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Impact of Wood Species, Dimensions and Drying Temperature on Sorption Behaviour of Wood

Utjecaj vrste, dimenzija i temperature sušenja drva na njegovu sposobnost sorpcije

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ABSTRACT • *This research paper examines the interdependence between wood sorption properties and its dimensions, species and drying temperature. The research was carried out on specimens of six species of wood (oak, ash, aspen, birch, spruce and pine) which had different dimensions and were dried at temperatures ranging between 30 and 90 °C. Subsequently specimens underwent the moistening and air drying process, and the following parameters were recorded: moistening and drying rate, moisture content distribution, steady moisture content and sorption hysteresis. It was established that sorption hysteresis was most affected by the cross section dimensions of the specimen. It was determined that, when the thickness of wood specimens increases from 7 to 30 mm, sorption hysteresis grows up to 8 times. The steady moisture content depends on the density, measurements and drying temperature of the specimen.*

Key words: *drying temperature, adsorption, desorption, moisture content, sorption hysteresis, water vapour*

SAŽETAK • *U ovom se istraživačkom radu ispituje međusobna ovisnost svojstva sorpcije drva i njegovih dimenzija, vrste drva i temperature sušenja. Istraživanje je provedeno na uzorcima izrađenima od šest vrsta drva (hrasta, jasena, jasike, bukve, smreke i bora), različitih dimenzija, sušenih na temperaturama između 30 i 90 °C. Uzorci su potom prošli proces vlaženja i sušenja na zraku te su bilježene vrijednosti ovih parametara: brzine vlaženja i sušenja, raspodjele sadržaja vode, stalnog sadržaja vode i histereze sorpcije. Utvrđeno je da su na histerezu sorpcije najviše utjecale dimenzije poprečnog presjeka uzorka. Tako je pri povećanju debljine uzoraka drva od 7 do 30 mm, sorpcija histereze rasla do osam puta. Stalni sadržaj vode ovisi o gustoći, dimenzijama i temperaturi sušenja uzoraka.*

Ključne riječi: *temperatura sušenja, adsorpcija, desorpcija, sadržaj vode, histereza sorpcije, vodena para*

1 INTRODUCTION
1. UVOD

Wood is a complex natural polymer which has a capillary, annular and layered structure. It is known that wood absorbs and evaporates water vapour, when it undergoes the moistening and drying processes. This results in sorption hysteresis, supposedly due to the difference in the sorbate filling and emptying of the pores (Popper *et al.*, 2009). Usually a sorption isotherm is expressed as the function of wood moisture and relative humidity at a constant temperature. However, scientific

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studies and modelling show that ambient temperature has also influence on sorption/desorption processes and the size of the hysteresis loop (Merakeb *et al.,* 2009). Wood drying is a complex process of heat and mass transfer, which is conditioned by some phenomena, such as heat/moisture exchange between wood and environment, and heat/moisture movement in wood (Kajalavičius, 2008). In the macrocapillary system, hygroscopic moisture moves only in the form of vapour (due to its partial pressure gradient), whereas in the microcapillary system, moisture moves in the form of both vapour and liquid (due to diffusion penetration).

A number of research projects have been carried out to evaluate the impact of various factors on wood sorption properties. The research (Esteban, 2010) examines sorption properties of *Quercus* spp. wood aged 5910 ± 250 BP, which has been recently sawn and discovered underground. It was determined that, due to the physical and chemical changes in the cell wall, the equilibrium moisture content (EMC) of the unearthed wood was higher both in case of sorption and desorption. Another paper (Huang *et al*., 2009) focuses on how the acid/alkaline balance of wood (pH) affects sorption properties of wood elements (cellulose and lignin). It was found that wood, which does not undergo chemical modification, absorbs lesser amounts of copper chloride under the same conditions than modified wood. A further paper (Nkolo Meze'e *et al*., 2008) explores the effect of temperature on sorption properties of wood exposed to water vapour at different temperatures (20 °C, 38 °C, 50 °C and 60 °C). It was established that sorption hysteresis is observed at all temperatures. In addition, the research revealed that changes in parameters, such as Gibbs energy, entropy and enthalpy, are negative in the presence of adsorption and positive in the presence of desorption, however, the amount of these changes hardly depends on temperature. Even when drying occurs at relatively low temperatures, there are residual phenomena which alter the further behaviour of wood. Higher temperature drying causes the following changes to the chemical composition of wood: hemicellulose, lignin and extractive substances begin to decompose, and cellulose becomes more crystalline (Esteves and Pereira, 2009). As a result of the reduced number of hydroxyl groups, wood tends to be more hydrophobic. Furthermore, due to a more crystalline structure of cellulose, water cannot easily enter cell walls of wood, which leads to a decrease in the EMC of heated wood (Akyildiz and Ates, 2008). The higher the temperature, the greater the change in the chemical structure of wood and the lower the EMC.

Scientists developed various mathematical models on the basis of which it would be possible to predict wood moisture content under changing conditions and moisture movement in wood (Svensson *et al*., 2011; Krabbenhoft and Damkilde, 2004). Other research papers provide two-dimensional and three-dimensional computer models imitating the wood drying process (Turner, 1996; Truscott and Turner, 2005). The paper by Merakeb *et al.* (2009) presents a model for wood sorption hysteresis, when wood undergoes moistening and drying in the environment of different parameters. A universal model was designed that can describe actual wood moistening/drying processes. Authors of another article carried out research into moisture movement in layered porous building structures (Johannesson and Janz, 2009). It was determined in the above mentioned papers that, when moisture moves in the form of both steam and water, sorption and desorption processes occur according to slightly different principles due to sorption hysteresis.

The examination of sorption properties of six species of wood (China fir, Japanese cedar, Western hemlock, red oak, red meranti and hard maple) under conditions of high relative humidity (RH) allowed establishing that, when RH varied from 40 % to 0 %, there was no noticeable difference in the EMC, however, when RH changed from 100 % to 50 %, some differences were observed: when RH was lower than 90 %, coniferous wood had a higher moisture content in comparison to hardwood; however, when RH was higher than 90 %, hardwood had higher EMC (Wang and Liau, 1998). The assessment of the effect of temperature on the EMC of Pine radiata wood under pure saturated steam conditions allowed determining that, when temperature increases, the EMC decreases in a linear dependence (Pearson *et al*., 2012). Wood moisture sorption is also affected by wood properties (its species, density, etc.), therefore, the objective of this paper is to evaluate how drying temperatures and dimensions of specimens influence sorption behaviour of wood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Tests involved the use of the highest quality, branch, crack and other visible defect–free specimens of deciduous (oak (*Quercus robur* L.), ash (*Fraxinus excelsior* L.), aspen (*Populus tremula* L.), birch (*Betula* L.)) and coniferous (spruce (*Picea abies* L.), pine (*Pinus sylvestris* L.)) wood with the following densities: 777.3, 623.9, 453.6, 627.1, 487.3, 490.3 kg/m^3, respectively. Each wood species was represented by 30 specimens with the following dimensions: 450×50×30 mm. In order to assess the effect of specimen thickness on drying, 4 separate groups of 30 birch specimens were formed with the following thickness variations: 7 mm, 12 mm, 25 mm, 30 mm, respectively. The length and width of these specimens were analogous to the ones of other specimens (450 mm in length and 50 mm in width). Prior to the start of tests, specimens underwent conditioning at the temperature of 25 °C and relative humidity ranging from 58 to 60 %. After the exposure to conditioning their moisture was 10.8 ± 0.7 %.

2.1 Equipment
2.1. Oprema

Specimens underwent moistening and drying in an environmental chamber, where temperature and relative humidity were maintained to an accuracy of 1 °C and 1 %, respectively. In order to ensure the uniform distribution of air parameters, a circulation system was installed (air velocity 0.5 – 1.0 m/s). Wood moisture content was established applying a weighing method to a precision of 0.1 %. Changes in dimensions of specimens were recorded using an electronic sliding calliper with an accuracy of 0.01 mm.

2.2 Wood sorption / desorption studies
2.2. Ispitivanja sorpcije / desorpcije drva

After the exposure to conditioning, specimens underwent moistening for 70 days at 30 °C and 90 % relative humidity. Afterwards they were subjected to drying for 20 days at the temperature of 30 °C and 30 % relative humidity. Birch specimens of different thickness were subjected to drying at the temperature of 60 °C and 6 % relative humidity. Specimens were exposed to moistening and drying until they reached steady moisture content.

