Three-Dimensional Pneumatic Molding of Veneers

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The goal of this paper is to introduce a new testing method suitable for the evaluation of the three-dimensional (3-D) moldability of veneers and to use this method to test the impact of specific factors on the 3-D pneumatic molding process. The tested factors included veneer moisture content, wood species, shape of test piece, and fixing method on the maximum wood deflection. Veneers were molded using compressed air on equipment designed by our group for the sole purpose of this experiment. The results indicated that the monitored factors had an effect on deflection during the 3-D molding process. The results of this investigation extend the state-of-the-art knowledge regarding this technology and indicate the possibility of utilizing this innovative testing method for 3-D molded veneers.

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

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INTRODUCTION

The increasing demand for new and unusual furniture pieces has led designers and process engineers to fabricate pieces with many different shapes (Gašparík and Barcik 2013). Therefore, manufacturers are placing an emphasis on the diversity and functionality of the products, as well as the development of processes that allow for the production of these items to be at a maximum yield, minimum cost, and low time demand (Zemiar 2014).

Three-dimensional molding of flat pieces is one of the most sophisticated chipless molding methods for wood (Gáborík and Dudas 2008), and is defined as a shape change involving all the three axes (x, y, and z). Complicated compressive and tensile stresses are generated in the wood during 3-D molding, which becomes increasingly complicated with anisotropic wood (Glos *et al.* 2004).

One of the companies dealing with this issue worldwide is Danzer, who developed a method based on cutting the veneer into thin strips (Processing/Technology 2014). This process is based on the cutting of veneer sheets longitudinally from 1.1 to 1.2 mm thick, oriented in the fiber direction, and in strips 1 mm in width. Subsequently, these strips are pressed together and bonded mutually using polyamide fibers. These fibers are oriented perpendicularly to the direction of the cut strips, with a mutual distance of 10 mm (Čapka 2012). Bonding takes place immediately after the veneer cutting to avoid longitudinal shifting of the veneer strips. The treated veneers are laid in a multi-layer assembly in a manner similar to that of plywood boards. The adhesive is applied on the veneer layers, which are pressed using a mold. This mechanical modification ensures that the transversal expansivity increases, which prevents the formation of longitudinal cracks present in non-treated veneers (Čapka 2012). The impact of this process on veneer is evident (Fig. 1) when compared to molded veneer without such treatment (Fig. 2). However, this method is not perfect, and the deflection sizes achieved are still limited. Another disadvantage is the difficulty of the method and the destructive treatment caused by cutting the veneers.

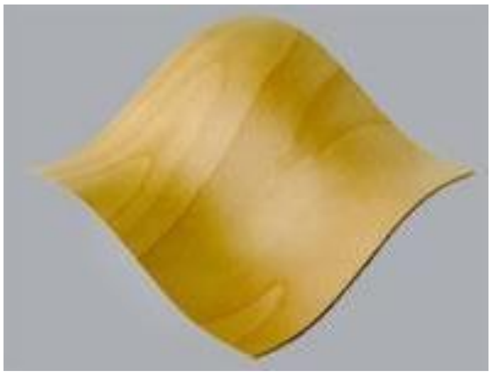


Fig. 1. Treated veneer molding

Fig. 2. Untreated veneer molding

As shown in the work of Wagenfuhrer *et al.* (2006), pressure stresses during molding act in the tangential direction and tensile stresses act in the radial direction (Fig. 3). Therefore, veneer margin undulation and cracks in the veneer center appear. Both undulation and cracks are evaluated as defects in 3-D molding. Undulation occurs at the plane perpendicular to the fiber orientation because of compression. When the veneer thickness is small (less than 0.5 mm), pressing will not cause veneer undulation. In thicker veneers, cracks occur in the center of the test piece and radial stresses exceeding the fiber transversal tensile strength cause the formation of cracks (Fig. 3) (Wagenfuhrer *et al.* 2006).

