The Development of Stresses during the Shaping of the Surface of Aspen Wood and Their Impact on the Quality of the Surface

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This work investigates the influence of wedge shape and depth of pressing on creation of stresses, as well as the influence of these stresses on quality of wood surface during wood embossing. For the identification of stresses, *SolidWorks* software was used, through which a simulation was made for the progression of monitored stresses which occur when pressing the wedges with various shapes to different depths of pressing. Based on these findings, it was possible to monitor factors that were modified so that embossing would achieve the desired shape and dimensionally stable surface without undesirable quality defects.

Keywords: Pressing; Embossing; Surface quality; Depth of pressing; Aspen; Wedge; Wedge shape

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INTRODUCTION

Surface embossing is a method for improving wood's surface appearance and creating decorative properties, in which the wood surface is formed using profile plates. In the case of smoothed plated pressing, the density and hardness of the wood surface increases (Dudas *et al.* 2003; Gáborík *et al.* 2002). During such embossing, uneven compression is used to achieve a densified structure of wood, create a decorative surface, keep the required quality of the embossed areas, and provide shape and dimensional stability to the created embossment.

For pressing, press machines are used with heated profiled plates. In general the desired surface shaping is achieved by the effects of heat and pressure on untreated or treated (by plasticizing) wood, which is stabilized in the allotted time. In case of continuous pressing (by rolling), a phase of stabilization under pressure is not necessary, and maintaining the new shape depends on wood stability (Gáborík and Žitný 2007; Gaff and Zemiar 2008).

This research was aimed at the industrial utilization of soft deciduous trees. Aspen wood (*Populus tremula* L.) falls under this category. It has an inexpressive wood structure, so it is possible to improve its decorative appearance by embossing it (Zemiar and Gaff 2005).

The process of surface shaping by pressing usually takes place in three phases: plasticizing, custom pressing, and conditioning. The result of this technological process is the product, which is characterized by certain technological characteristics (quality of embossed surface, shape, and dimensional stability, *etc*.) (Gáborík *et al.* 2003; Gáborík and Žitný 2007; Gaff and Zemiar 2008; Gáborík and Dudas 2008; Barcík *et al.* 2008).

This work focused on the quality of embossed aspen wood and on the manner in which the quality can be influenced by stresses that arise in the surface zone as a result of embossing wedges of various shapes.

MATERIALS AND METHODS

Sample Preparation

The experimental aspen trees (*Populus tremula* L.) were 65 years old and grew in the Javorie mountains area in central Slovakia, southeast from Zvolen city. The zones suitable for samples were cut from the trunk at a height of 1.5 m from the stump. The zones, which were in middle distance between the pith and bark, were chosen for sample preparation. From these parts were cut 50 cm long sections which contained 20 mm wide annual rings. For experiments, clear aspen samples with dimensions of 10 × 80 × 80 mm were used. All the samples were air-conditioned in the conditioning room for more than five months before moisture conditioning.

The air-conditioned samples with 12% moisture content were conditioned in a humidity-controlled chamber such that they achieved an equilibrium moisture content (EMC) of 6.4%, which was selected as the moisture content for testing. The conditioning chamber provided suitable conditions in relation to relative humidity of air and temperature (Table 1). The actual EMC of each sample was measured by a weighing method after conditioning. Table 1 shows the average values of equilibrium moisture contents for the whole group of samples. For each combination (shape of wedge x depth of pressing), 40 samples were used, so that the entire research contained 360 samples.

Table 1. Moisture Contents and Conditioning Conditions of Samples

Required initial moisture content (%)	Average values of EMC after conditioning (%)	Scattering of EMC values after conditioning (%)	Conditions during conditioning	
			Relative humidity of air (%)	Temperature (%)
6.4	6.415	5.98 – 6.85	32.5	20

Treatment

Treatment was carried out by the pressing of wedges with 3 different shapes (45° cutting-edge angle, concave, and convex) (Fig. 1) into 3 depths of pressing (2, 4, and 6 mm) on the tangential surface of sample with parallel orientation of wedge relative to the direction of wood grain.

