3D Molding of Veneers by Mechanical Means

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The 3D moldability of veneers, as opposed to the moldability of plastic or other materials, is limited because of the characteristics of wood. By mechanical treatment under appropriate conditions, it is possible to partially modify veneer characteristics. In this study, the intention was to determine the effect of factors influencing the 3D moldability of veneers. Therefore, this study was focused on determining the 3D moldability of veneers with square and circular shape, which were stressed under six moisture content levels (*i.e.,* 0%, 8%, 16%, 20%, 30%, and 100%). To determine the influence of wood species, the results for beech veneers of 0.5-mm thickness were compared to the results for birch veneers of 0.5-mm thickness. These sets of samples were stressed with a spherical stamping tool with three different radii of curvature (*i.e.,* 20, 40, and 80 mm). There is currently no standardized method for assessing the 3D moldability of veneers, as opposed to metals (metal sheets). Because of the low moldability of veneers compared to metal materials, Erichsen's method for assessing the moldability of metal sheets was modified for veneers. The 3D moldability was determined based on maximal deflection of the veneer stressed by the stamping tool before rupture. Based on the established method, the effects of wood species, moisture content of veneers, diameter of stamping tool, and shape of samples on deflection during 3D molding were determined.

Keywords: Veneer; 3D molding; Deflection; Erichsen deep-drawing test; Moldability

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INTRODUCTION

Increasing demands for novel and uncommon furniture shapes require furniture designers and technologists to produce furniture parts of many diverse shapes (Gašparík and Barcík 2013). Hence, manufacturers try to emphasize the diversity, and of course, the functionality of their goods and design technical-technological procedures that allow the production of these goods and products with the lowest possible burden, lowest costs, and in the least amount of time (Zemiar 2014).

The term "veneer" belongs to a group of sliced wood materials that contribute decorative and constructional functions. In the construction, veneers are most often bonded with an adhesive and used as structural elements because of their high strength (Bomba *et al*. 2014). But in the furniture industry, they can be used as components for creating planar, bent (2D-molded), or 3D-molded products. The 3D molding technology is the process by which an element changes its shape in three mutually perpendicular planes under the action of external forces. The application of three-dimensional molding is significantly limited because of the characteristics of wood, including its slight tensile deformations, small ratio of plastic deformations, and anisotropic characteristics (Požgaj *et al*. 1997; Buchelt *et al.* 2009). It is possible to adjust or modify the aforementioned characteristics to some extent and therefore increase the moldability of the wood.

The three-dimensional molding of wood is the most complicated non-cutting type of molding process for wood (Gáborík and Dudas 2008). In the present work, this three-dimensional molding is defined in terms of a relative change in the x, y, and z axes. During three-dimensional molding, complex pressure and traction tensions are generated in the wood. This is a complicated process from the aspect of wood anisotropy (Glos *et al.* 2004; Buchelt and Wagenführ 2008).

Compression stresses affect the wood in the tangential direction and tensile stresses in the radial direction, causing curling on the edges of the veneer and ruptures in the center of the veneer, respectively. In three-dimensional molding, curling and cracks are considered as defects. On a surface plane, curling takes place perpendicularly to the direction of fibers with compression. If the veneer thickness is small, then the compression pressure does not warp the veneer. Curling takes place in veneer up to a thickness of 0.5-mm. With thicker veneers, cracks occur in the middle of the sample. These cracks are caused by radial tensions that exceed the material's tensile strength across the fibers. According to Wagenführ *et al.* (2006), it is possible to prevent curling on the edges of the veneer by securing a loose fixation of the samples in the appliance during bending.

By establishing adequate conditions, it is possible to effectively modify veneer characteristics during three-dimensional molding and therefore to increase the moldability of pieces while adhering to the qualitative and aesthetic parameters of the manufactured product. Besides securing the fixation of the samples, additional factors entering the process may affect the achieved deflections of veneers during three-dimensional molding. This includes, for example, the type of wood, shape of sample, diameter of molding tool, and moisture content of wood during molding.