In order to evaluate the effect of drying temperature on wood sorption properties, oak, ash, pine, spruce and aspen specimens were divided into three groups (1.1; 1.2; 1.3), and each group underwent drying at different temperatures (the first group at the temperature of 30 °C, the second group at the temperature of 60 °C and the third group at the temperature of 90 °C) and 30 % relative humidity. Then specimens were subjected to conditioning for a two week period at 20 °C and 55 ± 5 % relative humidity and were repeatedly exposed to moistening at 30 °C and 90 % relative humidity. Subsequently specimens were dried at 30 °C and 30 % relative humidity. In order to assess changes in moisture and dimensional stability, specimens underwent mass and dimensional measurement.

3 RESULTS
3. REZULTATI

3.1 Adsorption
3.1. Adsorpcija

Figure 1 shows changes in moisture content of specimens of different wood species (a) and of different dimensions (b) by storing them in an environmental chamber for 70 days at 30 °C and 90 % relative humidity. The equilibrium moisture content of wood should be approximately 22.0 % in this case (Sergovskij and Rasev, 1987).

Figure 1(a) reveals that the highest moisture content was adsorbed during the first 7 days, i.e. moisture content alteration was up to 54 %. The largest change in moisture content was observed in oak specimens (54 %), the smallest change occurred in pine specimens (35 %); however, as a result of the further moistening process, oak wood adsorbed a noticeably lower moisture amount than other wood species. It was determined that during the moistening process all species of wood specimens, which were 30 mm thick, achieved a steady moisture content within 7 weeks (this moisture content ranged from 19.2 to 19.6 % and specimens failed to reach the theoretical moisture content). Fig. 1 shows (b) that thinner specimens achieved this moisture content in a shorter period of time, i.e. within 5-6 weeks. Furthermore, in comparison to 30 mm thick specimens, thinner specimens had higher steady moisture content as follows: 25 mm – 7 %, 12 mm – 13 %, and 7 mm – 20 %, respectively.

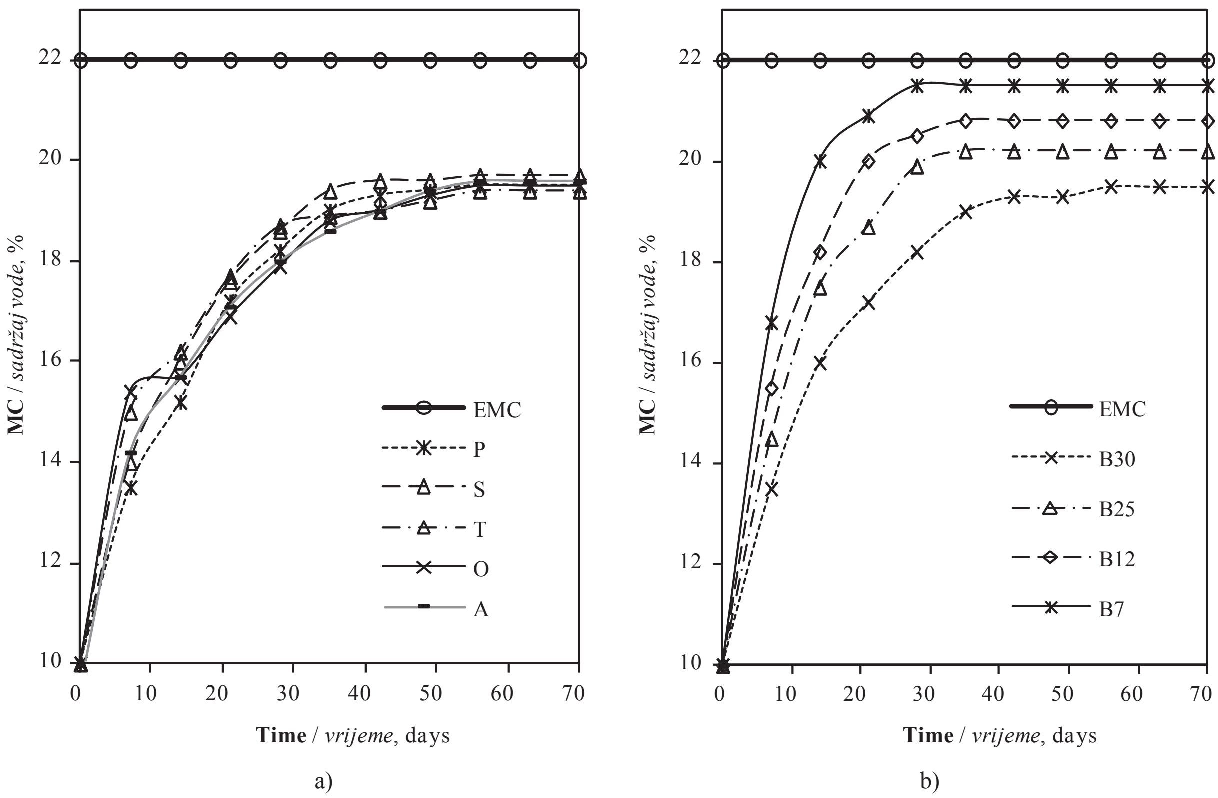


Figure 1 Changes in wood moisture content during the moistening process: a) oak (O), ash (A), spruce (S), pine (P) and aspen (T) specimens; b) birch (B) specimens
Slika 1. Promjene sadržaja vode drva tijekom procesa vlaženja: a) uzorci hrasta (O), jasena (A), smreke (S), bora (P) i jasike (T); b) uzorak breze (B)

3.2 Desorption
3.2. Desorpcija

Afterwards the same specimens underwent drying at the temperature of 30 °C and 30 % relative humidity, while birch specimens were dried at 60 °C and 6 % relative humidity. In this case the equilibrium moisture content should be 6.2 % and 2.2 %, respectively (Sergovskij and Rasev, 1987). Figure 2 reveals changes in wood moisture content depending on drying duration and specimen thickness. Figure 2 (a) shows that the drying tendencies of 30 mm thick specimens of different types of wood were similar and wood did not reach the equilibrium moisture content. It was found that the moisture content of specimens ranged between 7.1 and 7.5 % and differed from the equilibrium moisture content by 0.9 – 1.3 %.

It was found (Fig. 2, b) that during the drying process birch specimens of 30 mm thickness also failed to reach the theoretical equilibrium moisture content and had 3.3 – 3.4 % moisture content after the drying period of 20 days, whereas, thinner specimens (7 mm, 12 mm, 25 mm) achieved this theoretical equilibrium moisture content (2.2 %). In addition, 7 and 12 mm thick birch specimens reached this moisture content within 8 – 10 days and in the case of 25 mm thick specimens it was achieved within 10 – 12 days. These processes occur due to the moisture content gradient (Eq. 1), since wood specimens have uniform distribution of temperature and pressure, and their moisture content does not exceed the fibre saturation point (Kajalavičius, 2008).