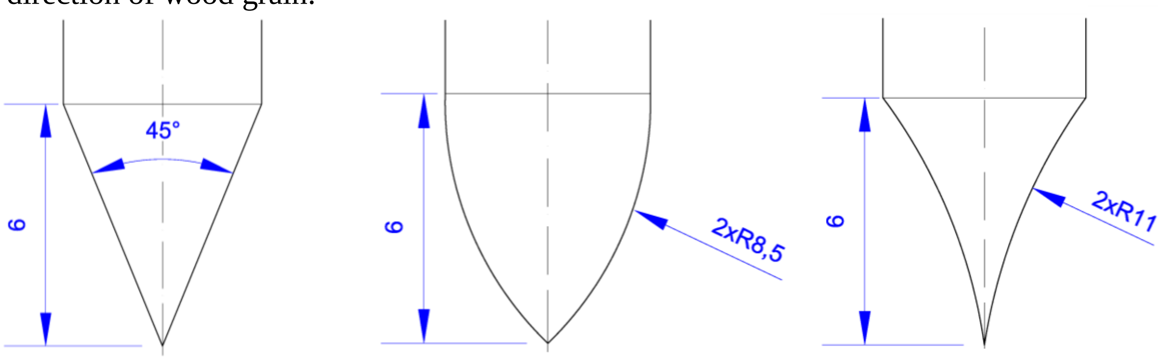

Fig. 1. Selected shapes of embossing wedge - 45º cutting-edge angle (*left*), concave shape (*center*), and convex shape (*right*)

Pressing (embossing) was carried out in a standard tensile-pressing machine FPZ 100/1, which contained a special jig for fixation of steel wedges (Fryková 2007). Speed of loading was set to 0.96 cm/min. First the testing samples were fixed in the bottom plate (Fig. 2 *left*) and then the wedge was pressed to required depth of pressing (Fig. 2 *center*). Immediately after pressing, the force was measured and recorded using a sensors and data logger Almemo 2690 which was connected to a laptop.

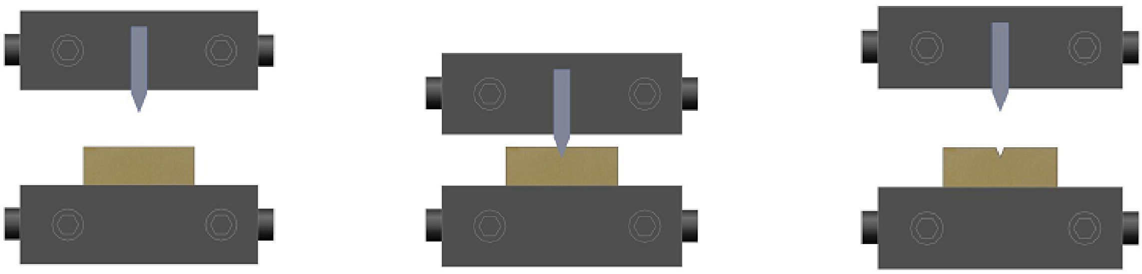

Fig. 2. Scheme of embossing – before embossing (*left*), during embossing (*center*), and after embossing (*right*)

In order to gain physical and mechanical characteristics of aspen wood, preliminary tests were carried out. These tests were performed also on this tensile-pressing machine. During the preliminary tests, measurements were taken and values were calculated for compressive and tensile strength, modulus of elasticity, limit of proportionality, and density. Only density was calculated according to the equation listed in the Calculations section. All other characteristics were calculated directly using the data logger and particular software in the laptop.

Simulation and Evaluation

The simulation was modeled by pressing the wedges into the tangential surface of aspen wood at three depths of pressing. For correct calculation of the stresses, it was necessary to summarize the characteristics of the physical and mechanical properties of aspen.