The type of wood species further affects the bending parameters, the influence of which should not be excluded from the process of veneer three-dimensional molding. Wood species with long fibers and a regular structure of annual rings are more suitable for molding. Broad-leaved wood species are more bendable than coniferous wood species. Beech, ash, elm, and birch are among the more bendable wood species. Therefore, beech and birch woods were studied for the determination and comparison of bendability.

It is generally known that the bending characteristics of wood are affected mostly by moisture content. With increasing moisture content ranging from zero to the fiber saturation point (FSP), all mechanical characteristics decrease (Dubovský 1993). The decrease of mechanical characteristics as an influence of increasing moisture content favors moldability, because the rigidity of the wood decreases when its moldability increases (Zemiar *et al*. 1999). For verification of the role of moisture content on the behavior of wood during the three-dimensional molding of veneers, wood samples with a moisture content of 0, 8, 16, 20, 30, and 100% were studied. Zemiar and Fekiač (2014) found that the suppression of the effects of planar shape of veneer and veneer curling in certain edge areas can be achieved by ensuring an equal distance for each parametric curve of the center sample. To determine whether this is true, in the present work three-dimensional moldability testing was performed on circular- and square-shaped samples. Based on these findings it is hoped to determine the effect of selected factors on the bending of veneers during three-dimensional molding and thereby provide important data to help further advance the three-dimensional molding of veneers.

EXPERIMENTAL

Materials

Samples (Figs. 1 and 2) were inserted between the support and the down-holder in a way that allowed for molding force action on the right side of the sample. In order to determine which the more suitable type of wood, it was decided to compare the results acquired for the three-dimensional molding of beech veneers with those acquired for birch veneers. For this purpose, radially-cut veneers with a thickness of 0.55 mm were sliced from trees harvested in Poľana region, near Zvolen, Slovakia.

To achieve the required moisture contents (*i.e.*, 0, 8, 16, 20, 30, and 100%), the samples were placed in a climate chamber ED, APT Line II (Binder; Germany) under the conditions listed in Table 1.

Table 1. Conditioning Parameters for the Samples

Parameter	Wood moisture content					
	0%	8%	16%	20%	30%	100%
Relative air humidity (%)	0	40	78	87	96	6-hour dipping in water
Environment temperature (°C)	103 ± 2	20	20	20	20	20

To determine the effect of shape on deflections during 3D molding, both circular (Fig. 1) and square (Fig. 2) veneers were tested. The circular shape of a sample provides the same distance from the center of the sample to every point on the peripheral curve. This demand comes from the suppression effect of the sample's planar shape on veneer curling in its marginal zone (Zemiar and Fekiač 2014). The square-shaped sample was selected because of two assumptions: (1) from a process aspect, this is the natural shape of the veneer parts after their manufacture by cutting or peeling; and (2) the confirmation of a hypothesis of the planar shape's suppression effect on veneer curling during molding in its marginal zone. For these reasons, square samples (100 × 100-mm dimensions) and circular samples (60-mm diameter) were tested. For every examined set, 10 samples were tested and the results acquired for each individual set of samples. All data is reported as the mean ± standard deviation.

Fig. 1. Samples of circular shape

Fig. 2. Samples of square shape

For testing, a special jig (Fig. 3), consisting of a matrix (lower part) and a securing holder (upper part), was loosely installed under the upper jaw of the testing machine (Fig. 5). The spherical stamping tool (Fig. 4) was then inserted into the upper jaw. The measured values were transferred to a computer, which processed the measured results in graphic and tabular form after each test.

Fig. 3. 3D-bending testing jig

Fig. 4. Stamping tools of 3D-bending

Fig. 5. LaborTech test machine

Methods

The focus of this work was to determine the effect of selected factors that affect the three-dimensional moldability of veneers. For this purpose, a new innovative method of moldability assessment was implemented. Erichsen's method for assessing the moldability of metal sheets (Veles 1989) was modified for wood veneers. Based on this, the study focused on determining the effects of the following factors: (1) type of wood species: beech (*Fagus sylvatica* L.) and birch (*Betula pendula* L.); (2) moisture content (0, 8, 16, 20, 30, and 100%); (3) shape of the sample (square or circular); and (4) diameter of the stamping tool (20, 40, and 80 mm).