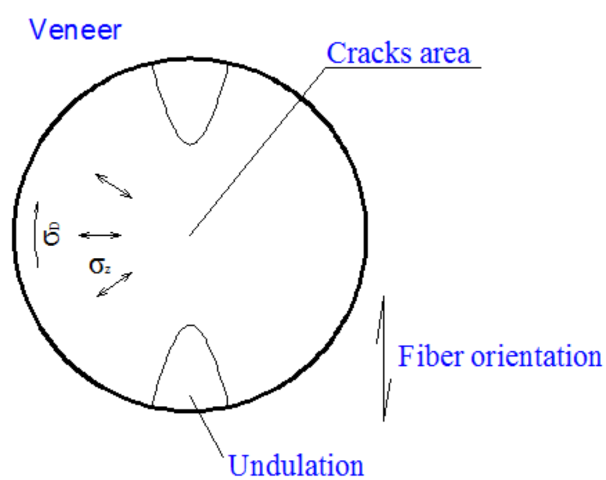


Fig. 3. Illustration of the stresses that occur in the veneer and the failure points

Based on this, the goal is to learn more about the impact of the specific factors on veneer deflection sizes during 3-D molding and thereby expand the knowledge of these issues to enable progress in the development of 3-D molding. Successful 3-D molding depends on the properties of a material. The wood species essentially affects the bending, but each species can be bent with different outcomes. The most suitable species are the deciduous trees with hard wood. From among the local species, beech, ash, birch, oak, nut tree, and locust are optimal. Less suitable are the soft deciduous and coniferous species (Nemec 1985). For this research, the properties of beech and birch were investigated due to their availability in the market. Wood bending parameters are affected mainly by moisture. When moisture increases from zero to the fiber saturation point (FSP), all mechanical parameters become impaired (Dubovsky 1993). The impairment of mechanical properties due to a moisture increase is beneficial for bending since wood rigidity decreases and moldability increases (Zemiar *et al.* 1999).

The test piece in this study was circular in shape, providing the matrix cavity/hole shape and the requirement of equidistant points of the perimeter curve with regard to the center. Test pieces with this specific shape, derived to eliminate of the effect of a flat shape on ply corrugation during the molding process in certain marginal zones (Zemiar and Fekiač 2014), were compared with square test pieces. For practical reasons, the preparation of square test pieces is suitable since rectangular plywood is available and no additional shape adjustment is required. Based on the findings of Wagenfuhrer *et al.* (2006), the impact of the attachment method was investigated. It was assumed that the corrugation of the ply margins could be avoided means of a fixed attachment of the test pieces during bending.

EXPERIMENTAL

Materials

This study attempted to determine the impact of factors influencing the 3-D moldability of veneers. For this purpose, a testing tool was developed that allows determination of veneer moldability by a pneumatic method (Fig. 4). Factors that were investigated include wood species (European beech, *Fagus sylvatica* L.; silver birch, *Betula pendula* L.) and sample moisture (0%, 8%, 16%, 20%, 30%, and 100%), shape of piece (square *vs* circle), and attachment method, *i.e.*, fixed (Fig. 7a) or holding (Fig. 7b). For this purpose, radially cut veneers (thickness 0.55 mm) from Poľana locality east of Zvolen, Slovakia were used. To achieve the required moisture levels, the test samples were placed in a Binder climate chamber (ED, APT Line II; Germany), at the conditions shown in Table 1. The monitored 3-D moldability feature was the maximum deflection value. During the work, the maximum deflection was deemed to be the deflection that caused the test pieces to rupture (Fig. 4).

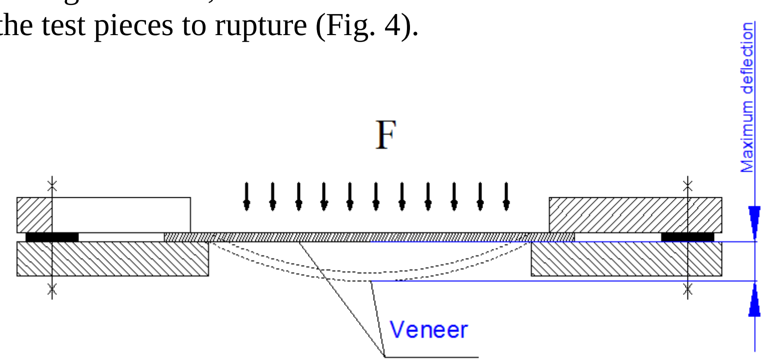


Fig. 4. Deflection measurement principle for 3-D molding

Table 1. Conditioning Parameters for the European Beech and Silver Birch

Parameter	Wood moisture					
	0%	**8%**	**16%**	**20%**	**30%**	**100%**
Air relative humidity (%)	0	40	78	87	96	soaking in water
Ambient temperature (°C)	103 ± 2	20	20	20	20	

To determine the effect of piece shape on the deflection values, the test pieces were comprised of 10 circular test pieces, 60 mm diameter (Fig. 5), and 10 square test pieces, 100 x 100 mm (Fig. 6).