The experimental procedure can be divided into the following steps:

1. Getting the physical characteristics and mechanical properties of aspen.
2. Finding the values of forces needed for pressing of wedges into the wood for individual depths, with data logger device.
3. Calculation and simulation of stresses behavior by *Solid Works* software.
4. Analysis of obtained results and their comparison with the real results, obtained using the *Profile* software (comparison of real shape with simulated shape).

Physical-mechanical properties of aspen wood

Physical and mechanical characteristics of aspen were obtained from the preliminary tests (values at 6.4% moisture content) previously described. Other values (values at 12% moisture content) served as a comparison and were introduced by Požgaj *et al.* (1997). All of the properties necessary for simulation of the embossing process, together with the values employed are given in Table 2.

Table 2. Basic Physical-Mechanical Properties of Aspen Wood

Characteristics	Values at *w*=12%	Values at *w*=6.4%	Units
Modulus of elasticity (parallel to grain)	8,100.0	8,548.8	MPa
Modulus of elasticity (perpendicular to grain, tangential direction)	300.0	748.8	MPa
Modulus of elasticity (perpendicular to grain, radial direction)	630.0	1,078.8	MPa
Poisson's ratio T-R	0.496	0.496	
Poisson's ratio R-L	0.054	0.054	
Poisson's ratio T-L	0.022	0.022	
Density	411.97	400.70	kg/m^3
Tensile strength (perpendicular to grain, radial direction)	3.139	3.651	MPa
Compressive strength (perpendicular to grain, radial direction)	3.031	3.771	MPa
Limit of proportionality in compression (perpendicular to grain, radial direction)	3.091	3.846	MPa

Values of forces

Another important group of data needed for calculation of monitored stresses was the values of forces required for pressing the wedges into the wood in individual depths. These facts are also confirmed in research by Gáborík and Dudas (2006). Values of forces were found by connecting the device data logger to the tensile-pressing testing machine. The data obtained were analyzed, and the accuracy of the simulations was compared related to the real results that were collected using *Profile* software.

The values of measured forces, needed for pressing of wedges into particular depths, are presented in Table 3.

Table 3. Measured Force Values

Type of wedge	Force [N]						Depth of pressing [mm]
	Range		Arithmetic mean	Standard deviation	Coefficient of variation	Standard error	
	minimum	maximum					
45º wedge	583.7	659.3	621.5	71.00	0.114	11.22	2
	1,187.6	1,298.4	1,243	307.18	0.247	48.57	4
	1,658.9	2,073.1	1,866	353.12	0.189	55.83	6
Concave wedge	599.1	670.9	635	109.51	0.172	17.32	2
	1,053.4	1,486.6	1,270	360.81	0.284	57.05	4
	2,788.7	3,039.3	2,914	767.32	0.263	121.33	6
Convex wedge	530.8	657.2	594	135.16	0.227	21.37	2
	1,010.3	1,365.7	1,188	254.77	0.214	40.28	4
	1,287.8	1,632.2	1,460	279.01	0.191	44.12	6

Simulation of stresses

The first necessary step was to create a finite element mesh. The mesh set is made up of volume elements, and the software allows the selection of one of the following types of elements (Fig. 3):

a) A draft-quality mesh is created by generating linear tetrahedral volume elements.
b) A high-quality mesh is generated by the software using parabolic tetrahedral volume elements.

A linear tetrahedral element is defined by four corner nodes, connected by six straight edges. Parabolic tetrahedral element is defined by four corner nodes, six central nodes, and six edges. Figure 3 is a schematic representation of the linear and parabolic tetrahedral volumetric elements.

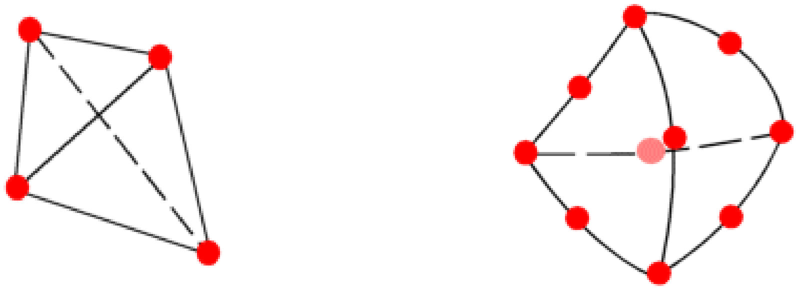

Fig. 3. Network of finite elements - linear tetrahedral element (left) and parabolic tetrahedral element (right)

Generally, for the same mesh density (number of elements), better results can be obtained using the parabolic elements than linear due to:

- More accurate representation of curved boundaries,
- Providing better mathematical approximations.