The difference between the diameters of stamping tool and the opening was 4-mm; therefore, the diameters of the openings were 24, 44, and 84 mm. The 3D moldability was assessed based on maximal deflection of the veneer loaded by the stamping tool before rupture (Fig. 6). In these studies, a securing holder was employed for loosely holding the veneer, which means that there was a distance washer about 10% thicker than the thickness of the veneer between the flanges; this allowed a certain amount of horizontal movement of the veneer during its loading.

A system was developed with the purpose of preventing potential curling on the periphery of the sample. As shown in Fig. 6, the sample is fixed to the supports by a peripheral holding force.

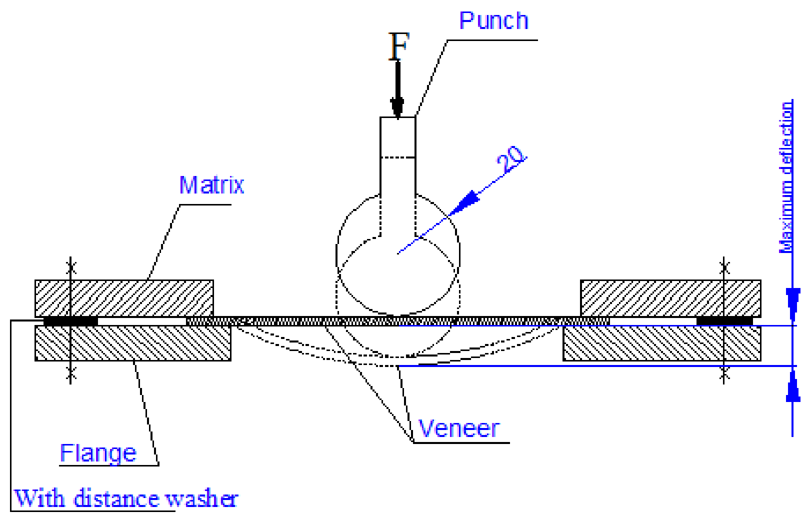

Fig. 6. Scheme of principle of molding system

Molding force, acting on the sample from a spherical stamping tool, was applied by a testing machine LabTest 4.050 (LaborTech Co., Czech Republic) (Fig. 5) at the advancing speed of 10 mm/min. The peripheral holding force was technically feasible due to the use of distance mounts (washers) of the same thickness as the samples inserted between the matrix and the securing holder.

STASTICA 7 software (StatSoft Inc.; USA) and a four-factor analysis were used to statistically assess the measured results.

RESULTS AND DISCUSSION

To evaluate the measured results, a four-factor analysis of variance was used to assess the effect of individual factors as well as the effect of interactions between two, three, and four different factors. The results of the four-factor analysis of variance are listed in Table 2. Based on the values of significance levels (P-values), it can be asserted that the type of wood, the moisture content of samples, and the diameter of the stamping tool all are factors that significantly ($P < 0.05$) affect the values of the examined characteristic.

Based on the results listed in Table 2, one can consider the interactions of wood species with the moisture content of samples, type of wood species with diameter of stamping tool, and moisture content of samples with diameter of stamping tool to be significant combinations of factors. Among the three-factor interactions listed in Table 2, the effects of all the examined three-factor combinations were judged to be significant ($P < 0.05$), with the exception of the synergistic effect of the combination of wood species with shape of sample and diameter of stamping tool; the significance level was $P=0.350266$.

Based on the results listed in Table 2, the synergistic effect of all four examined factors can be considered a combination of factors that significantly ($P < 0.05$) affects deflection.