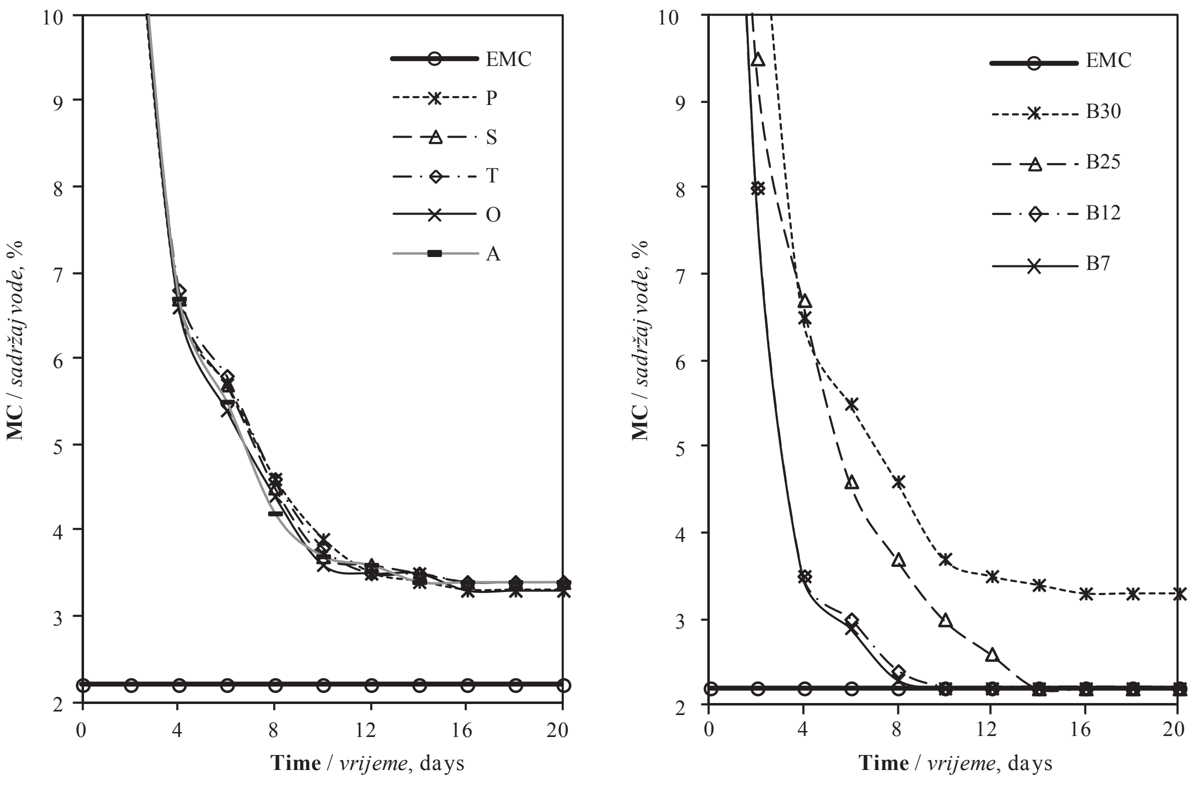
$$i = -a' \cdot \rho_0 \cdot \frac{du}{dx}, \tag{1}$$

here i – moisture flux density; a' – moisture diffusion coefficient; ρ_O – wood density when moisture is 0 %; $\frac{du}{dx}$ – moisture content gradient.

3.3 Drying impact
3.3. Utjecaj sušenja

In order to examine the effect of drying temperature on wood sorption properties, specimens underwent drying at different temperatures without air moistening. Oak, ash, pine, spruce and aspen specimens assigned to subgroup 1.1 were subjected to drying at the temperature of 30 °C until they reached steady moisture content conditions, specimens attributed to subgroup 1.2 were exposed to drying at the temperature of 60 °C and specimens attached to subgroup 1.3 were dried at the temperature of 90 °C during the same period of time. Table 1 provides mean moisture content of specimens of the above-mentioned groups and the range of moisture content values of each subgroup after drying. The initial moisture content of wood specimens was 12 % ± 0.5 %.

Table 1 shows that, when specimens underwent drying at the temperature of 30 °C, they achieved 10.2–11.2 % moisture content after a two week period, and when they were subjected to drying at the temperature of 90 °C, 1.9 – 2.5 % moisture content was reached during the same period of time. When the range of



a) b)

Figure 2 Changes in wood moisture content during the drying process: a) oak (O), ash (A), spruce (S), pine (P) and aspen (T) specimens; b) birch (B) specimens

Slika 2. Promjene sadržaja vode drva tijekom procesa sušenja: a) uzorci hrasta (O), jasena (A), smreke (S), bora (P) i jasike (T); b) uzorak breze (B)

Table 1 Mean moisture content of specimens dried at different temperatures and the range of moisture content values (coefficient of variation)
Tablica 1. Prosječna količina sadržaja vode u uzorcima sušenim pri različitim temperaturama te raspon vrijednosti sadržaja vode (koeficijent varijacije)

Wood species *Vrsta drva*	**Drying at 30 °C** *Sušenje pri 30 °C*	**Drying at 60 °C** *Sušenje pri 60 °C*	**Drying at 90 °C** *Sušenje pri 90 °C*
	MC, % (Coef. of Var.)	MC, % (Coef. of Var.)	MC, % (Coef. of Var.)
Oak / *Hrast*	10.5 (3.5)	5.8 (3.4)	1.9 (4.4)
Ash / *Jasen*	10.8 (3.7)	5.7 (3.8)	2.5 (4.0)
Spruce / *Smreka*	11.2 (3.3)	4.7 (3.9)	2.2 (4.4)
Pine / *Bor*	10.8 (3.5)	5.7 (3.8)	2.3 (4.1)
Aspen / *Jasika*	10.2 (3.7)	4.5 (4.2)	2.2 (4.5)

moisture content values was assessed, it was established that the greatest range of moisture content values was observed in specimens subjected to the highest temperature drying – the coefficient of variation ranged from 4.1 to 4.5 %, meanwhile, in the case of specimens dried at the temperature of 30 °C, the range of moisture content values was smaller by 17.8 – 19.5 % - the coefficient of variation ranged from 3.3 to 3.7 %.

In order to evaluate changes in sorption behaviour of specimens dried at different temperatures, specimens underwent conditioning for two weeks at 20 °C and 50 – 60 % relative humidity, and achieved 8 % ± 0.5 % moisture content. Afterwards specimens were exposed to moistening at 30 °C and 90 % relative humidity. Figure 3 reveals the main principles of changes occurring in moisture content of specimens during the moistening process.

Figure 3 shows that, when specimens underwent the moistening process, they adsorbed the highest moisture content during the first week. The mean moisture content of coniferous wood increased from 7.8 – 8.0 % to 13.6 – 13.9 %, i.e. approximately 74 %, and the average moisture content of deciduous wood rose from 8.0 – 8.3 to 11.8 – 12.1 %, i.e. about 48 %. Specimens subjected to drying at the temperature of 30 and 60 °C, achieved a steady moisture content within 56 days. In the case of coniferous wood, this moisture content was 20.1 % on average at respective drying temperatures and in the case of deciduous wood it was 19.8 and 19.6 % at respective drying temperatures. Specimens exposed to drying at the temperature of 90 °C, reached a steady moisture content within 63 days. In the case of coniferous wood it was 19.0 % and in the case of deciduous wood it was 19.2 % on average.

Figure 3 (b) reveals that, when deciduous wood reaches moisture content up to 14 %, aspen and ash specimens, in contrast to oak specimens, absorb noticeably higher moisture content up to the 14th day of the moistening process (after 7 days the moister content reached by aspen and ash specimens was higher by 15 % and 10 % than the one absorbed by oak specimens). This can be explained by different densities of oak, ash and aspen wood (density of oak wood was

