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3D FORMABILITY OF MOISTENED AND STEAMED VENEERS

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ABSTRACT

The paper deals with the evaluation of 3D formability of veneers modified by moistening and steaming. Formability of three wood species (*Fagus sylvatica* L., *Betula pendula* Roth. and *Fraxinus excelsior* L.) was compared. To determine the 3D formability, the method based on the principle of forming by air pressure was used. 3D formability was evaluated according to deepening and according to the force required to change the shape of veneer, calculated per unit of deepening. The results indicate an increase in 3D formability of modified veneers. Increasing moisture content of veneers had a positive impact on the change in 3D formability; and also positive impact of steaming was demonstrated. It has been demonstrated that 3D formability of veneers modified by moistening and 3D formability of veneers modified by steaming are comparable (almost the same). Formability of beech veneer and ash veneer are almost the same (are at a similar level). Birch veneer showed the best formability. If the veneer of a given thickness is steamed, plasticization time of 10 minutes is sufficient.

Key words: 3D formability, modification, moisture content, moistening, steaming, veneer.

INTRODUCTION

Constantly increasing requirements for originality and shape unique of furniture encourage continuous research in the field of material inputs. Veneer as the wood-based material is often used as a construction and decoration material. However, its application is limited to a considerable extent. It is because of anisotropy of wood – wood properties differ within the three anatomical directions. The properties can be modified by certain methods. It allows creating a material formable better; material molded in two dimensions (2D forming) or in three dimensions (3D forming).

2D forming of wood and veneer is relatively widely researched area and increasingly used also in practice. In contrast, increased attention is paid to 3D forming of veneers particularly in recent years; which led to more improvements and patents in the field. So-called 3D-veneer (developed by REHOLZ GmbH) can be considered as a significant progress. The patent describes longitudinal cutting of veneer and its subsequent bonding (WAGENFÜHR *et al*. 2009, SCHRÖDER *et al*. 2011, NAVI and SANDBERG 2012, SCHELLBERG 2012). On modification of veneers for the purpose of 3D molding, more research was carried. Worth mentioning are the works by HEROLD and PFRIEM (2011, 2013) concerning modification of veneers by furfuryl alcohol. The surface densification of veneer (WAGENFÜHR *et al*. 2006 and ZEMIAR *et al*. 2013), moistening (GAFF 2014), hydrothermal plasticizing (ROSENTHAL 2009, PETRO 2013), thermal modification (BUCHELT *et al*. 2010), modification by resins, coatings, and polystyrene (SLABEJOVÁ, ŠMIDRIAKOVÁ 2013, 2014), and also the impact of reinforcement by melt adhesive and glass fiber (ZEMIAR *et al.* 2014) was also researched. An interesting method of modification of veneers, local densification and incision, was done by LANGOVÁ and JOŠČÁK (2014). In this way only 2D formability has been detected so far. In order to identify shape deformation, LANGOVÁ *et al.* (2013) used several methods of assessing 2D formability of veneers.

Based on the already achieved results and also in terms of economic perspectives, we consider it appropriate to examine in more detail and compare just two methods – moistening and hydrothermal treatment.

Water itself acts as a plasticizer for wood reducing the temperature of softening of the wood components (MELCER *et al.* 1989). In synergy with heat (hydrothermal treatment) plasticizing effect is increased and accelerated. In the process of hydrothermal treatment, a change in wood structure, and so temporarily or permanently changes in physical and mechanical properties, are caused due to the interactions of wood with water, and heat (KÚDELA 2005). For forming of wood and veneer (2D and 3D) just temporary changes are used. Under temporary changes, it is possible to achieve more significant changes in shape if compared with native (unmodified) wood; while after re-drying, no reduction in its mechanical properties should be. The exposure time of heat also has significant influence on wood, particularly in the temperature range 80–100 °C (KÚDELA 1990).

In spite of several already implemented researches in the field of 3D forming of veneers, no standard methodology for assessment of formability of veneer has been known. Currently used methods for that purpose are based on the assessment of formability of sheet metal. They are based on the Erichsen test, adjusted in using different diameter punches, holes in the matrix, and also different ways of generating molding force (punching or air pressure). Investigations on evaluation of 3D formability, through testing 2D formability, were also carried.