Table 2. Analysis of Variance Assessing the Effect of Individual Factors and Their Combinations

Monitored Factor	Sum of Squares	Degrees of Freedom	Variance	Fisher's F-test	Significance Level P
Overall diameter	15,210.8	1	15,210.8	42,260.73	0.000001
{1}Wood species	131.70	1	131.70	365.90	0.000001
{2}Shape of sample	3.42	1	3.42	9.51	0.002126
{3}Moisture content	820.97	5	164.19	456.19	0.000001
{4}Diameter of stamping tool	922.30	2	461.15	1,281.22	0.000001
Wood species * Shape of sample	0.25	1	0.25	0.69	0.405711
Wood species * Moisture content	163.21	5	32.64	90.69	0.000001
Shape of sample * Moisture content	2.94	5	0.59	1.63	0.148841
Wood species * Diameter of stamping tool	26.76	2	13.38	37.18	0.000001
Shape of sample * Diameter of stamping tool	4.38	2	2.19	6.08	0.002412
Moisture content * Diameter of stamping tool	75.13	10	7.51	20.87	0.000001
Wood species * Shape of sample * Moisture content	8.20	5	1.64	4.56	0.000426
Wood species * Shape of sample * Diameter of stamping tool	0.76	2	0.38	1.05	0.350266
Wood species * Moisture content *Diameter of stamping tool	68.33	10	6.83	18.98	0.000001
Shape of sample * Moisture content * Diameter of stamping tool	16.85	10	1.69	4.68	0.000002
Wood species * Shape of sample * Moisture content * Diameter of stamping tool	8.68	10	0.87	2.41	0.008041
Error	254.83	708	0.36		

Figure 7 depicts the effects of wood species type. As is apparent in Fig. 7, more statistically significant values were observed for birch wood.

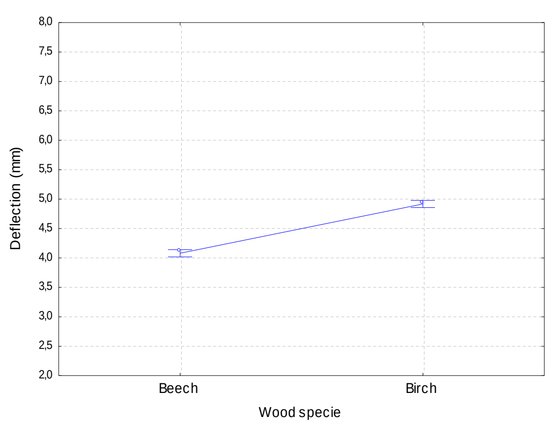

Fig. 7. Effect of wood species type on deflection

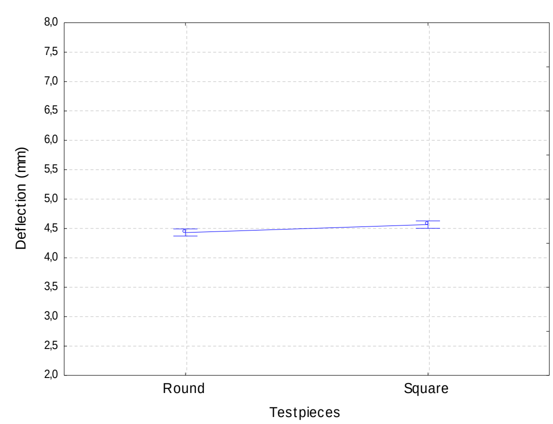

Fig. 8. Effect of shape of sample on deflection

In general, one can assert that wood species characterized by a more regular structure of annual rings, such as birch, is more appropriate for the given purpose of application. Frese and Blaß (2006) found similar results in their work. Based on the results depicted in Fig. 8, the shape of a sample can be considered to be a medium-significant factor. In general, a higher deflection was observed for square-shaped samples. Similar results were found in the work of Durček (2014).

In general, it can be concluded that with increasing moisture content, deflection of veneers was also increased (Fig. 9).

The effect of stamping tool diameter on deflection (Fig. 10) increases with an increase in stamping tool diameter. However, the results of higher deflection values cannot be attributed to the effects of various diameter tools, but due to increase of veneer dimensions, with the exception of the thickness which has not changed.