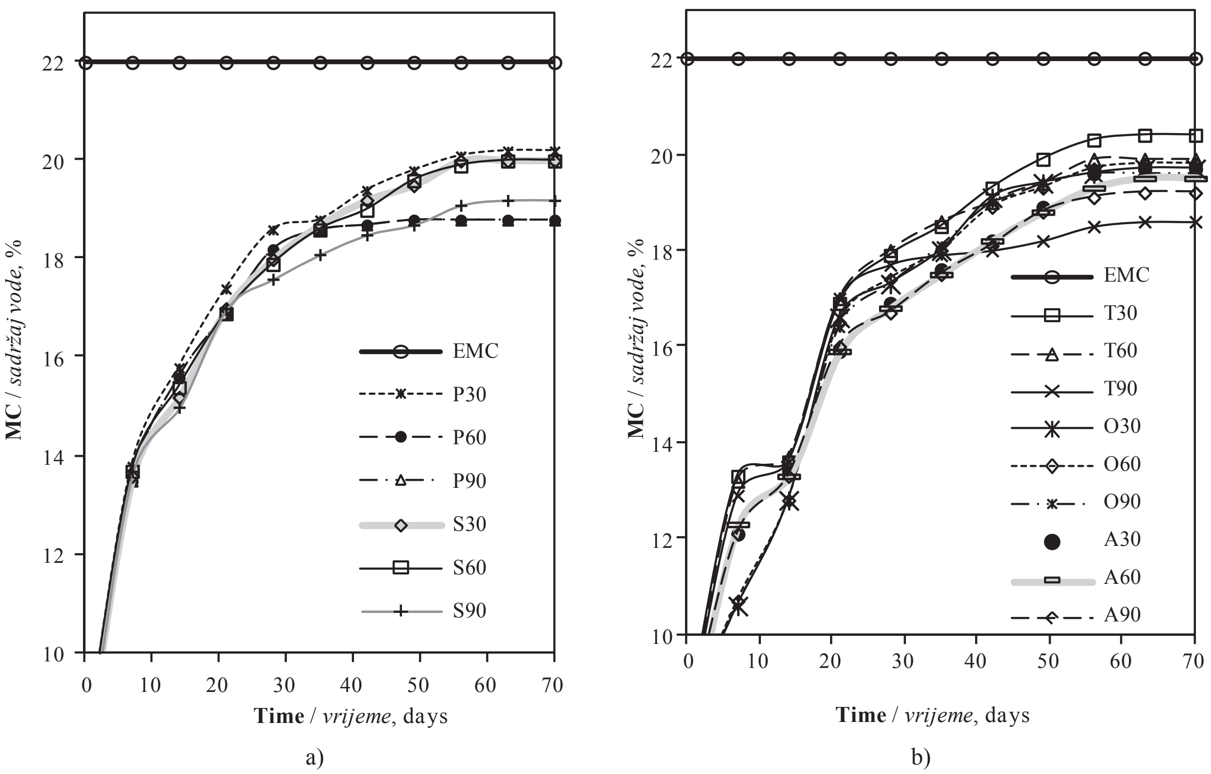
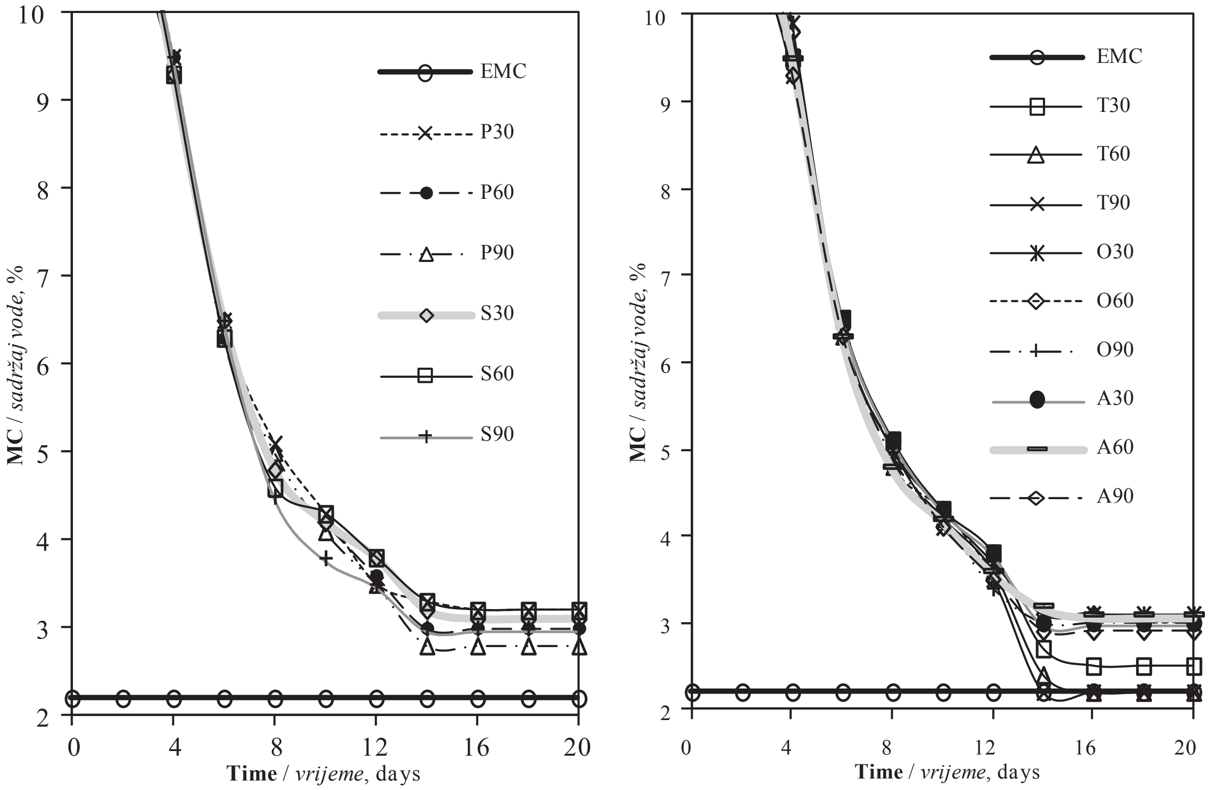


Figure 3 Changes in moisture content of specimens dried at different temperatures during the moistening process: a) coniferous wood, P – pine, S – spruce; b) deciduous wood, T – aspen, O – oak, A – ash
Slika 3. Promjene sadržaja vode u uzorcima sušenim pri različitim temperaturama tijekom procesa vlaženja: a) crnogorično drvo, P – bor, S – smreka; b) bjelogorično drvo, T – jasika, O – hrast, A – jasen



a) b)

Figure 4 Changes in moisture content of specimens dried at different temperatures during the drying process: a – coniferous wood, P – pine, S – spruce; b – deciduous wood, T – aspen, O – oak, A – ash
Slika 4. Promjene sadržaja vode u uzorcima sušenim pri različitim temperaturama tijekom procesa sušenja: a) crnogorično drvo, P – bor, S – smreka; b) bjelogorično drvo, T – jasika, O – hrast, A – jasen

20 % higher than ash wood and 42 % higher than aspen wood).The higher the density of wood, the smaller the internal surface of cell cavities, whose holes contain bound moisture. Meanwhile lower density wood is characterized by a relatively larger surface area, therefore at the beginning of the moistening process it adsorbs more moisture. This can be observed in the case of aspen and partially in the case of ash (see Figure 3 (b)). However, after some time moisture penetration into deeper layers of lower density wood becomes slower as a result of a smaller number of microcapillaries. In higher density wood, moisture adsorption tends to be slower but steadier. Subsequently the moisture content becomes equal and similar to the one of deciduous wood until the 21st day.

Afterwards, specimens underwent drying at 30 °C and 30 % relative humidity. Figure 4 shows the main principles of changes in moisture content of specimens during the drying process.

When specimens were exposed to drying, the largest change in moisture content was recorded during the first 6 days: the moisture content of specimens decreased by about 50 % (from approximately 20.0 % to 9.1 – 9.7 %). Subsequently the drying process was slowed down. Specimens achieved steady moisture content within 14 – 16 days. The figure reveals that, after exposure to the temperature of 90 °C, coniferous and deciduous wood reached 6.8 – 7.2 % and 6.2 – 7.0 % moisture content, respectively. The mean moisture content of specimens dried at the temperature of 30 °C was 7.1 – 7.2 % in the case of coniferous wood and 6.2 – 7 % in the case of deciduous wood. Figure 4 also shows that coniferous specimens failed to reach the theoretical steady moisture and in the case of deciduous wood it was achieved only by aspen specimens.

4 DISCUSSION AND CONCLUSIONS
4. RASPRAVA I ZAKLJUČCI

Tests show that specimens with larger cross sections, in contrast to specimens with smaller cross sections, reach steady moisture content after longer periods of time. This occurs because the moisture content gradient was the only major force to drive moisture in the present case. In both sorption and desorption cases, specimens with larger cross sections have uneven distribution of moisture content and their deeper layers fail to achieve the equilibrium moisture content (as a result of weaker forces that drive moisture). At the temperature of 30 °C, sorption hysteresis depends on thicknesses of specimens: in the case of 30 mm thick birch specimens, the change in hysteresis was 3.5-3.8 %, and in the case of 25 mm, 12 mm and 7 mm thick birch specimens, it was 1.8 %, 1.2 % and 0.5 %, respectively. In addition, sorption behaviour is also affected by drying temperatures of specimens. Specimens with uniform cross sections, which undergo drying at higher temperatures during the same period of time, reach lower moisture content (specimens dried at the temperature of 30 °C, 60 °C and 90 °C achieved up to 10.2 – 11.2 %, 4.5 – 5.8 %, and 1.9 – 2.5 %, respectively). Furthermore, the greatest range of moisture content values was observed in specimens with the lowest moisture content. This could be explained by different wood structure along the moisture transport direction. When wood is dried at higher temperatures, the distribution of moisture is more uneven along the cross-section of wood than it is in the case of low-temperature drying. Other research revealed that, when wood undergoes drying, wood cells are exposed to extremely high stresses and cell walls develop microcracks (Thuvander *et al*., 2001; Thuvander *et al*., 2002). Even when drying occurs at relatively low temperatures, there are residual phenomena that affect further behaviour of wood. It is known that subjecting wood to drying already at 50 – 60 °C leads to a decline in its hygroscopy (Sergovskij and Rasev, 1987).