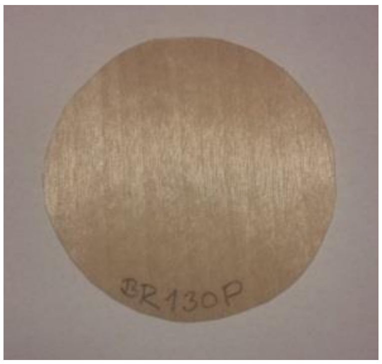


Fig. 5. Circular test piece

Fig. 6. Square test piece

The method of securing the test piece to the testing tool was chosen as the last factor. This method is provided by the test limits. According to Wagenfuhrer and Buchelt (2005), veneer margin undulation can be prevented by a fixed attachment of the test pieces to the tool during bending. Therefore for these studies, the monitoring of test pieces were fixed to the test tool during stress caused by the veneer 3-D molding. The results were compared with those measured on test pieces that were secured lightly in the tool (Fig. 7b). For fixed attachment, the veneer was fixed between the upper and lower flange of the test tool without the possibility of horizontal movement during the molding (Fig. 7a). Lightly held attachment was accomplished with a distance washer 10% thicker than the veneer thickness set between the flanges to allow a horizontal movement of the veneer by compressed air while it is loaded (Fig. 7b) (Zemiar and Fekiač 2014). The effect of the attachment method was evaluated by visual assessment and on the basis of formation undulation.

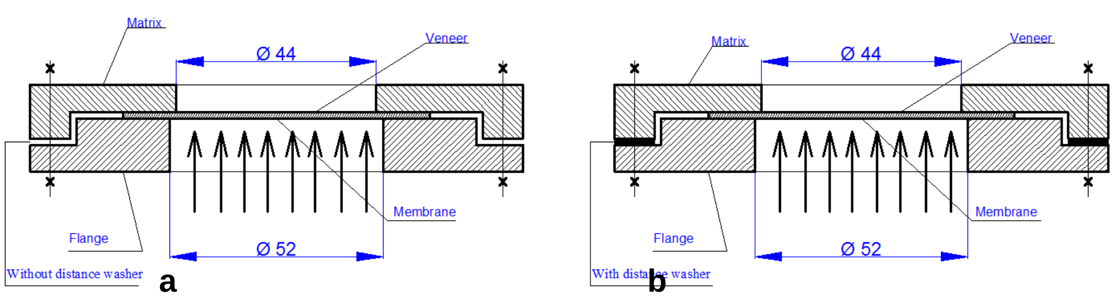


Fig. 7. Methods of securing test pieces to the testing tool. (a) fixed attachment and (b) Lightly held attachment with a distance washer 10% thicker than the veneer (Zemiar and Fekiač 2014)

For a better view, Fig. 8 shows a flow chart of the monitored groups of the square test pieces. Figure 9 shows a flow chart of the monitored groups of the circular test pieces. The results obtained for both groups were compared at the end of the study. Each set of test specimens was composed of 10 individual samples.