The aim of the present paper is to assess the 3D formability of veneers after modification by moistening and steaming. Veneers of the selected wood species were examined.

MATERIAL AND METHODS

Having regard to good bendability, three wood species were chosen: beech (*Fagus sylvatica* L.), birch (*Betula pendula* Roth), and ash (sapwood and heartwood) (*Fraxinus excelsior* L.). Experimental material was the sliced veneer with radial wood texture. The average thickness of veneer sheets, and so the thickness of test specimens, ranged in the interval 0.51 ÷ 0.59 mm. The average wood moisture content was 8÷9 %.

From each veneer sheet, test specimens of circular shape with diameter 60 mm were cut out with a punch. The shape and size of the test specimens was set with respect to the method for determining 3D formability. An auxiliary circle concentric with the circuit of the specimen was drawn on the left surface of the specimen. The circle served for correct centring of the specimen with the hole in matrix.

Set of 20 specimens was prepared for each proposed modification.

Prepared test specimens were modified by two methods: by increasing their moisture content (moistening) or by plasticizing in indirect steaming – at given moisture content and plasticizing time.

The test specimens had being moistened until the wood moisture content reached 16 %, or reached a wood moisture content corresponding with fiber saturation point (FSP) of wood species, which the specimens were made of (approximately 30 %). Moistening was done in airtight closed container (in desiccator), where conditions corresponding to the wood moisture content were created. For conditioning to the moisture content of 16 %, saturated aqueous solution of potassium chloride (KCl) was used; and for conditioning to the moisture content of FSP, pure water. The test specimens were placed above the surface of aqueous solutions for a period until they achieved desired moisture content.

Before modifying the test specimens (increasing their moisture content), the average initial moisture content (w_a – in percentage) was measured at a representative set of specimens using mass method. From the further set of test specimens, intended to be modified, each specimen was weighed in order to found out the initial mass (m_w). The average initial moisture content and the mass of the individual specimens were subsequently used to calculate the assumed mass at the moisture content of 16 % (m_{16}) and 30 % (m_{FSP}) according to the equation (1) a (2):

$$m_{16} = \frac{m_w}{1+\frac{w_a}{100}} \cdot 1.16 \qquad (1)$$

$$m_{FSP} = \frac{m_w}{1+\frac{w_a}{100}} \cdot 1.30 \qquad (2)$$

The other modification method (plasticizing by steaming) was done in a container where, after the water boiled, the test specimen was placed on the sieve (4 cm above the water surface) and the container was closed for specified time. The plasticizing time was set on the basis of preliminary experiments as 2 min, 5 min, 10 min, or 15 minutes.

Before plasticizing, each test specimen was weighed to verify its initial moisture content (w_a).

From the weight of test specimens measured after modification, the wood moisture content of veneers, for which 3D formability was evaluated, was determined.

Determination of 3D formability was done according to one of the methods which were presented by ZEMIAR and FEKIAČ (2014). In experiments, the method based on pneumatic forming of the test specimens was used. The deformation force was generated by air pressure and during the test the specimens were hold peripherally. To detect monitored indicators, we used electronic digital sensors of deepening, air pressure sensors, and temperature sensors connected to a measuring instrument ALMEMO 2690-AKSU. It allowed synchronizing sensors and increasing sensitivity of measuring instrument. The instrument is shown in Fig. 1.

The very principle of the test was in pushing the test specimen into the circular opening in the matrix by air pressure while holding the specimen; and in finding out the size of resulting deformation – the size of deepening. The size of deepening was regarded the fundamental criterion expressing ability of a veneer to be formed in three directions. The size of deepening can be defined as "the maximum depth of veneer pushed into the matrix by shaping force before the breach" FEKIAČ *et al.* (2015).

The principle of testing is shown in Fig. 2. It shows a membrane (stretch film with thickness of 10 μm) placed under the test specimen. The membrane is a seal preventing air (pressure) to escape through the test specimen. Between the matrix and the holder (near the edges of test specimen), distance pads were placed. Their thickness corresponded to the thickness of the specimen. Distance pads ensured that test specimen was not firmly fixed between the matrix and the holder, but it could move parallel to the surface of the matrix and the holder. It prevented waving on the circumference of the specimen; this is a defect that may occur in 3D molding.