Research showed that w,hen specimens underwent the moistening process, they adsorbed the highest amount of moisture during the first week. Besides, the mean moisture content of coniferous wood increased by 26 % more than deciduous wood. This could be explained by the fact that the sorption rate of coniferous wood was higher than that of deciduous wood during this period due to different wood microstructure and chemical composition of coniferous and deciduous wood. The major portion of coniferous wood consists of tracheids, which may reach a length of roughly 5 mm. Moisture can rather easily penetrate superficial layers of wood through cut open tracheids and later through bordered pit pairs into other cells. Deciduous wood is denser and its libriform fibre cells are only 1 mm in length, therefore, moisture penetration into wood layers is slower. Moreover, coniferous wood has more cellulose with free hydroxyl groups. Further wood moistening leads to substantially slower moisture penetration, as the moisture content of superficial layers of specimens approaches the fibre saturation point under those conditions and water molecules are forced to reach deeper layers.

Results revealed that, when specimens were subjected to drying, the difference between the equilibrium moisture content and steady moisture content of coniferous wood and deciduous wood was 1.8 – 2.0 % and 1.6 – 2.3 %, respectively, and when specimens were exposed to drying at the temperature of 90 °C, it was 2.8 – 3.2 % and 2.4 – 3.4 %, respectively. When wood specimens were dried at the temperature of 30 °C and 90 °C, sorption hysteresis for coniferous wood was 2.8 – 3.0 % and 3.1 – 3.6 %, respectively, and for deciduous wood 1.9 – 3.2 % and 3.0 – 3.4 %, respectively. Obviously thickness of the specimens, but not drying (heating) temperature, has a greater effect on the width of the hysteresis loop. Research carried out by other authors demonstrates that ,after the completion of the drying process, moisture is unevenly distributed along the cross-section of specimens (internal layers retain more moisture than external layers), which results in the formation of internal stresses (Kowalski and Musielak, 1999). Specimens with smaller cross-sections tend to have more considerable shrinkage/swelling on a relative basis (Stöhr, 1988). It is known that there is dependence between the hysteresis loop and the measurements of the specimen (Sergovskij and Rasev, 1987). The smaller the cross-section of the specimen, the smaller the hysteresis loop. The research also showed that coniferous specimens failed to reach the theoretical steady moisture, and in the case of deciduous wood, it was achieved only by aspen specimens. This can be explained by the existing hysteresis loop during drying process and by the fact that coniferous wood and lower density wood have better moisture and gas permeability (especially across the fibre) (Kajalavičius, 2008). Since the moisture content gradient was the only major force to drive moisture in the present case, it was probably insufficient to ensure the moisture content that would be even and equal to the equilibrium moisture content through the entire cross section. Tests reveal that, in the presence of higher temperature drying, the total pressure gradient has significant effect on the moisture transport phenomena (Remki *et al*., 2012).

The obtained results demonstrate that wood, which has different measurements and undergoes drying at different temperatures, is characterized by different sorption behaviour. This is relevant when it is necessary to examine the probable behaviour of wood and to exploit wood under certain conditions.

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Log Splitter Design and Construction

Projektiranje i konstrukcija uređaja za cijepanje drva

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ABSTRACT • *Heating by solid fuels, and especially fire wood, belongs to the most asked and requested types of heating in cottages. One of the main problems of heating is wood splitting as a first operation. A very useful tool for splitting of wood material is a log splitter. This contribution is focused on how to apply a screw type log splitter in wood splitting. A set of experiments have been realized to get an appropriate shape of the splitting cone, which will provide an improved splitting action. The cone has been manufactured on the basis of the experimental results. The experimental apparatus has been developed to determine the validity of the splitting cone and its geometry design.*

Keywords: *log splitter, splitting cone, material selection, tool geometry, wood splitting*

SAŽETAK • *Grijanje na kruta goriva, posebno na drva za ogrjev, pripada među najčešće vrste grijanja u vikend kućama. Jedan od glavnih problema tog načina grijanja jest potreba cijepanja drva prije loženja. Vrlo koristan alat za cijepanje drvnog materijala jest cjepač drva. Ovaj je rad usmjeren na specifičnu upotrebu vijčanog tipa cjepača drva koji znatno olakšava cijepanje drva. Klin za cijepanje drva proizveden je na bazi eksperimentalnih rezultata istraživanja. Razvijena je eksperimentalna oprema za cijepanje drva kako bi se ispitala valjanost klina za cijepanje i njegova geometrija.*

Ključne riječi: *cjepač drva, klin za cijepanje, odabir materijala, geometrija alata, cijepanje drva*

1 INTRODUCTION
1. UVOD

Wood is an important natural resource, one of the few that are renewable. It is prevalent in our everyday lives and economy, in wood-frame houses and furniture; fence posts and utility poles or fire wood. The anatomical structure of wood affects strength properties, appearance, resistance to penetration by water and chemicals, resistance to decay, pulp quality, and the chemical reactivity of wood. Many mechanical properties of wood, such as bending and crushing strength and hardness, depend upon the density of wood; denser woods are generally stronger.

Wood is a complex polymeric structure consisting of lignin and carbohydrates, which form the visible lignocellulosic structure of wood. Minor amounts of other organic chemicals and minerals are also present, but not contributing to wood structure. The organic chemicals are diverse and can be removed from the wood with various solvents. The minerals constitute the ash residue remaining after ignition at a high temperature (Kretschmann, 2007).

Heating by solid fuels, and especially fire wood, belongs to the most asked and requested types of heating in cottages. With increasing costs of electric energy and gas, the traditional type of fuel comes into attention also by people living in family houses. One of the

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main problems of heating is wood splitting as a first operation.

A very useful tool for splitting of wood is a log splitter. Splitting a log is a hard work, whether you do it with an axe or with sledgehammer and wedge. The cone achieves a high degree of efficiency because of its shape and weight.

This contribution is focused on how to apply a splitting cone in log splitting. The cone has a tapered conical shape, which extends from a pointed forward end to an enlarged diameter base. A log to be split is positioned contiguous to the pointed end of the cone. As the cone rotates, its threads draw the log onto progressively larger diameter portions of the cone, causing the log to split apart. This cone provides an improved splitting action, and is relatively easy and cheap to build. Moreover, it prevents logs from becoming stuck on the base part. The disadvantage could be the safety of the operator, because with loose clothes there is a risk of getting caught in the rotating cone or the cone can be dangerous if it becomes stuck in the log. Although a good log splitter can save the operator hours of work with a maul, it is not possible to make it 100 percent safe. Many occupational diseases and injuries occur in forestry and wood processing industry (Suchomel *et al.*, 2011), and therefore work safety is very important. A safety zone should be established around the splitter to prevent injury from flying splinters of wood.

2 THEORETICAL BACKGROUND
2. TEORIJSKE OSNOVE

Fracture mechanics is a series of models used to describe the influence of cracks and defects on material behaviour. The work of Griffith (Griffith, 1921) proved that cracks and defects dictate the strength of material more than any other single feature. He arrived at a formula for the fracture stress:

$$\sigma_{crack} = \sqrt{(E \cdot R / \pi \cdot a)} \tag{1}$$

where E is Young's modulus, R the specific work of fracture and a the size of the crack that extends through the thickness of the body. It can be seen that σ_{crack} depends upon both stress and size of crack, not just stress alone. The cracking stress is high when the crack size is small and vice versa. There is a critical crack length below which the crack will not run for a given applied stress, and a critical applied stress below which a crack of given length will not run. The lowest possible value for R is the thermodynamic surface free energy Υ that Griffith believed was correct for his experiments on glass, so he wrote Υ in place of R.