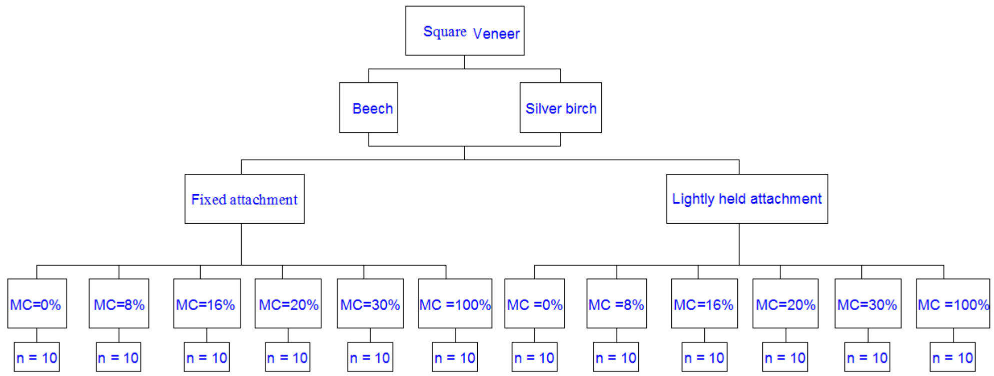


Fig. 8. Categorization of square test pieces

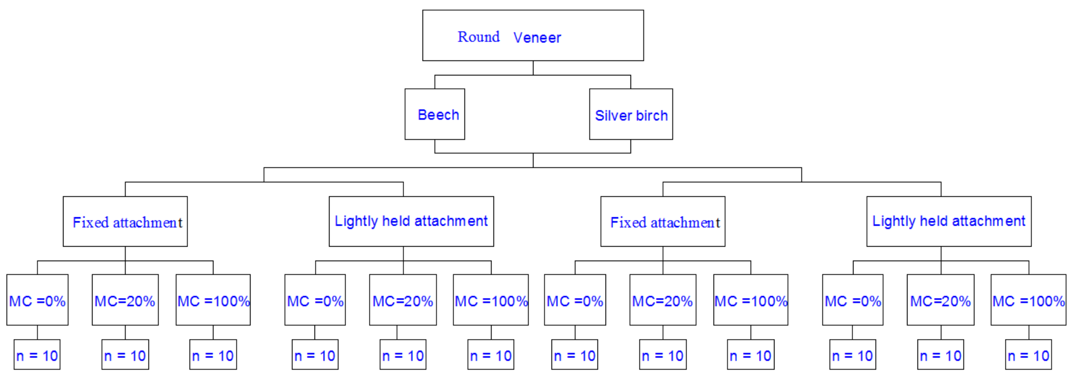


Fig. 9. Categorization of round test pieces

Methods

Maximum deflection during 3-D molding

After the pieces were conditioned to the required moisture level, the individual groups of test pieces were tested on a dedicated instrument designed by Professor Ján Zemiar and constructed in our laboratory (Fig. 10). The testing equipment operates by loading the veneer sample with compressed air. In this pneumatic molding/testing, the molding stress acts with the same specific load at any moment across the entire surface of the piece; this load increases gradually over time (Zemiar and Fekiač 2014). The air supply is regulated to cause the veneer to rupture within 1.5 min.

Veneers were covered by a stretch polyethylene (PE)-type foil on the air supply side to avoid air penetration throughout the veneer during the test, and were introduced between the lower and upper flanges of the testing tool. The upper flange was placed on the lower flange and secured by adjusting the eccentricity to ensure peripheral thrust.

The veneers were secured according to the chosen method, either by fixed attachment or by light attachment (*i.e.*, limited movement). With the fixed attachment, the peripheral thrust prevents the piece from moving horizontally. When secured by light attachment, the peripheral thrust allows the test piece to move in the horizontal direction during molding/testing. The thrust is designed to prevent veneer margin undulation on the piece during molding/testing (Wagenfuhrer and Buchelt 2005). The maximum deflection, recorded the moment the sample ruptured (*i.e.*, when a crack appeared in the veneer), was measured by a Mitutoyo 513-415E contact deviation meter (USA).

The results were evaluated within factorial ANOVA using Fisher's F-test at a significance level of 95% using STATISTICA 7 software (StatSoft Inc.; Tulsa, OK).