In the construction configurations, each node has, for a volume element, three degrees of freedom, representing displacement in the three orthogonal directions. The software uses the directions X, Y, and Z of a global Cartesian coordinate system for formulating problems.

For purposes of simulation, a mesh consisting of tetrahedral volume elements was used. For accurate simulations, refinement of the mesh (increasing the number of elements) of finite elements on the contact surface of wedge and samples was used. This is shown in Fig. 4, to refine the network using 45° wedge and pressing depth of 6 mm. With increasing depth of pressing, the contact areas are increasing, and the mesh becomes finer, but it is just sufficient to record the changes in the wood.

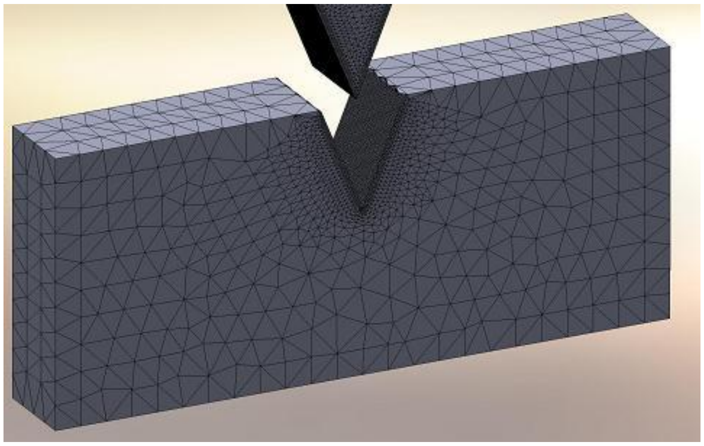

Fig. 4. Demonstration of refinement tetrahedral network elements at 45° wedge and pressing depth 6 mm

Calculation

Density, examined in preliminary tests, was calculated according to Equation 1 from ISO 3131 (1975),

$$\rho_w = \frac{m_w}{a_w * b_w * l_w} = \frac{m_w}{V_w} \quad (1)$$

where ρ_w is the density of the test sample at certain moisture content w [kg/m^3], m_w is the mass (weight) of the test sample at certain moisture w [kg], a_w, b_w, l_w are dimensions of the test sample at certain moisture w [m], and V_w is the volume of the test sample at certain moisture w [m^3].

During the experiments it was necessary to determine and verify the initial moisture content of samples. These calculations were carried out according to ISO 3130 (1975) and Equation 2,

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

where w is the moisture content of the samples [%], m_w is the mass (weight) of the test sample with a certain moisture [kg], and m_0 is the mass (weight) of the oven-dry test sample [kg].

Drying to oven-dry state was also carried out according to ISO 3130 (1975) using the following procedure: The samples were placed in the drying oven at a temperature of 103 ± 2 ºC until constant mass was reached. Constant mass is considered to be reached if the loss between two successive weighing carried out at an interval of 6 h is equal to or less than 0.5% of the mass of the test sample. After cooling the test samples to approximately room temperature in a desiccator, each sample was weighed rapidly enough to avoid an increase in moisture content by more than 0.1%. The accuracy at weighing shall be at least 0.5% of the mass of the test sample.

RESULTS AND DISCUSSION

Figure 5 shows the progression of stresses generated by the wood during pressing of a wedge with a 45^o cutting-edge to a depth of 2, 4, and 6 mm. The red color shows the area in which the value of stress exceeds the value of 4 MPa, *i.e.* near the border of the ultimate strength for aspen wood.