Fracture mechanics deals with the whole field of stress and strain around discontinuities to determine the critical loads for fracture. Formulae for stress intensity K has the general form

$$K = \sigma\sqrt{(\pi \cdot a)} \cdot Y \cdot (a / W) \tag{2}$$

where s is applied stress and a is the size of the crack (in general, 'size' may be length, half-length, depth of the crack depending on circumstances; for a small crack in a large plate, a is the half-length of the crack that extends through the thickness of the body). W is some characteristic dimension of the cracked body. $Y(a/W)$ is a non-dimensional 'shape factor' that depends on the geometry of the body, orientation of crack and the way in which loads are applied.

When a cracked body is loaded, a stress intensity appears around the crack tip and if the body is unloaded before cracking occurs, K disappears in the same way that stress (or indeed strain) increases or decreases in a flawless body. However, experiments show that cracking takes place at a critical value of the stress intensity factor, called K_C, and this becomes another mechanical property to indicate resistance to cracking. Then, for fracture at stress σ_{crack},

$$K_c = \sigma_{crack}\sqrt{(\pi \cdot a) \cdot Y \cdot (a / W)} \tag{3}$$

where K_C has peculiar units $N/m^{3/2}$.

Comparison of Eq. (3) and the Griffith expression (1) shows that

$$K_c^{\,2} = E \cdot R \tag{4}$$

where K_C is a combination of two parameters, i.e. Young's modulus E and the specific work of fracture R. The attainment of a critical stress intensity factor at fracture is the same as satisfying an energy-based criterion determined from the integrated stress and strain fields around the crack and in the body generally. $Y(a/W)$ generalizes the Griffith formula to any type of cracked body.

Stress intensity factors are often written with Roman number subscripts I, II or III. The subscripts represent the mode of cracking, i.e. the way in which separation occurs at the crack tip. Mode I refers to crack opening by simple tension; mode II to in-plane shear cracking where the crack faces slide along one another; mode III also refers to shear, but to cracking by out-of-plane (twisting) sliding motion across the crack faces (Figure 1). The notation is sometimes used inconsistently, since a subscript I is often employed to indicate tensile cracking in plane strain (thick plates, where the critical stress intensity factor K_{IC} is least owing to high hydrostatic stresses, thus leading to conservative design), whereas it is just as possible to have tensile cracking under plane stress (thin sheets) where toughness is greater owing to less constraint). A further confusion is that critical stress intensity factors are sometimes called the 'fracture toughness'. Fracture toughness means the specific work of cracking R. In

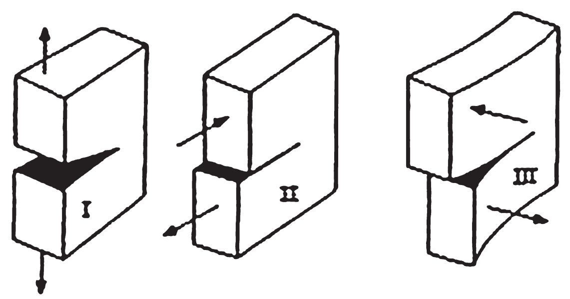


Figure 1 Types of cracks
Slika 1. Vrste pukotina

any case, much cracking takes place in mixed mode, meaning that the crack opening has both tensile and shear components, as when the path of cracking is curved (Atkins, 2009; Smith *et al*., 2003).

Some investigations on the fracture behaviour of wood in relation to its microstructure were reported by Stanzl-Tschegg (2006). The fracture properties of different hard- and softwood species have been characterized by the wedge splitting technique (Tschegg, 1986) as a rather new fracture mechanical method and were correlated with the resulting fracture morphology. With this method, not only the fracture toughness K_{IC}, but also the specific fracture energy G_f needed to completely separate a specimen, has been determined. Several parameters, which do not only determine the mechanical, but also the fracture properties, have been studied (Stanzl-Tschegg, 2006).

3 MATERIALS AND METHODS
3. MATERIJAL I METODE

At first, the material of the cone has to be chosen. In the previous study (Mečiarová and Minárik, 2012), some aspects in choosing the material were considered:

- conditions of dividing;
- properties and structure of divided wood and its amount (periodicity of cone using);
- machine tool construction (its stiffness);
- cone construction;
- material price.

When selecting a material, the most important factors to consider are hardness and ductility, especially in processes with a higher load. In addition, wood fibres can contain a natural acid, which can cause damage to machines.

Based on the above findings, four materials - steels - have been chosen for the cone production: common carbon steel/structural steel (E335), alloy special steel (16MnCr5), martensitic stainless steel (X39Cr13) and high-speed tool steel (HS10-4-3-10). Each of these steels has certain limitations, properties, structure, price and use. The surface quality of processed wood was not important in this case.

The steels X39Cr13 and HS10-4-3-10 had a better wear resistance than the steels E335 and 16MnCr5, so they are more suitable in this case. According to different total costs of selected materials (Table 1), additional experiments for material selection were carried out. In the experiments, the tooth shape and tool material have been investigated.

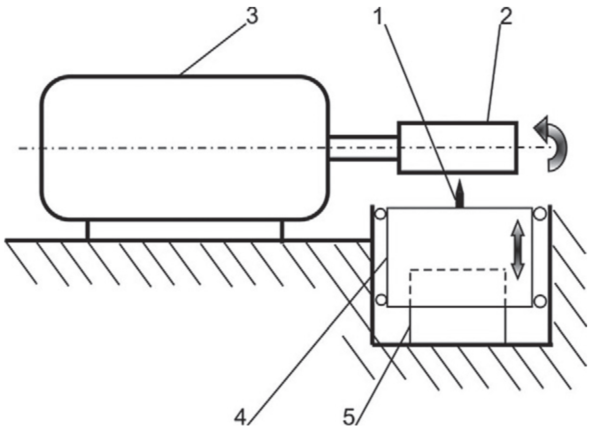


Figure 2 Scheme of mechanisms for the determination of tooth shape (1 – teeth; 2 – wood: oak, spruce; 3 – drive unit; 4 – fixture, 5 – linear support)
Slika 2. Shema mehanizma za određivanje oblika zuba (1 – zub; 2 – drvo: hrast, smreka; 3 – pogonska jedinica; 4 – učvršćenje; 5 – linearna potpora)

Selected materials and teeth specimens are shown in Table 2. The teeth specimens were pressed into the rotated wood (oak, spruce) on a machine tool (Figure 2). Cutting conditions were selected as follows: spindle speed n = 350 rev/min, depth of cut a_p = 2 mm; cutting time t_c = 1 min. The tooth behaviour during cone rotation was simulated by real conditions in the experiment. At the tooth, it comes to wear and forces action. The forces components and their interaction were analysed in detail. The teeth on the cone were designed on the basis of this analysis and the experiment (performed by Mečiarová and Minárik, 2012) has confirmed that steels X39Cr13 and HS10-4-3-10 are the most suitable for the cone production.

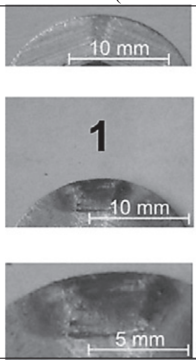
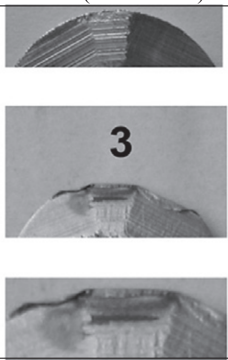
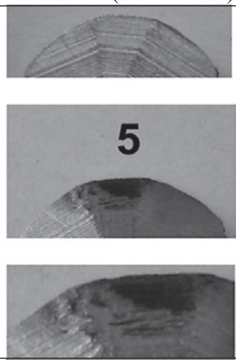
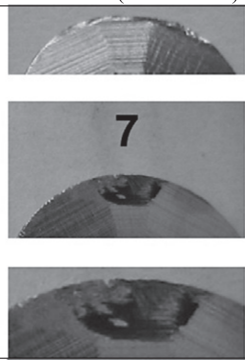
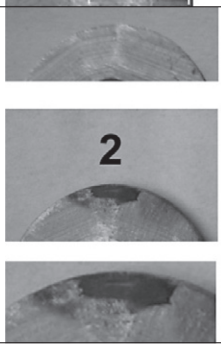
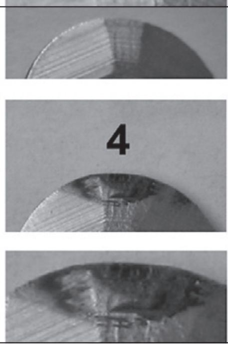
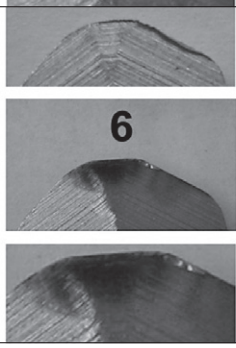
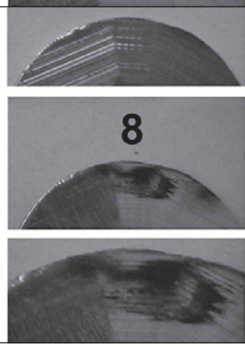
Splitting is often used with wet wood cutting, therefore the suitable material for cone production is steel X39Cr13. It is a martensitic stainless steel, which resists weak acids contained in wood fibres. Another advantage of this material is the hardness and abrasion resistance resulting in preserving ductility in product core. The disadvantage (shown in Table 1) could be the higher purchase costs, but with respect to the total costs of the machined cone and its tool life, it is not a primary criterion for its selection.