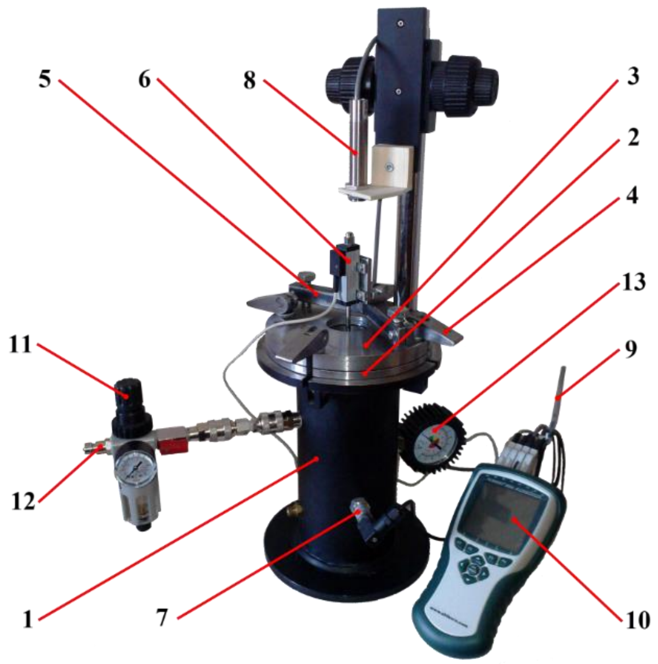

Fig. 1 Equipment testing 3D formability of veneers. 1 – pressure vessel, 2 – holder, 3 – matrix, 4 – clamping mechanism (eccentric), 5 – holder for sensor of deepening, 6 – sensor of deepening (AHLBORN FWA025T), 7 –pressure sensor (AHLBORN FDA602L5R), 8 – IR temperature sensor for test specimen (Amir FIA844), 9 – temperature sensor for environment (Pt 100 ZA9030-FS2), 10 –recording instrument – dataloger (ALMEMO 2690-AKSU), 11 – regulation valve, 12 – quick coupling for compressed air supply, 13 – manometer for pressure control.

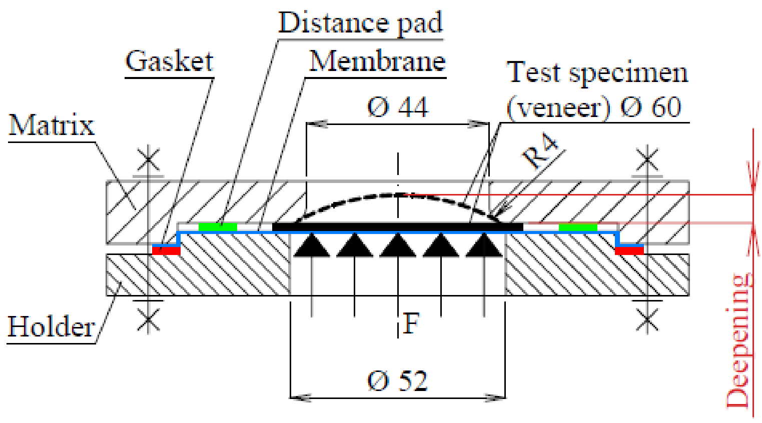

Fig. 2 Schema of detection of 3D formability under air pressure at test with holding of specimen.

Considering that we did not detect directly the force but the pressure needed to achieve changes in shape of the veneer, it was necessary to calculate the pressure on the force (equation 3).

$$F = p \cdot \pi \cdot r^2 \quad (3)$$

where: F – forming force [N];
p – air pressure [MPa];
r – radius of hole in holder [mm].

To compare the proposed methods of modification also from the viewpoint of forming force, it was necessary to take into account that the test specimens breached at various deepening and at various forces. Therefore the forming force was calculated per unit of deepening (equation 4).

$$F_h = \frac{F}{h} \quad (4)$$

where: F_h – forming force per unit of deepening [N · mm^{-1}];
F – of forming forces [N];
h – deepening [mm].