The use of this wedge will cause significant stresses in the bottom part of embossment created in the direction of pressing wedge. The deformation of the surface layers occurs only to a small extent. The use of this wedge is also characterized by significant deformations in the direction perpendicular to the pressing direction of wedge, and may result in the displacement of wood layers. The directions of deformations emerging during pressing of the wedge can be observed. The zone of stress direction is parallel with the direction of pressing, and these stresses became greater with increasing depth of pressing.

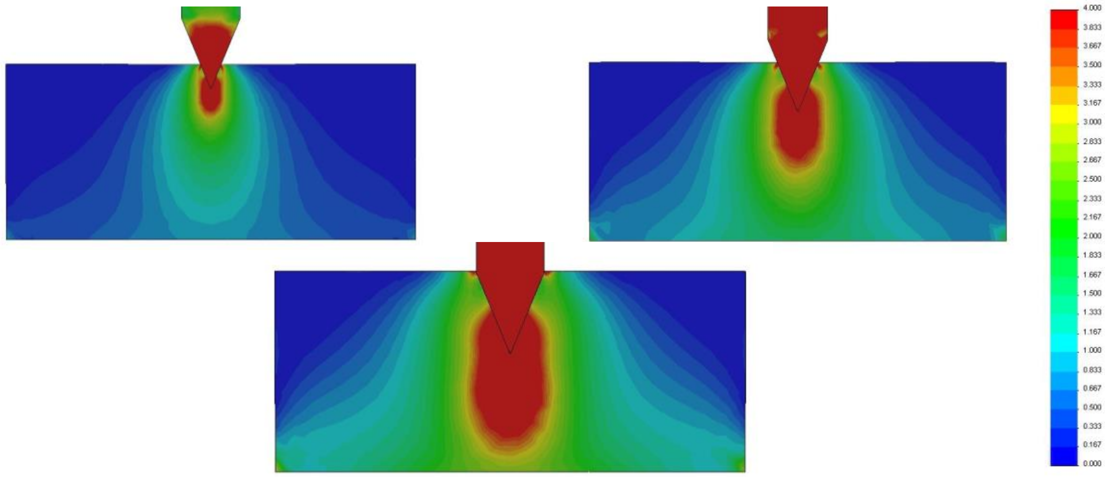

Fig. 5. Stresses in wood during pressing of 45° wedge to the depth - 2 mm (*top left*), 4 mm (*top right*), and 6 mm (*bottom center*)

Progressions of stresses arising in wood during pressing of the concave wedge to depths of 2, 4, and 6 mm are shown in Fig. 6. This wedge influences the largest area of all tested wedges. Force caused by pressing of concave wedge is not only oriented downwards, as at 45° wedge, but also runs in directions perpendicular to the pressing direction. This perpendicular force is greater than the force acting in the direction of pressing. Compared to the 45^{o} cutting-edge angle, this wedge generated stresses over a larger area, which occupied up to 95% of the thickness of the test sample. When using the concave wedge, the stresses occur in the wood around the lower part of the embossment but also in a large area below. Therefore, cracks probably arise not only inside the created embossment, but also at its bottom.