Secondly, the point angle of the cone needs to be determined. In the experiment, three cone specimens made of E335 structural steel have been used. The cone specimens (Figure 3) with point angle of 40° (cone 1), 60° (cone 2), and 80° (cone 3), were sunk into the spruce wood (*Picea abies)* with 18 percent humidity (Figure 4). Each cone had a 40 mm diameter and was

Table 1 Comparison of the total costs of selected steels
Tablica 1. Usporedba ukupnih troškova odabranih čelika

Steel / Čelik	E335 (No. 1.0060)	16MnCr5 (No. 1.7131)	X39Cr13 (No. 1.4031)	HS10-4-3-10 (No. 1.3207)
Material costs / *Troškovi materijala* (∅80 × 200)	7.03 €	15.54 €	20.35 €	27.85 €
Heat treatment costs / *Troškovi toplinske obrade*	0 €	20.75 €	20.75 €	20.75 €
Production costs / *Troškovi proizvodnje*	26.55 €	26.55 €	34.50 €	34.50 €
Total costs / *Ukupni troškovi*	33.58 €	62.84 €	67.65 €	83.10 €

Table 2 Teeth specimens
Tablica 2. Uzorci zubi

	Type of steel / *Vrsta čelika*			
	HS10-4-3-10 (No. 1.3207)	E335 (No. 1.0060)	16MnCr5 (No. 1.7131)	X39Cr13 (No. 1.4031)
Used for beech tree (*Fagus sylvatica*) *Primijenjeni za drvo hrasta*				
Used for spruce (*Picea abies*) *Primijenjeni za drvo smreke*				

applied to 9 wood specimens, making a total of 27 measurements.

While the cone specimens were sunk, the splitting force process was monitored. The results were recorded by software, which was connected with the universal strength testing machine Testometric M500-100CT with maximum operating force of 100 kN (Figure 5). Working speed was set to 10 mm/min and the measurement was carried out until the wood breakage. The specimen dimensions are shown in Figure 4.

The way how the cone penetrates the piece of wood (shown in Figure 6) and specimen stress behaviour are specific for elastic-plastic fracture mechanics.

Figure 3 Cone specimens
Slika 3. Uzorci klina

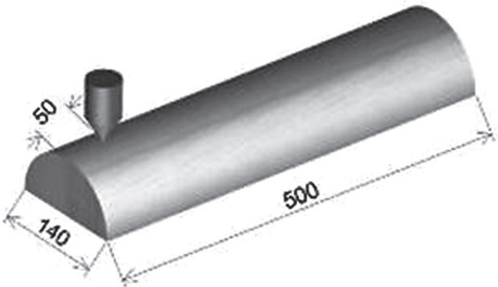


Figure 4 Geometrical parameters of a specimen
Slika 4. Geometrijski parametri uzorka

4 RESULTS AND DISCUSSIONS
4. REZULTATI I RASPRAVA

The graph (Figure 7) shows the results of splitting force monitoring. Nine measurements were made for each cone and afterwards a representative force devel-

Figure 5 Cone testing
Slika 5. Testiranje klina

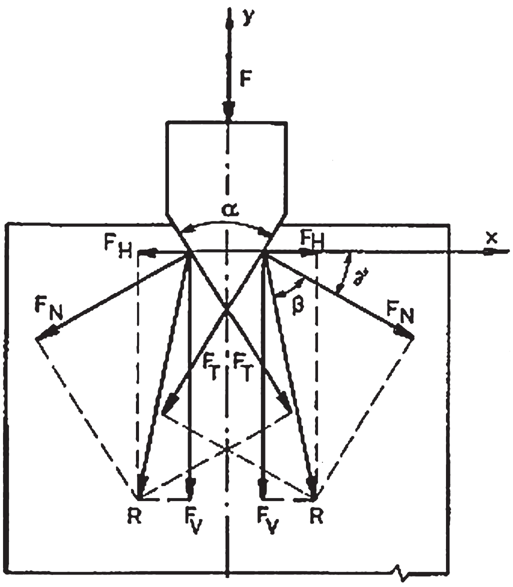


Figure 6 Resolution of forces caused by cone penetration (F – splitting force, F_H – horizontal force, F_V – vertical force, F_N – normal force, F_T – tangential force, R – resultant force, a - point angle)
Slika 6. Raspodjela sila pri prodoru klina (F – sila cijepanja, F_H – horizontalna sila, F_V – vertikalna sila, F_N – okomita sila, F_T – tangencijalna sila, R – rezultantna sila, a – kut klina)

opment was statistically chosen by median and plotted into the graph. The graph indicates that the optimal point angle is between 40 and 60 degrees. This fact has been confirmed by the calculated values of mechanical work, which represents the area below the splitting force curve. The calculation was performed in Microsoft Excel. The value for cone 1 (point angle of 40°) is represented by mechanical work of 151.3 J. Value 124.6 J belongs to cone 2 (point angle of 60°). The third value 680.8 J was calculated for cone 3 (point angle 80°). This shows that the cone with point angle of 60° (with the lowest splitting force) is the most suitable.

When splitting, it is necessary to exert a mechanical work that causes the plastic deformation. The created crack consequently helps to split the log, so it is necessary to design a broken pointed angle. At first, a smaller angle mitigates the penetration in a log and afterwards a bigger angle finishes the splitting. The cone shape was developed based on theoretical findings and obtained experimental values (Figure 8).

Finally, the cone was manufactured. Martensitic stainless steel (X39Cr13) was used as a workpiece material with dimensions ∅80 × 200 mm. At first, a clamping part with a 45 mm diameter and hole with a 24 mm diameter were machined at a lathe. Then, a roughing

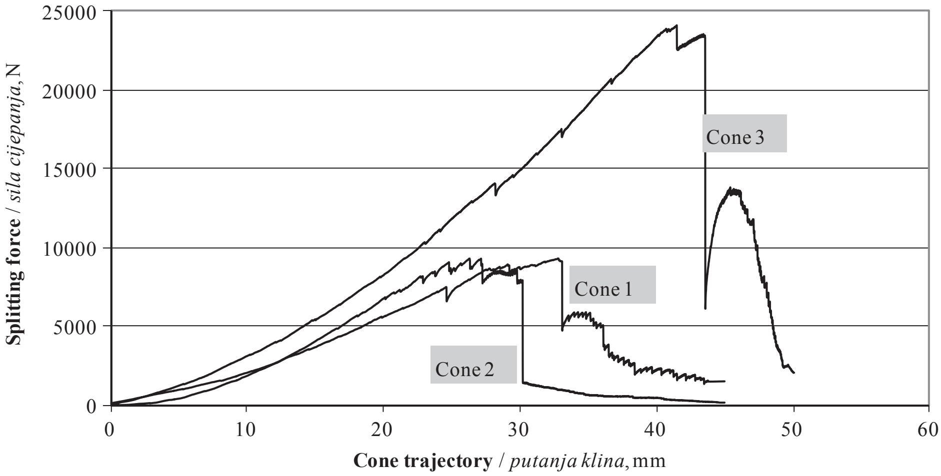


Figure 7 Splitting force process (cone 1 - point angle of 40°, cone 2 - point angle of 60°, cone 3 - point angle of 80°)
Slika 7. Promjena sile cijepanja (klin 1 – kut klina 40°, klin 2 – kut klina 60°, klin 3 – kut klina 80°)