During testing of 3D formability, the temperature of the test specimens and also the temperature of surrounding environment (room) were monitored. The temperature of specimens was measured by infrared touchless sensor and the temperature of the environment by resistance sensor. Measurement was done from the start putting a load (air pressure) on the test specimen until the end of the test.

RESULTS AND DISCUSSION

Influence of modification methods on the change in 3D formability of veneers was evaluated on the basis of sizes of investigated indicators. The main 3D formability parameter was the size of deepening and a supplementary indicator was the force calculated per unit of deepening.

Values of indicators measured before and after modification, obtained on the basis of the methodology described above, were evaluated using the STATISTICA 10 through the multifactorial ANOVA. The investigated factors were the modification methods and wood species. The results are presented in tables and graphs.

All indicators of 3D formability were evaluated separately. Modified veneers were compared to each other and also with the referential (unmodified) veneer.

From the viewpoint of deepening, on the levels of significance shown in Tab. 1, we can conclude that both modifications (moistening and plasticization by steaming) influence the size of deepening and thus the change in 3D formability statistically significantly. Also the impact of wood species was manifested as significant. From the viewpoint of the examined wood species, more detailed analysis through Duncan test showed that the differences in size of deepening between sapwood ash and heartwood ash, and also between beech and ash were not significant. The test confirmed statistically significant difference in 3D formability of birch from all other examined wood species for all modifications. The modification method, the wood species, and also a combination of the two factors were statistically significant. 3D formability depends on wood species and the method of modification.

Tab. 1 Statistical evaluation ANOVA – influence of modification method, wood species, and combination of both factors on size of deepening.

Effect	SS	Degr. of Freedom	MS	F-test	p
Intercept/ Total average	8866.7	1	8866.7	84414.7	0.000
Modification method	92.8	6	15.5	147.2	0.000
Wood species	242.5	3	80.8	769.6	0.000
Modification method*Wood species	13.8	18	0.8	7.3	0.000
Error	55.880	532	0.105		

The values of deepening measured before and after modification (by moistening and steaming) are shown in Fig. 3. The graph shows that increasing moisture content and increasing plasticizing time increased deepening (3D formability) – for all wood species. It was confirmed the statement by MELCER, *et al*. (1989) who stated that also water works as a wood plasticizer. ZEMIAR *et al*. (1999) reported that decrease in wood stiffness, caused by increasing moisture content, results in increasing wood formability.

When evaluating the moistened veneers, we can state that the veneers moistened up to the fiber saturation point demonstrated larger deepening than veneers moistened to 16 % moisture content. It was confirmed that deformation of wood increased with increasing moisture content up to the fiber saturation point – stated by DUBOVSKÝ (1993). This fact has also been confirmed by GABĽAS (2012), ĎURČEK (2014), CIKATRICIS (2014), and GAFF (2014).

Regardless of the wood species, deepening increased after moistening to 16 % moisture content by 0.48 ÷ 0.98 mm (16.4 ÷ 25.7 %). After moistening up to the fiber saturation point (approximately 30 %) it was from the range from 0.96 ÷ 1.5 mm (33.6 ÷ 41 %).

By evaluating the deepening, we found out that the greatest deepening was measured for birch veneers both before modification and after it (by moistening and steaming). In the case of moistening, the deepening increased to 5.31 mm; which represented an increase in 3D formability (if compared with referential veneers) by 39.8 %. Steamed veneers reached deepening of 5.72 mm (50.1 % increase).

The graph also shows that deepening of birch veneers moistened to 16 % moisture content is bigger than deepening of the other wood species (modified by all methods). When assessing deepening of beech and ash veneers we did not record so significant differences as it was at birch veneers. All examined wood species differ from each other by their structure and properties resulting in differences in their behavior when 3D formed. WAGENFÜHR *et al*. (2006) reported that wood species with a small number of vessels, high homogeneous fraction of wood fiber, uniform width of rays, and no differences between spring and summer wood are best formable. Of all examined wood species, birch meets the mentioned conditions best. If compared to beech and ash, birch contains a middle proportion of vessels, the largest proportion of fibers, and the least number of rays. The proportion of the particular elements and their arrangement are creating the preconditions for better 3D formability. Excellent formability of birch veneers in comparison with other wood species has also been confirmed by WAGENFÜHR and SCHEIDING (2010) and GAFF (2014).

At beech and ash veneers plasticized by steaming, the increase in deepening was 0.92 ÷ 1.04 mm (31.4 ÷ 36.4 %). After steaming the veneers during the shortest time (2 minutes), we recorded increase in deepening in the range 0.35 ÷ 1.19 mm (12.2 ÷ 31.2 %).

After comparing significance levels (at various plasticizing time) resulting from Duncan test, we can conclude that plasticization by steaming during 10 minutes is sufficient to create optimal conditions to obtain as large as possible deformation of the veneers, and thus the maximum in 3D formability.

The forming force, calculated per unit of deepening, was another monitored indicator of 3D formability. It has been demonstrated that the force decreased with increasing wood moisture content, as well as with increasing steaming time at all wood species when compared with referential (unmodified) veneers. Moistening to the fiber saturation point (approx. 30 %) significantly affected the force. When compared to referential veneers, the force decreased by 1.9 ÷ 21.1 $N \cdot mm^{-1}$ (5 to 34 %). Moistening to 16 % moisture content and plasticization by steaming for two minutes had no impact to the forming force, except for birch veneers (decrease by 7.2 ÷ 12.6 $N \cdot mm^{-1}$, thus by 12 ÷ 20 %, when compared with referential veneers). After moistening to the fiber saturation point as well as plasticization by steaming for the other times, decrease in force per unit of deepening was in the range from 5 to 31% at all examined wood species. Decrease in force per unit of deepening was closely related with an increase in plasticity resulted from increased moisture content or temperature (at steaming).