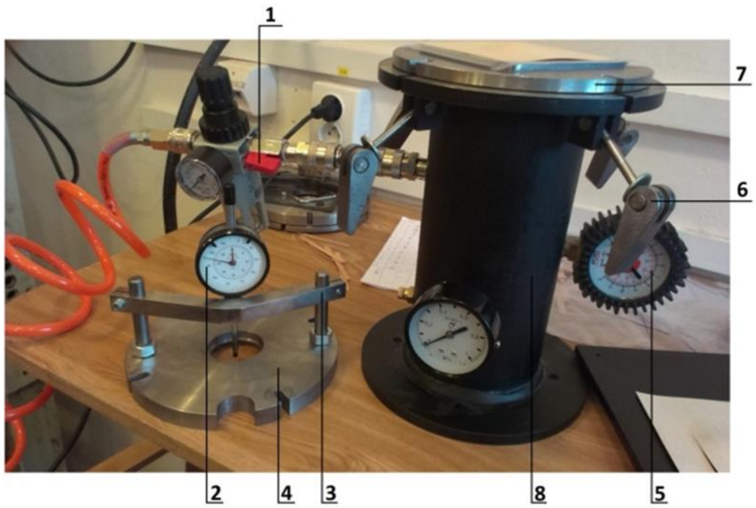


Fig. 10. Testing equipment for 3-D pneumatic molding of veneers. (1) compressed air supply valve, (2) deviation meter, (3) deviation meter holder, (4) upper flange, (5) spring manometer, (6) attachment device (eccentric), (7) lower flange, and (8) pressure vessel

RESULTS AND DISCUSSION

Table 2 shows the resulting effects of the individual factors and their interactions on the deflection for square test pieces. As shown in Table 2, the individual variables of each species (*i.e.*, beech and silver birch) such as moisture (0%, 8%, 16%, 20%, 30%, and 100%) and attachment (fixed attachment and holding attachment), based on the significance level P, can be deemed as factors significantly affecting the values of the monitored deflection.

Table 2. Two-Factor Variance Analysis Evaluating the Effect of Individual Factors and Two-Factor Interactions on Deflection during 3-D Molding

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Overall diameter	3114.289	1	3114.289	65944.22	0.000001
Wood species	8.649	1	8.649	183.14	0.000001
Moisture	133.844	5	26.769	566.82	0.000001
Placement	1.754	1	1.754	37.15	0.000001
Wood species + Moisture	0.821	5	0.164	3.48	0.004828
Wood species + Attachment	1.591	1	1.591	33.69	0.000001
Moisture + Attachment	1.736	5	0.347	7.35	0.000002
Wood + Moisture + Attachment	0.054	5	0.011	0.23	0.949321
Error	10.201	216	0.047		

The results of the evaluation of the two-factor interactions demonstrated that the synergic effect of species and moisture is at the limit of statistical significance. Based on these results, the effect of species plus attachment interactions and moisture plus attachment interactions can be deemed as factor combinations with great statistical influence of the monitored deflection value. A total of 240 test pieces was evaluated, *i.e.*, 24 different groups with 10 samples each. Because of its high P-value (0.949321), the interactions among wood species, moisture, and attachment is deemed statistically insignificant (P>0.05).

Figure 11 shows the maximum deflection values of beech and silver birch during 3-D molding are significantly different. The deflection values increased with an increase in moisture, as shown in Fig. 12. Figure 13 shows that higher deflection values were achieved with a loose (holding) placement of the test pieces.

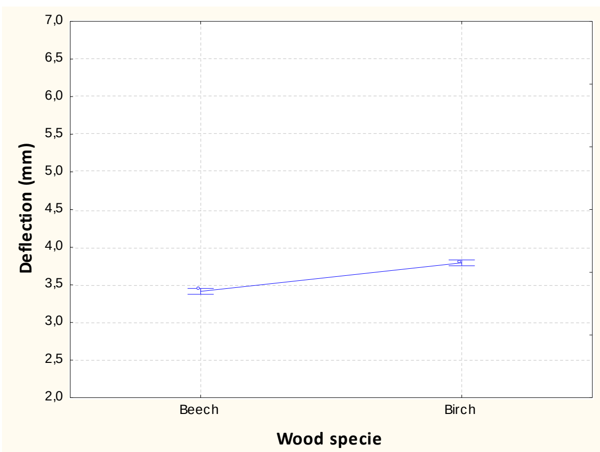


Fig. 11. Wood species effect on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