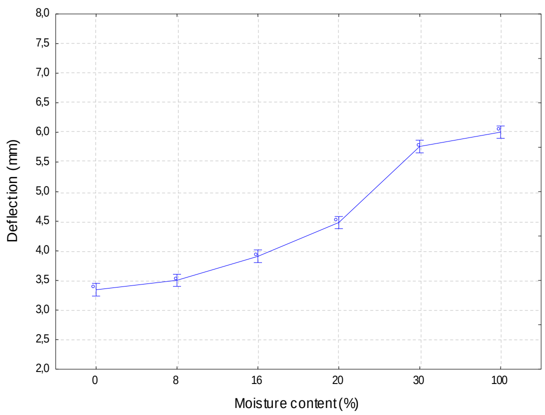

Fig. 9. Effect of moisture content on deflection

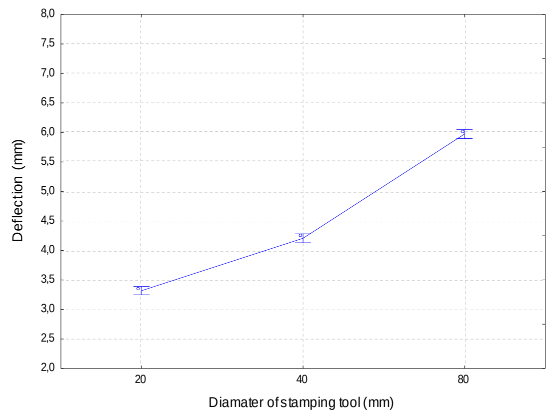

Fig. 10. Effect of stamping tool diameter on deflection

Figure 11 depicts the synergistic effect of the factors of wood type and moisture content of samples. As is apparent from the diagram, with increasing moisture content, deflection also increased.

Higher deflection values were generally found for birch wood than for beech wood. The anomalous group of samples was the set of beech samples with 100% moisture content, for which a lower deflection was found compared with the set of beech wood with 30% moisture content. From the determined results, it is apparent that one can consider 30% moisture content during three-dimensional molding as the maximal moisture content for beech wood; a decrease in deflection values takes place for the aforementioned wood species with higher moisture content. One of the reasons for this could be free water. According to Požgaj *et al.* (1997), the optimal conditions for bending of beech wood can be achieved at the fiber saturation point, and therefore free water is undesirable. An increase in pressure during bending causes the partial compression of free water, resulting in disruption of the wood structure (rupture).

From Fig. 12, which shows the interaction of the factors of wood species and the diameter of the stamping tool, higher deflection were measured for birch wood. The effect of stamping tool diameter was also confirmed. Based on previous results, one can assert that with increasing stamping tool diameter, a higher deflection of veneers was achieved during three-dimensional molding. Considering the structural composition of individual wood species, the optimal conditions for its bending are long fibers and a regular width of annual rings (Požgaj *et al.* 1997); in general, birch has a more regular width of annual rings than beech.

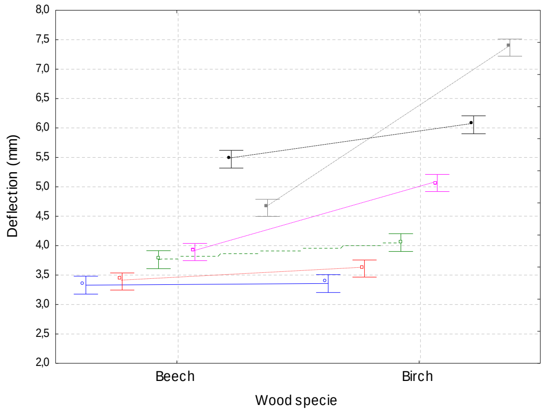

Fig. 11. Effect of interaction between wood species type and moisture content on deflection

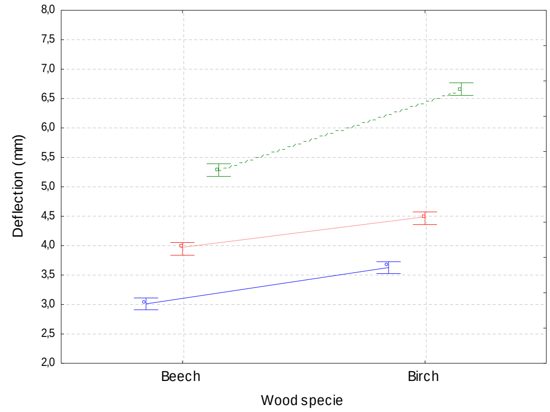

Fig. 12. Effect of interaction between wood species type and diameter of stamping tool on deflection

Based on the results depicted in Fig. 13, the synergistic combination of shape of samples and diameter of stamping tool does not significantly affect deflection of veneers during three-dimensional molding. A significant ($P < 0.05$) difference in values was found only for samples of circular and square shape stressed by stamping tools with a 20-mm diameter.

An evident increase in deflection resulting from increased moisture content and stamping tool diameter is shown in Fig. 14, which depicts the effect of interactions between moisture content and diameter of stamping tool.

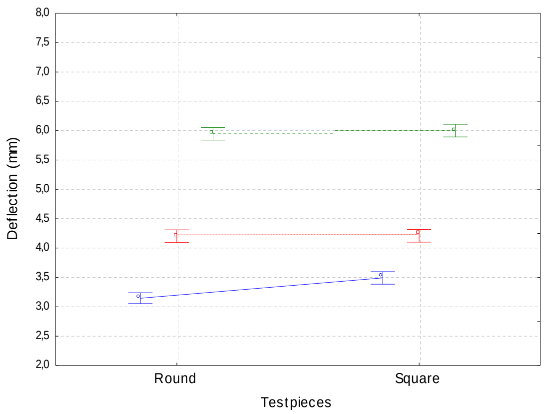

Fig. 13. Effect of interaction between shape of sample and diameter of stamping tool on deflection

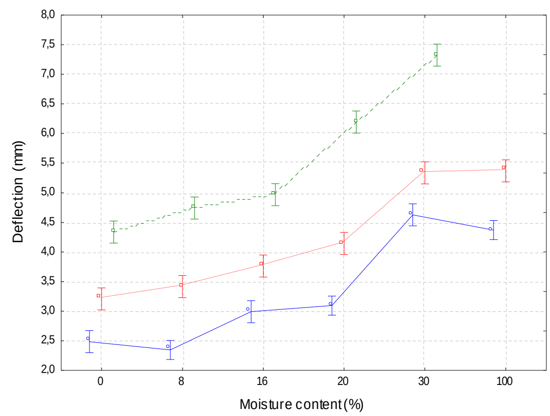

Fig. 14. Effect of interaction between moisture content and diameter of stamping tool on deflection

Figure 15 depicts the synergistic effect of three-factor interactions assessing the effect of the combination of moisture content with type of wood species and shape of samples. From the values shown in Fig. 15, higher deflections for birch wood are apparent; the increased deflection during three-dimensional molding was caused by an increase in moisture content. The shape of samples had no significant effect on veneer deflection during three-dimensional molding. For circular- and square-shaped beech samples tested at 100% moisture content, it was observed that there was significantly (P < 0.05) lower deflection compared with birch samples tested at the same moisture content. Deflection for the aforementioned sets of samples were lower than for birch samples loaded at a moisture content of 30%.

From the results assessing the interaction of factors diameter of stamping tool with type of wood species and moisture content of samples (Fig. 16), generally higher deflection values were observed for birch wood; deflection increased with increasing moisture content (mostly above 20%), as well as with increasing stamping tool diameter.

A statistically significant difference was found when comparing beech and birch samples at 100% moisture content for all three stamping tool diameters. For beech samples, the deflection was comparable to the values measured at 20% moisture content in all three aforementioned cases. For birch wood, however, deflection can be increased by moisture content modification of the samples by dipping in water.

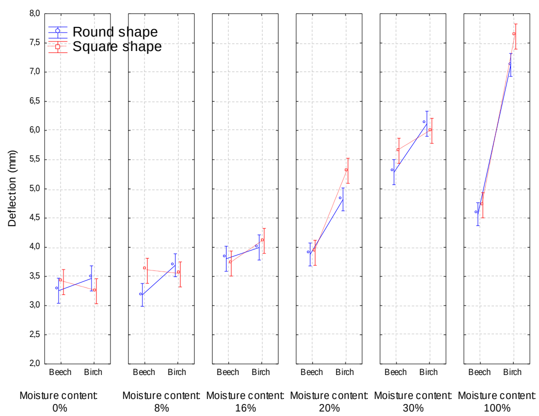

Fig. 15. Effect of interactions between type of wood species, moisture content, and shape of sample on deflection