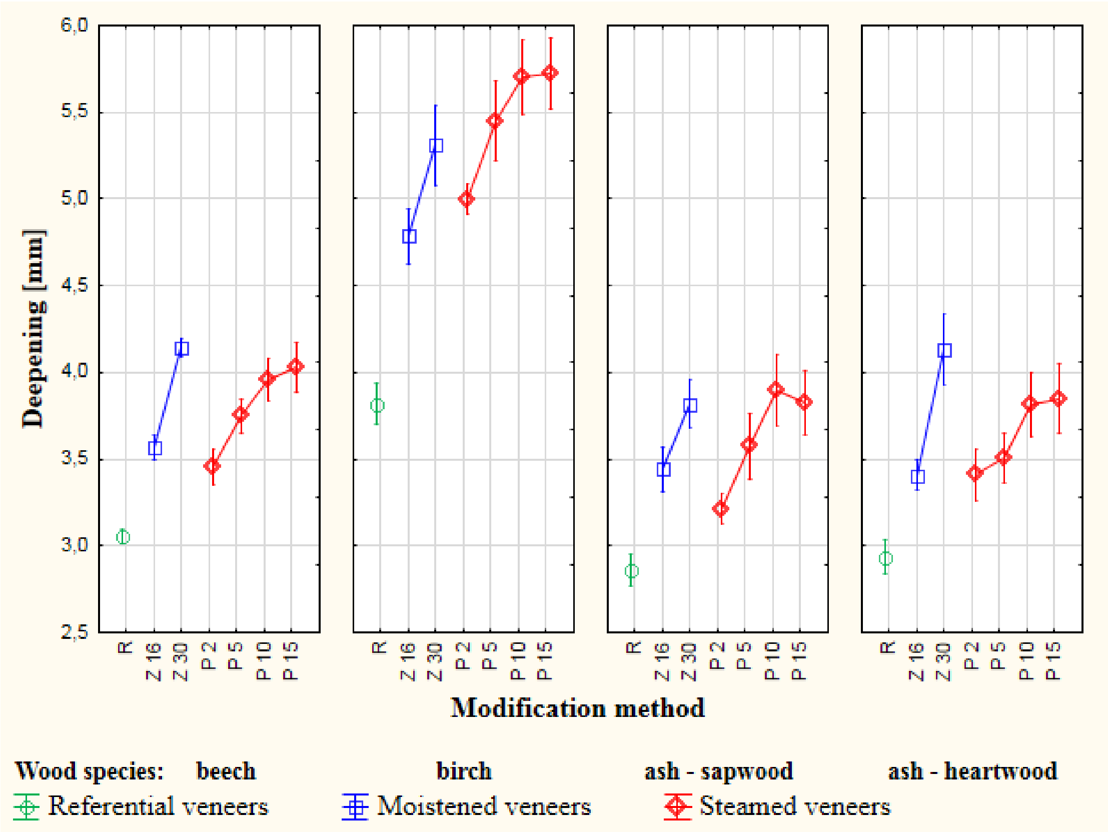

Fig. 3 Deepening for beech, birch, and ash veneers.
Note: R - referential veneer, Z 16 - moistened to 16 %, Z 30 - moistened to fiber saturation point (approx. 30 %), P 2 - steamed for 2 minutes, P 5 – steamed for 5 minutes, P 10 - steamed for 10 minutes, P 15 - steamed for 15 minutes.

The results indicate that the force per unit of deepening at beech, sapwood ash, and heartwood ash is approximately the same. The average value was from the interval of 30.5 ÷ 42.3 N·mm^{-1}. When ascertaining the 3D formability at birch, we recorded bigger force per unit of deepening (41.2 ÷ 62.3 N·mm^{-1}) if compared to the other examined wood species. The course of force per unit of deepening before and after modification for the examined wood species is shown in Fig. 4.

The effect of plasticizing on the change of wood properties is characterized by the size of force required. In practical terms, it is an important indicator influencing parameters of the technical equipment used for 3D forming.

Both proposed modification methods depend on exposition of the test specimens to moisture content. Analysis of wood moisture content demonstrated the known fact that the exposure time has significant impact on wood moisture content of veneers. It was also confirmed that moisture content depends on the wood species.

Comparison of wood moisture content at examined wood species and used modification methods is shown in Fig. 5. The moisture content of referential (unmodified) veneers was at the level of 8 ÷ 9 % at all examined wood species. After modification to 16 % moisture content, we found out a fluctuation of moisture content ± 1% depending on wood species. The wood moisture content in the fiber saturation point differed between wood species. Moisture content of beech veneers was 27 %, birch 31 %, and sapwood ash and heartwood ash veneers of 28 %. Wood moisture content in the fiber saturation point depends on wood species; it was confirmed also by LEXA *et al*. (1952), POŽGAJ (1997), NIEMZ (2005), and many other authors. LEXA *et al*. (1952) stated that the moisture content in the fiber saturation point varies in the range from 24 to 35 %.