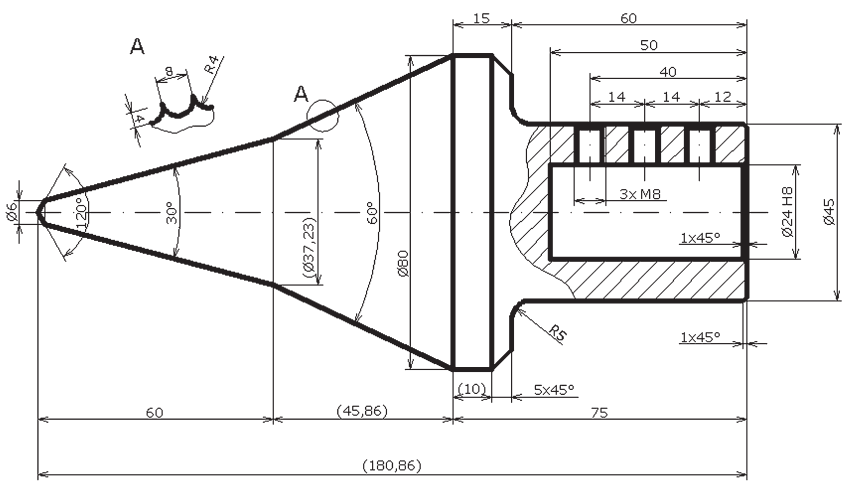


Figure 8 Design of the cone
Slika 8. Dizajn klina

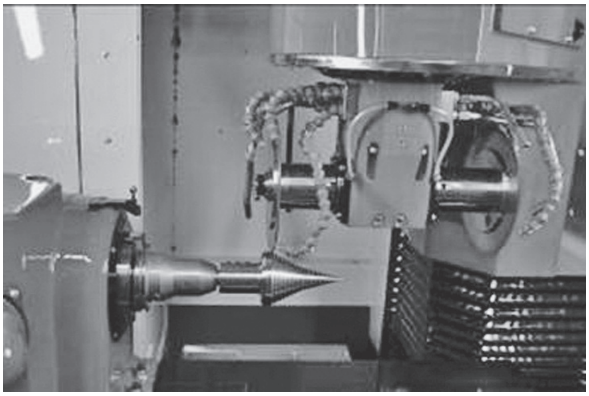


Figure 9 Manufacturing of cone
Slika 9. Proizvodnja klina

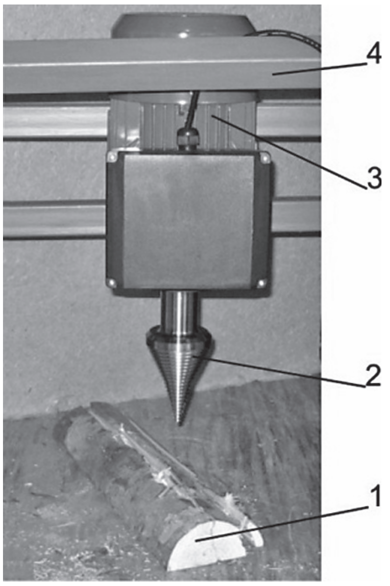


Figure 10 Experimental apparatus (1 – wood specimen, 2 – cone, 3 – electromotor / engine, 4 – frame)
Slika 10. Eksperimentalni uređaj (1 – uzorak drva, 2 – klin, 3 – elektromotor / pogon, 4 – okvir)

process was performed at a lathe with working allowance of 5 mm on the conical part. The three holes were drilled and threaded at a drilling machine for engine shaft connection. The screw teeth were produced by milling at a CNC machine tool. They were afterwards grinded (Figure 9).

The log splitter (experimental apparatus) has been developed to determine the validity of the cone and its teeth shape design (Fig. 10). The electromotor has a power of 1.5 kW and the maximum rotational speed is 1420 rev/min. The movement of the splitting cone (connected with the electromotor) into the splitting process is provided by the frame.

The initial experiments indicate that the material selection and geometry design were determined correctly. Four initial power measurements have been made with beech (*Fagus sylvatica*) specimens by using MI 2492 POWER Q instrument and the values ranged between 110 and 160 W. The maximum power of the electromotor is 1.5 kW, so obviously the splitting power is only 11 %.

5 CONCLUSION
5. ZAKLJUČAK

This contribution deals with the design and construction of a log splitter. A set of experiments have been carried out to get an appropriate shape of the splitting cone and its teeth. The cone with point angle of 60° (with the lowest splitting force) was chosen as the most suitable. On the basis of experimental results, the designed cone has been manufactured. The initial experiments indicate that the material selection and geometry design were determined correctly.

For the total verification of the log splitter, it is necessary to gather a sufficient amount of measurement data, and this will be the aim of the next study.

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The Effect of Application Method of Lacquer Products on Emissions of Volatile Organic Compounds

Učinak metode lakiranja na emisiju hlapljivih organskih spojeva

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ABSTRACT • *The aim of the study was to determine the effect of lacquer product application methods used in the furniture industry on emissions of volatile organic compounds (VOCs). The air samples for analyses came from three industrial plants, located in Poland, producing case furniture. In each of these plants, the finishing process was performed using waterborne lacquer products, but using different types of lacquer application machines and devices: automated finishing lines, automated vertical spray machines, a curtain coater and classical pneumatic spray guns. The compounds found in the air collected for analyses were adsorbed on a Tenax TA synthetic sorbent. The volatile compounds were analyzed by gas chromatography combined with mass spectrometry and thermal desorption. The results showed differences in the amounts of identified compounds depending on the type of the used lacquer application machine. It was found out that the use of automated finishing lines for lacquering of furniture elements does not only lead to an increase in the efficiency of the process, but also results in a reduction of pollution in the production halls.*

Keywords: *volatile organic compounds, surface finishing, waterborne products, furniture industry, air analysis, GC/MS/TD*

SAŽETAK • *Cilj istraživanja bio je utvrditi utjecaj primijenjenih metoda lakiranja proizvoda u proizvodnji namještaja na emisiju hlapljivih organskih spojeva (VOCs). Uzorci zraka za analizu prikupljeni su u tri industrijska postrojenja u Poljskoj u kojima se proizvodi namještaj. U svakome od tih postrojenja za proces površinske obrade upotrebljavaju se vodeni lakovi, ali se primjenjuju različiti uređaji i strojevi za nanos laka: automatizirane linije za površinsku obradu, automatizirani vertikalni uređaji za prskanje, uređaji za površinsku obradu sa zavjesom i klasični pneumatski pištolji za prskanje. Spojevi nađeni u analiziranim uzorcima zraka adsorbirani su na Tenax TA sintetičkom sorbentu. Hlapljivi spojevi analizirani su plinskom kromatografijom u kombinaciji s masenom spektrometrijom i toplinskom desorpcijom. Rezultati su pokazali razlike u količinama utvrđenih spojeva ovisno o vrsti uređaja za nanošenje laka. Utvrđeno je da uporaba automatskih linija za lakiranje elemenata namještaja ne samo povećava učinkovitost procesa već i rezultira smanjenjem onečišćenja zraka u proizvodnim halama.*

Ključne riječi: *hlapljivi organski spojevi, površinska završna obrada, proizvodi na bazi vode, proizvodnja namještaja, analiza zraka, GC/MS/TD*

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1 INTRODUCTION
1. UVOD

In the recent years, the interest in indoor air quality has increased considerably. The presence of some substances in indoor air may cause many health problems, e.g. diseases of the respiratory tract, allergies, migraines and overall irritation**.** Many researchers are of an opinion that these health problems are caused by volatile organic compounds (Brinke *et al.,* 1998; Jones, 1999; Pappas *et al.,* 2000; Nielsen *et al.,* 2007). Volatile organic compounds are emitted from many sources, both internal and external.

The problem of air quality has been discussed in terms of indoor air quality in housing buildings (Wallace *et al.,* 1991; Brown *et al.,* 1994; Hodgson *et al.,* 2002; Park and Ikeda, 2004, 2006; