1.37	0.259
Plasticizing time * device power	55.8	2	27.9	2.55	0.083
Initial moisture content * device power	0.4	1	0.4	0.04	0.841
Plasticizing time * initial moisture content * device power	9.6	2	4.8	0.44	0.648
Error	1,184.6	108	11.0		

Statistical significance was evaluated at the 95% confidence interval

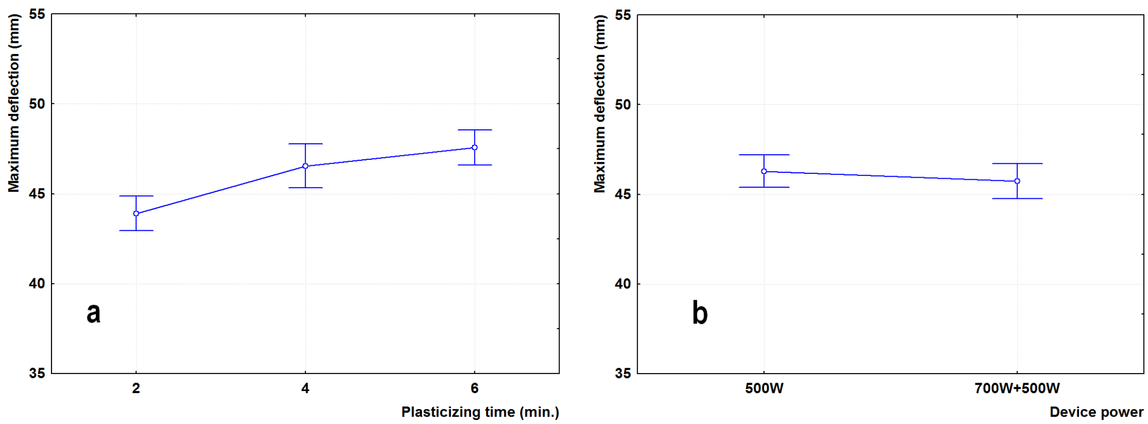

Fig. 4. Influence of (a) plasticizing time and (b) device power on maximum deflection

Figure 5 shows the influence of moisture content on maximum deflection, which is not statistically significant. One can see that higher values of maximum deflection were achieved at 78% wood moisture, but the differences were not significant.

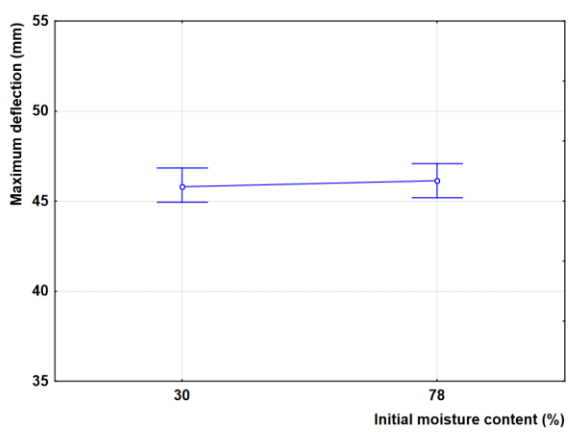

Fig. 5. Influence of initial moisture content on maximum deflection.

Figure 6 shows the influence of all three factors on maximum deflection, and the combination of all factors was not statistically significant. When comparing values of maximum deflection, it is clear that there was different behavior for a device power of 500 W and various moisture contents. While the maximum deflection of wood was the highest at a 78% moisture content and plasticizing time of 4 min, the samples with 30% moisture achieved the lowest values. The individual curves of maximum deflection did not have same behavior at different device powers. In this case, the maximum deflection increased equally with an increase in plasticizing time. Values achieved at a moisture content of 30% were marginally higher.