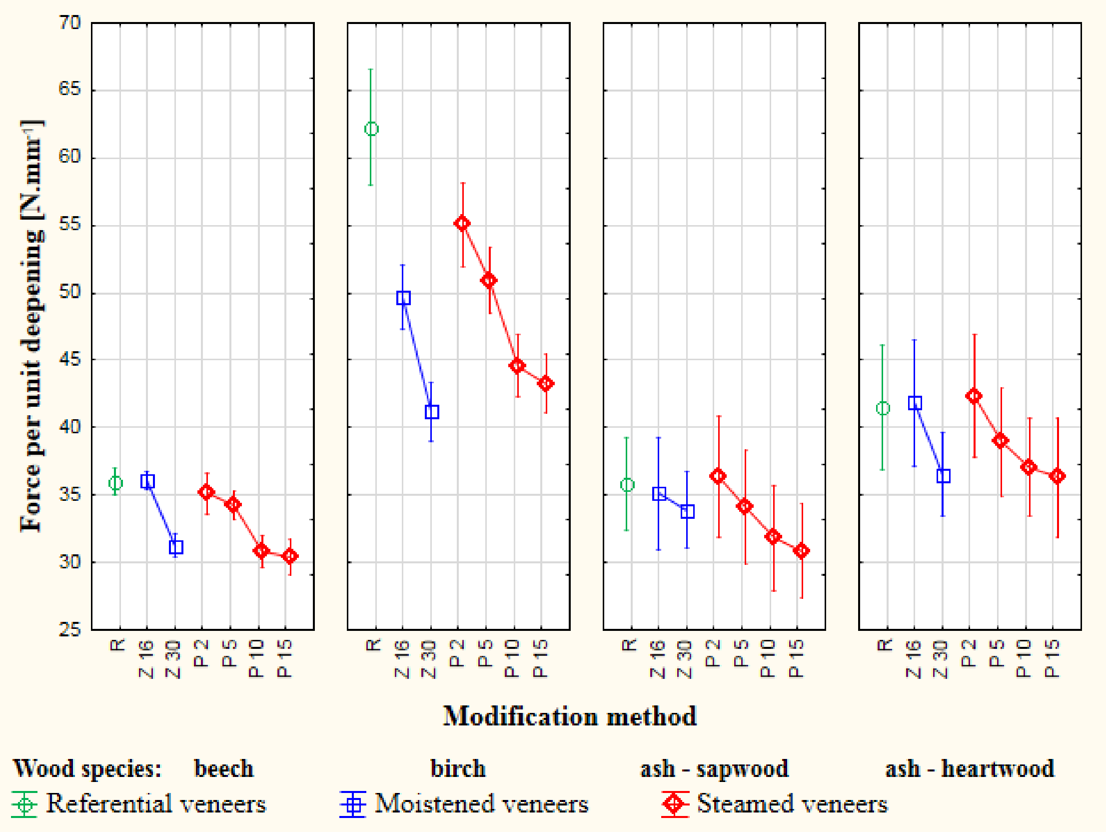

Fig. 4 Force per unit of deepening at beech, birch and ash veneers.
Note: R - referential veneer, Z 16 - moistened to 16 %, Z 30 - moistened to fiber saturation point (approx. 30 %), P 2 - steamed for 2 minutes, P 5 - steamed for 5 minutes, P 10 - steamed for 10 minutes, P 15 - steamed for 15 minutes.

At modification by steaming, we found out that, within the chosen plasticizing time, moisture content of veneers was increased to 13.5 ÷ 24.5 %. This implies that moisture content of veneers did not reach the value corresponding to the fiber saturation point.

Moisture content of the veneers after modification was evaluated primarily for subsequent evaluation of the impact of heat accumulated in the test specimens after steaming, in order to determine its the impact on the 3D formability.

After hydrothermal treatment of veneers, because of low thickness of the veneers, there is much more rapid drop in temperature when compared to the thicker wood dimensions. That is why it is necessary to mold modified veneers as soon as possible after plasticizing to use the effect of moisture and heat.

To assess the effect of heat objectively, it was necessary to find out how moisture influenced the change in deepening in the process of moistening and steaming (compare the graphs in Fig. 3 and Fig. 5). At the same average value of deepening (within the same wood species), ascertained after moistening and steaming, and mutual comparison of moisture content at that value of deepening, we found that the test specimens showed lower moisture content after steaming if compared with moistening. From the above it follows that not only the moisture but also the temperature at steaming increased the 3D formability.