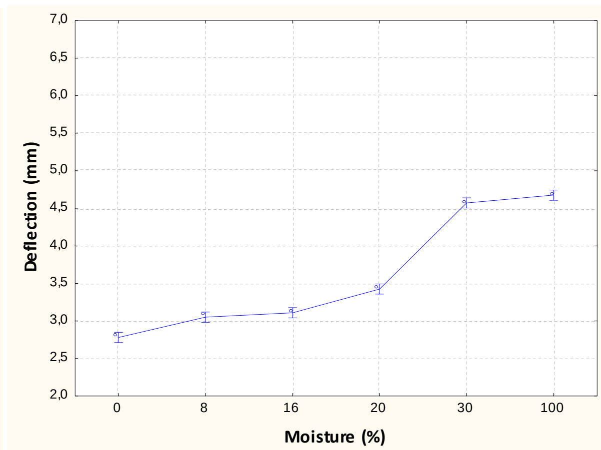


Fig. 12. Moisture effect on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

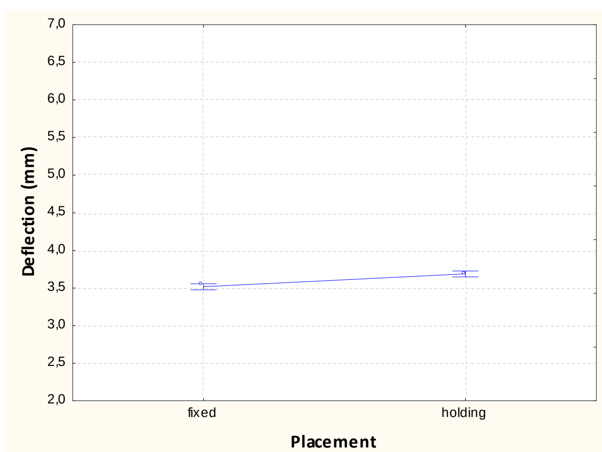
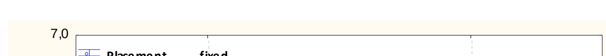


Fig. 13. Placement effect on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

Results of two-factor interaction of species plus moisture are shown in Fig. 14, with higher deflection values achieved in the birch species. The deflection values increased with an increase in moisture. Figure 15 shows the species plus placement



interaction, and the difference between values measured with loose attachment and fixed while attachment are significantly different. For birch species, the effect of this interaction has been proven as insignificant.

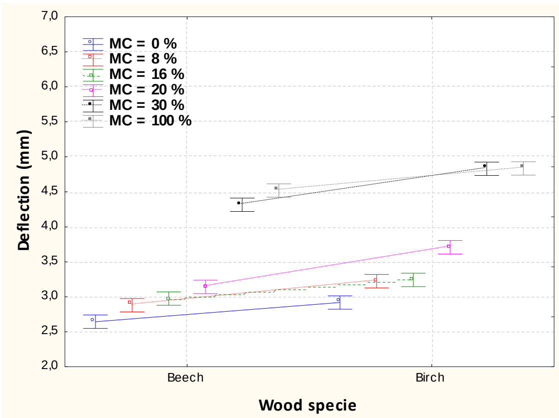


Fig. 14. Wood specie and moisture effect on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

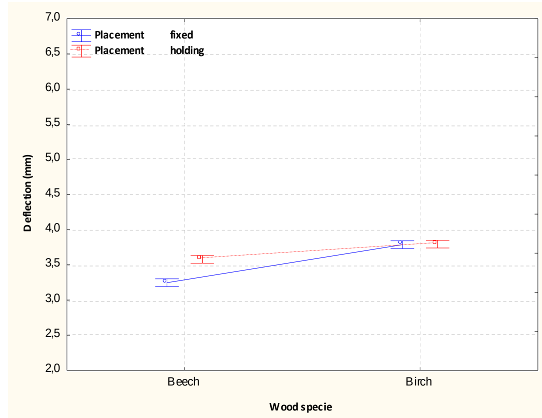


Fig. 15. Placement interaction on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

The results of the two-factor moisture plus placement interaction shown in Fig. 16 illustrate the increase of the monitored deflection values caused by the moisture increase. For loose placement, higher deflection values relative to fixed placement were measured, with the difference at the limits of statistical significance.