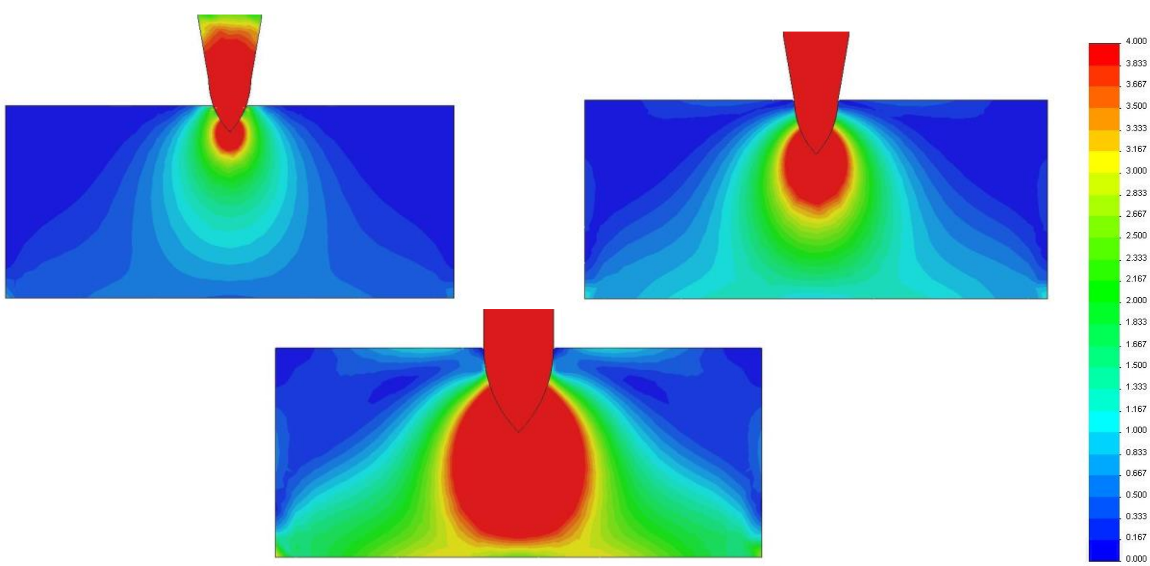

Fig. 6. Stresses in wood during pressing of concave wedge to the depth - 2 mm (*top left*), 4 mm (*top right*), and 6 mm (*bottom center*)

The progression of stresses arising in wood during pressing of the convex wedge to depths of 2, 4, and 6 mm are presented in Fig. 7. This progress is significantly different from previous ones. During pressing of convex wedge, the total force is, to a greater extent, oriented perpendicular to the tangential surface, *i.e.* in the radial direction. In this case, a predominance of plastic deformation over elastic deformations was found. This can be attributed to greater distortions of pith rays and their lower strength in this direction. Stresses that are directly within the zone under the pressed wedge were found to affect a significantly smaller area. Stresses are concentrated in the area of the embossment near the surface and in its surroundings, up to 10% depth of pressing, in the stress zone, where already at the depth of pressing 2 mm cracks occur. When using this wedge, there are no major stresses at greater depths (4 and 6 mm).

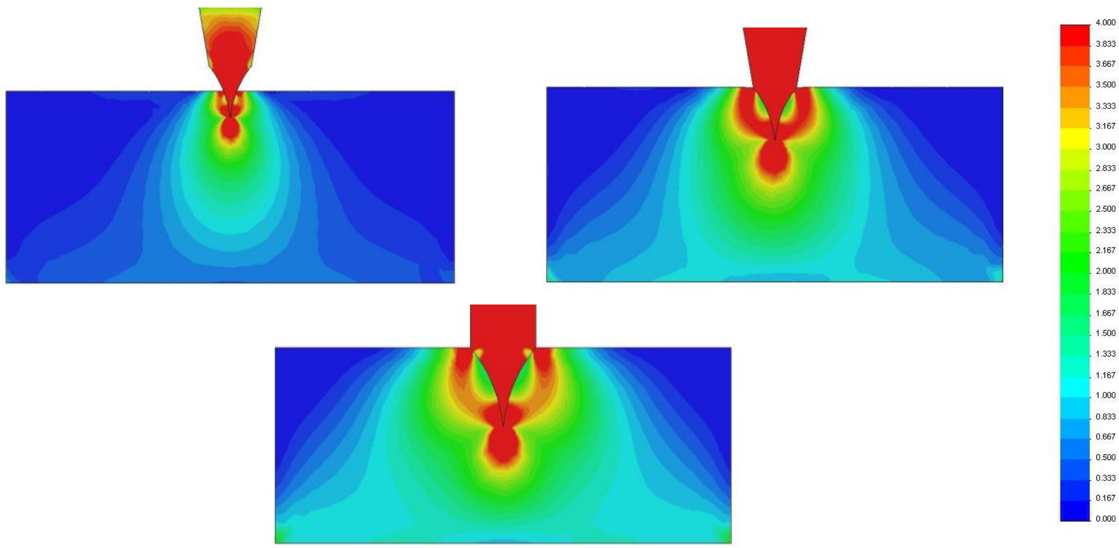

Fig. 7. Stresses in wood during pressing of convex wedge to the depth - 2 mm (*top left*), 4 mm (*top right*) and 6 mm (*bottom center*)