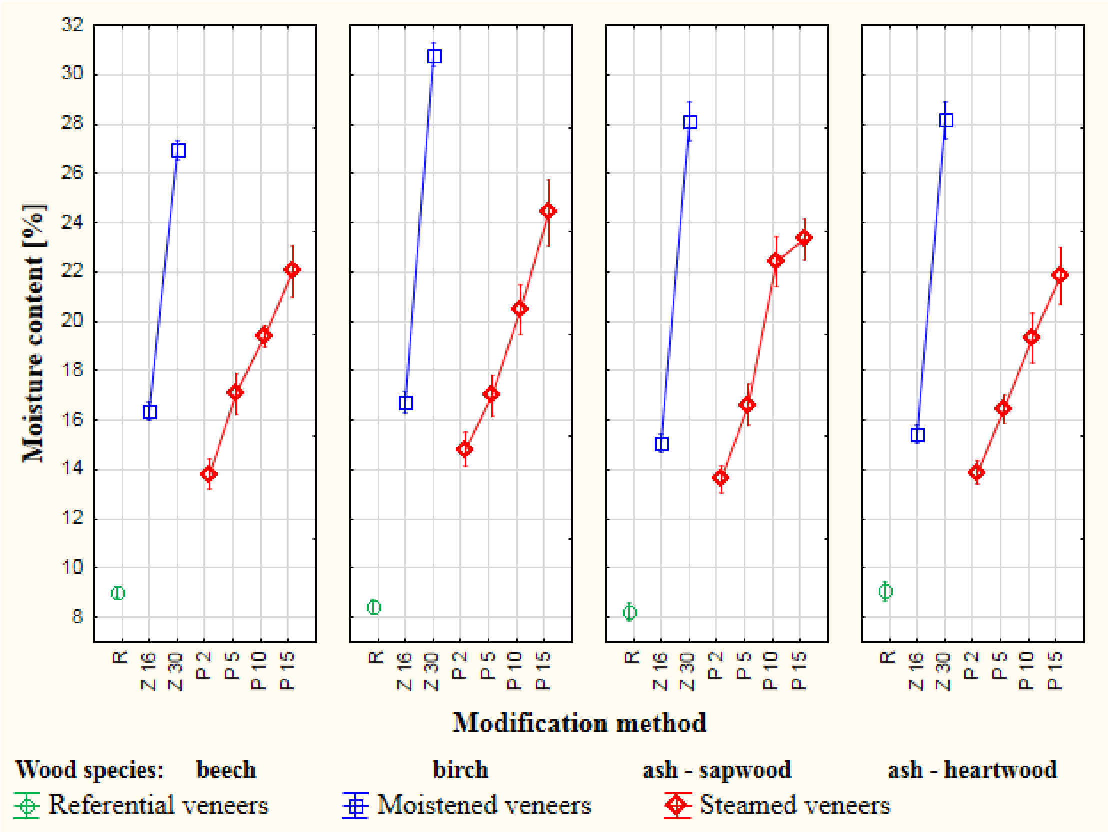

Fig. 5 Wood moisture content at beech, birch and ash veneers.
Note: R - referential veneer, Z 16 - moistened to 16 %, Z 30 - moistened to fiber saturation point (approx. 30 %), P 2 - steamed for 2 minutes, P 5 - steamed for 5 minutes, P 10 - steamed for 10 minutes, P 15 - steamed for 15 minutes.

During the testing the temperature of veneers varied according to the method of modification. At reference veneers and moistened veneers, the temperature of a veneer was equal to the ambient temperature (room temperature) 21 ÷ 22 °C. The temperature of steamed veneers was 24.9 ÷ 31.6 °C at start of the test (i.e. at starting the test equipment); and at the end it was close to room temperature (dropped to 22.5 °C, depending on duration of the test). Low temperature of steamed veneers at start of the testing of 3D formability can be attributed to their small thickness (on average 0.55 mm). Although the time taken to handle the plasticized veneer (after taking away the test specimen from the plasticizing devices up to run the test) was only about 15 seconds, due to the small thickness the accumulated heat was losing very quickly.

CONCLUSION

To achieve interesting shapes of products based on 3D-formed veneers, it is necessary to modify the veneers suitably before forming.

According to the main evaluation criterion, we can conclude that the proposed methods to modify the veneers increased the 3D formability (compared with unmodified veneers) by 12 up to 50 %. With increasing moisture content and steaming time the formability was increasing.

When comparing the values of deepening between examined wood species in unmodified state and modified state, we found that birch veneers had the biggest 3D formability and therefore they appear as most appropriate to form.

Beech and ash veneers showed almost the same formability after modification but smaller than birch by 15–38 %.

If evaluating the impact of moisture content to changes in 3D formability, we found out that steamed birch veneers has better formability by 5–11 % than moistened veneers in spite of the fact that the birch veneers were losing temperature and moisture very quickly during testing.

It has been shown that even a small increase in temperature of the test specimen resulted in increase of 3D formability. In practical terms, the difference between 3D formability of moistened veneers and steamed veneers is negligible. We found that for the tested thickness of veneers modified by indirect steaming, plasticizing time of 10 minutes is sufficient.

From the viewpoint of force per unit of deepening, we came to the knowledge that with an increase in moisture content and steaming time the force is decreasing. The biggest reduction by 34 % was recorded at birch veneers.

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