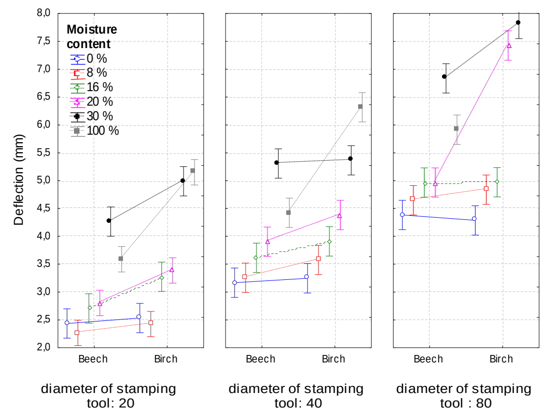

Fig. 16. Effect of interactions between type of wood species, moisture content, and diameter of stamping tool on deflection

The interaction of all four examined factors is depicted in Fig. 17, which shows an increase in veneer deflection as a result of increasing stamping tool diameter, an increase in deflection as a result of increased veneer moisture content, and generally higher deflection for square-shaped samples compared with circular-shaped ones.

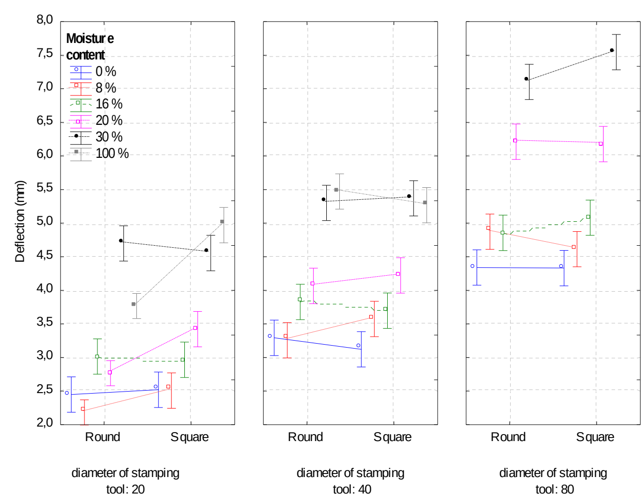

Fig. 17. Effects of interactions between wood type, moisture content, and shape on deflection

CONCLUSIONS

1. Birch wood can be considered generally to be a more appropriate material for the three-dimensional molding of veneer materials compared with beech wood. A statistically significant higher deflection ($P < 0.05$) was found compared with beech veneers in all the examined cases. The maximal deflection measured for birch wood was 7.5 mm, compared with 6.5 mm for beech wood.
2. The shape of the samples did not significantly affect the values of examined characteristics. Although slightly higher values of examined bending characteristics were measured during three-dimensional molding of square-shaped samples, this difference was on the margin of statistical significance. Based on the results, the square-shaped samples can be considered to be more suitable for the process of three-dimensional molding than circular samples. Therefore, the potential additional preparation of veneers into a circular shape before three-dimensional molding is unnecessary.
3. The effect of stamping tool diameter was found to significantly ($P < 0.05$) affect deflection values during three-dimensional molding. As is evident from the results, veneer deflection tends to rise with increasing stamping tool diameter. The consequence of increased deflection cannot be ascribed to the effect of stamping tool dimensions, but rather to the increase in sample dimensions, whose thickness did not change.
4. The assumed effect of moisture content on veneer deflection during three-dimensional molding was confirmed. Based on the determined measurements, it can be asserted that with increasing moisture content, the deflection of veneers during three-dimensional molding also increased. Interesting deflection values were observed during the three-dimensional molding of beech veneers modified by dipping. Although an increase in deflection was found for this set of samples in comparison with the aforementioned set of samples with 30% moisture content, a decrease in deflection values resulted from the high moisture content of the wood.
5. A new, innovative method was established for testing the three-dimensional moldability of veneers by mechanical means.

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