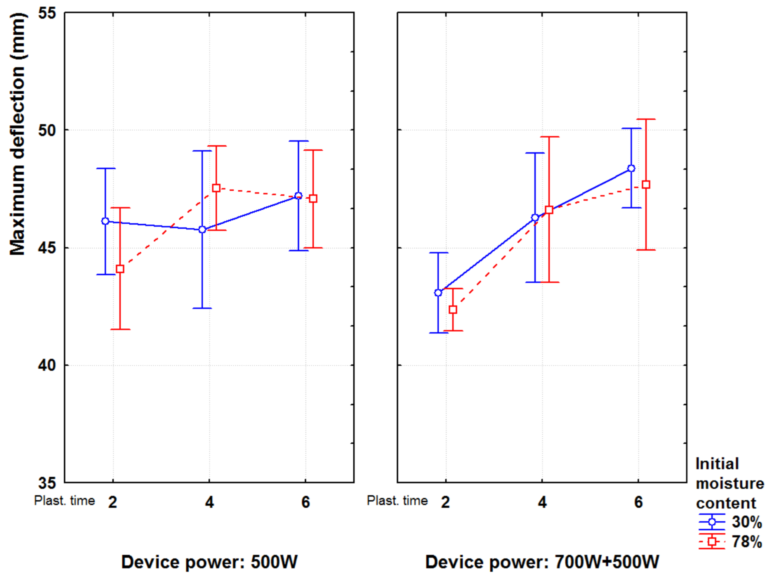

Fig. 6. Influence of moisture content, device power, and plasticizing time on maximum deflection.

Table 6. Comparison of the Maximum Deflection at Different Methods of Plasticizing and Non-Plasticized Wood

Plasticizing						Non-plasticized (control)	Initial moisture content
Microwave heating					Steaming		
Initial moisture content	Plasticizing time				Plasticizing time		
	2 min	4 min	6 min		20 min		
30%	46.2 (3.9)	45.8 (5.1)	47.3 (3.1)	Maximum <= deflection => y_{max} (mm)	38.7 (3.8)	20.1 (2.1)	30%
78%	44.1 (0.9)	47.5 (1.9)	47.1 (6.1)				
Device power 500W ↑							
30%	43.1 (2.1)	46.3 (3.2)	48.5 (1.7)		39.6 (4.0)	22.5 (1.7)	78%
78%	42.4 (0.8)	46.6 (4.5)	47.7 (3.0)				
Device power 700W+500W ↑							

Each mean (±SD) of maximum deflection represents twenty wood samples per combination of factors for each plasticizing method or control

A comparison of the maximum deflection of wood with different initial moisture contents found that the difference in values was not significant, although the highest values were achieved at a moisture content of 78%. Similar results were found by Zuzula (2002), who states that the maximum deflection of steamed wood with 30% moisture content was 38.7 mm with 30 min of plasticizing and 34.9 mm with 90 min of plasticizing.

When comparing the maximum deflection of wood plasticized by microwave heating for 4.5 min at an initial moisture content of 30%, Zuzula (2002) found a maximum deflection of 31.7 mm, whereas in the present work for a moisture content of 30%, we found maximum deflections of 46.3 mm for a plasticizing time of 2 + 2 min (device power 700 W+500 W) and 45.8 mm for a 4-min plasticizing time (Table 6).

CONCLUSIONS

1. The initial moisture content of wood higher than the fiber saturation point (FSP) has an important effect on the bending strength of beech just after it has been plasticized with microwave energy. It is important to keep the wood moisture content after heating at approximately the FSP. Equally important is the plasticizing time, because the bending strength of wood becomes reduced with an increase in time. The bending strength of wood plasticized by microwave is similar to that achieved by steaming. The impact of changes in the device power did not have a significant effect. The bending strength of wood was reduced by up to 47% using microwave heating, thus confirming that the results were comparable to steaming under the conditions used in the present work.
2. The plasticizing time was the only statistically significant ($p<0.05$) factor for maximum deflection. The increase in plasticizing time increased the values of maximum deflection. The moisture content and device power had a negligible effect on maximum deflection. The values of maximum deflection, achieved from samples plasticized by microwave heating, were about 7% higher than those with steam plasticizing (39.6 mm). In all cases, the maximum deflection of wood plasticized by microwave heating was higher than that with steaming.

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