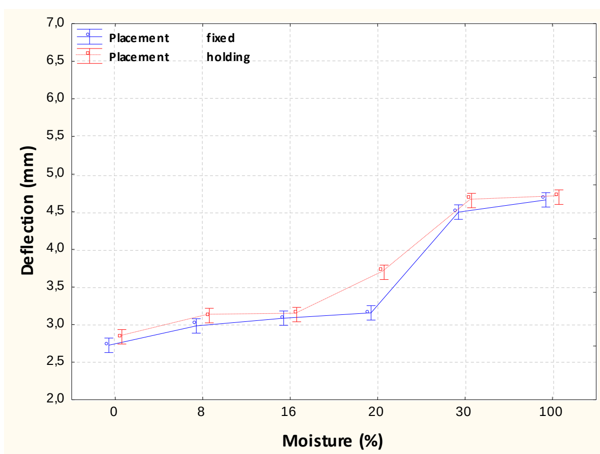


Fig. 16. Placement and moisture effect on maximum deflection values during 3-D molding of veneer. Data reported as mean±SD

As shown by the data in Fig. 17, the moisture level and deflection values increased during 3-D molding. Based on the comparison of the results obtained for the two wood species, greater deflection values were generally found for birch. These results are in agreement with the results of Petro (2013), and confirm the expected effect of moisture (Dubovsky *et al.* 1998). Generally, for this type of molding, wood species with more parallel width of growth rings, such as birch, are recommended (Frese and Blaß 2006).

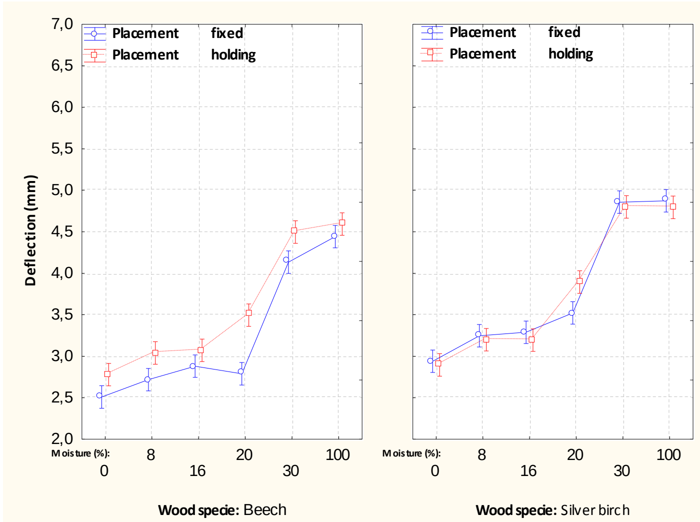


Fig. 17. Wood species and moisture effect on maximum deflection values during 3-D molding of veneers. Data reported as mean±SD

Table 3 shows the results of variance analysis evaluating the effect of specific factors on maximum deflection values for the round testing piece veneers during 3-D molding. A total of 120 test pieces was evaluated, *i.e.*, 12 different groups with 10 samples each. The results showed that the individual factors (beech, birch, moisture, and attachment) are statistically significant ($P<0.05$) in all cases. However, regarding the two-factor interactions, only the moisture-placement interaction is statistically significant. The joint effect of all three monitored factors, wood species-moisture-placement, are statistically insignificant ($P>0.05$).

Table 3. Three-Factor Variance Analysis Evaluating the Effect of Individual Factors and Three-Factor Interactions on Deflection during 3-D Molding

Monitored factor	Sum of squares	Degrees of freedom	Variance	Fisher's F - Test	Significance level P
Overall diameter	2295.125	1	2295.125	15604.62	0.000001
Wood species	8.501	1	8.501	57.80	0.000001
Moisture	82.000	2	41.000	278.76	0.000001
Placement	6.075	1	6.075	41.30	0.000001
Wood species + moisture	0.322	2	0.161	1.09	0.338262
Wood species + placement	0.184	1	0.184	1.25	0.265732
Moisture + placement	1.897	2	0.948	6.45	0.002264
Wood species + moisture + placement	0.320	2	0.160	1.09	0.341103
Error	15.885	108	0.147		

Due to the similarity of results for the square and round pieces (Table 2 and Fig. 17), we do not specify the results of the effect of the individual factors and two-factor interactions in diagram format in this part of the paper. However, we provide the diagram of 95% confidence intervals showing the synergistic effect of the other three monitored factors (wood specie, moisture, and placement), which indicates that the maximum deflection values increased with increasing veneer moisture (Fig. 18). As shown previously (Fig. 17), it can be concluded that birch is more suitable than beech for 3-D molding. When comparing the results of the monitored attachment methods, we can conclude that the light attachment led to better results (Fig. 18).

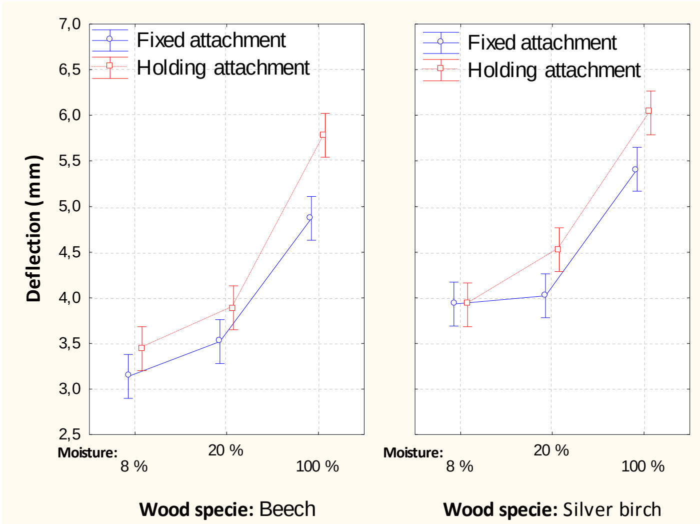


Fig. 18. Wood species, attachment method, and moisture effects on maximum deflection during 3-D molding of veneers. Data reported as mean±SD

Table 4 shows the average deflection values found for the individual groups of test pieces. The highest deflection values were found in the group of birch test pieces with light holding attachment and a moisture level of 100% (saturated). In this case, the achieved deflection was 6.1 mm.

Table 4. Average Deflection Values for the Individual Groups of Test Pieces

Group of test pieces	Wood specie / attachment method	Wood moisture content						Undulation
		0%	8%	16%	20%	30%	100%	
Square pieces deflection [mm]	beech/ fixed	2.5	2.7	2.8	2.7	4.3	4.5	No
	birch/ fixed	2.9	3.2	3.2	3.8	4.7	4.7	No
	beech/ light holding	2.8	3.0	3.1	2.9	4.5	4.6	Yes
	birch/ light holding	2.9	3.2	3.2	3.9	4.8	4.8	Yes
Circular pieces deflection [mm]	beech/ fixed	3.2	-	-	3.5	-	4.8	No
	birch/ fixed	3.9	-	-	4.1	-	**5.4**	No
	beech/ light holding	3.5	-	-	3.8	-	5.7	Yes
	birch/ light holding	3.9	-	-	4.6	-	**6.1**	Yes

Birch test pieces with fixed attachment and 100% moisture (saturated) were deemed the most suitable for 3-D molding. Although this group of test pieces had a deflection of 5.4 mm (Table 4), lower by 0.7 mm than that for the same group when lightly holding attached, it did not exhibit undulation on the veneer margin. Therefore, this group of test pieces can be deemed generally more suitable.

CONCLUSIONS

1. Wood species had a significant effect on test piece deflection values. Birch provides better deflection results, with an average of 4.15 mm compared to 3.65 mm for beech, higher than beech by 13.7%. Generally, for this type of treatment, wood species with typical uniform width of growth rings such as birch, are recommended (Frese and Blaß 2006).
2. Generally, the veneer deflection values during 3-D molding increased with increasing moisture. The highest deflection values were measured for a moisture content of 100%, with an average of 4.9 mm. Conversely, the lowest deflection values were measured at a moisture content of 8%, with an average of 3.3 mm.
3. The average deflection for circular samples was 4.2 mm. For square test pieces, an average value of 3.6 mm was found, lower by 16.7%. For practical purposes, square pieces are more appealing because fabrication and use are easier. The circular pieces are more suitable for testing because each point of the peripheral curve has the same distance from the center, which eliminates the influence of the piece shape on the test results.
4. Based on the results, the following is recommended for 3-D molding of veneers: circular shaped birch wood, 100% moisture content, and fixed attachment. Using these parameters, the best deflection values of the test pieces were achieved and undesirable defects (*i.e.,* cracks and undulation) prevented.

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