In general, the shape of the wedge is the first factor that affects the shape of obtained embossment. Effect of a wedge with a sharp tip depends on the cutting-edge angle α. Cutting-edge angle 60° is the limiting angle in terms of the resolutions of forces caused by the wedge. At cutting edge angles α less than 60° it is possible to achieve the resultant acting of the forces directed parallel to the wedge pressing, similar to the action of a convex wedge. Conversely, at cutting-edge angles α greater than 60°, the resulting force will be dependant on the size of the cutting-edge angle to act more in the tangential direction, much like when using a convex wedge. Figure 8 shows the wedges with different cutting-edge angles. Figure 8 *left* shows the cutting-edge angle α less than 60°, where it can be observed that the side force F_s is greater than the total force F acting vertically. By action of the wedge with this cutting-edge angle it can be expected that there will be a predominance of stresses acting in the plane where the wedge will be pressed, as compared with the stresses acting perpendicular to the plane. The opposite situation occurs under the action of wedge with cutting-edge angle α greater than 60° (Fig. 8 *right*). The figure shows a clear predominance of the total force F acting vertically to the plane of pressing compared to the side force F_s, which is smaller in this case. An interesting case is the resolution of forces in Fig. 8 *center*, where the cutting-edge angle α = 60°. In this case, the sizes of the total force F and the side force F_s are equally great. Based on this resolution of forces, it can be expected that the total resultant force will act perpendicular to the edge of the wedge according to Fig. 8 *center*. This is the worst case, in relation to the orientation of the wood fibers, since total orientation of forces to the greatest extent determines whether the shear strength of the wood is exceeded.

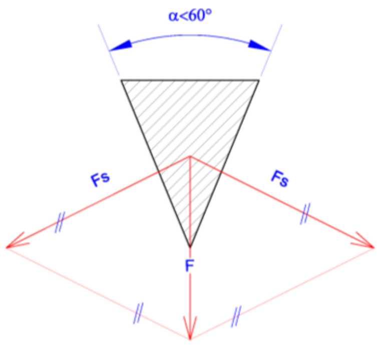

Fig. 8. Resolution of forces, depending on the cutting-edge angle - α < 60° (*left*), α = 60° (*center*) and α > 60° (*right*)

On the other hand, during embossing the stress that arises depends on the shape of the wedge. Moreover, a substantial part of this stress is also caused by wood structure. Anisotropy of wood is the basic characteristic of wood which affects embossing. The anisotropy also contributes to the different arrangement of the tracheae in the radial and tangential direction and the presence of pith rays. During embossing in the radial direction parallel to the fibers, the wedge acts to a greater extent perpendicular to the pith rays, which have in this direction less strength than in the tangential direction, wherein the pith ray is axially loaded (Kennedy 1968).

In wood with a high content of late wood, the tangential strength is often greater than the radial, while in wood with large or numerous pith rays, it is opposite. In the softwood with high amounts of late wood and a few pith rays, the elastic modulus and limit of proportionality are greater in the tangential direction (Kennedy 1968). During pressing in the radial direction, the cell walls bend flexibly toward the lumen in the first stage of linear elastic deformation, followed by the collapse of the cells of early wood. The first collapse occurs in the weakest cells of early wood, and the corresponding values range from 5 to 10 MPa (Tabarsa and Chui 2000). Kunesh (1968) and Bodig (1965) state that collapse occurs when the weakest part of the pith rays breach, and that the main function of early wood is to support pith rays, while Tabarsa and Chui (2001) claim that the strength of early wood is the directing factor for the strength in the radial pressing. The collapse continues until 30% of early wood is deformed, while late wood remains almost unaffected. Once the spring wood is deformed, further loading causes the predominant elastic deformation of late wood.

Comparison of Simulation with Real Shapes

Progressions of stresses from analysis were then compared with the real damage of the samples taken by digital camera and evaluated by *Profile* software (Fig. 9). This comparison served to validate the analysis, since cracks on test samples were created in premises where there had been the highest stresses according to simulation.

Cracks can be observed on the bottom of the embossed area, oriented in the direction of the pressing wedge, in the case of the 45^{o} wedge (Fig. 9 *bottom center*). For the concave wedge, the cracks were created in the bottom area of the embossment, which coincides with the development of stresses. For a convex wedge, stresses are created in the area of the embossment surface, generating small cracks, as demonstrated by the real impressing of the wedge.

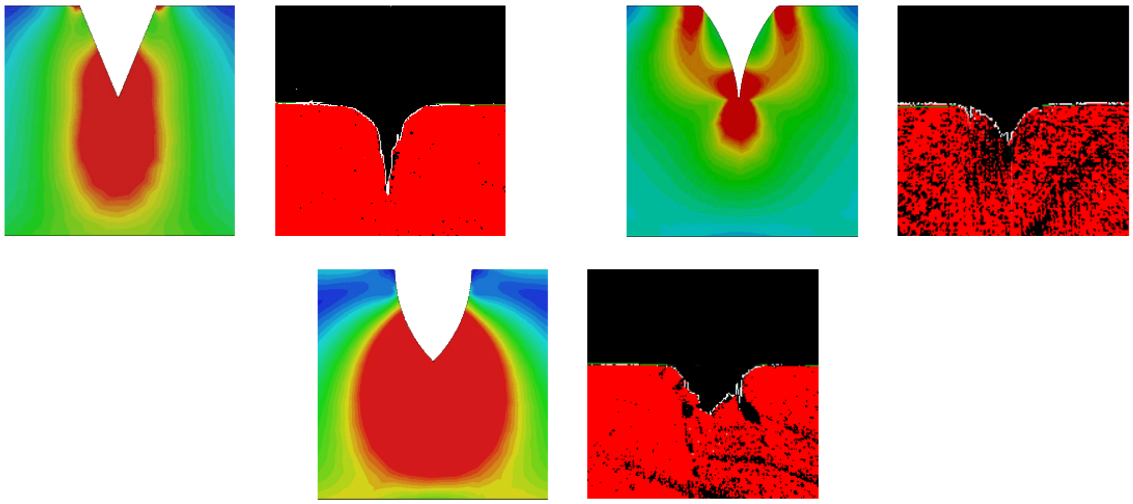

Fig. 9. Comparison of the results of simulation with real embossments - 45° wedge (*top left*), convex wedge (*top right*), and concave wedge (*bottom center*)

CONCLUSIONS

In this work, dimensional changes in aspen wood were evaluated by volumetric and linear shrinkage. This was done by identifying the influence of wedge shape and depth of pressing on progress of stresses created by uneven compression. Based on the results of this work, the following conclusions and recommendations can be made:

1. As a result of this work, it can be considered that progress has been achieved in determining the characteristics of stresses in the wood when using multiple wedges pressed to different depths. From these findings, a wedge with a 45° cutting-edge angle can be recommended, as well as the concave wedge for embossing to relatively small depths. A depth of 6 mm may lead to expected cracking.
2. A convex wedge creates stresses and therefore cracks in the surface layers. These cracks disturb the component appearance because they are visible. Therefore, the use of a wedge having a convex shape to depths of 4 and 6 mm is not recommended. If it were possible to remove the cracks in this area by pre-treatment of the surface (*e.g.*, plasticizing), or by subsequent modification of the surface and thus prevent their becoming visible, this wedge seems to be the most suitable alternative for embossing to greater depths.

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properties of wood by thermo-mechanically treatment for the creation of laminated material with specific properties."

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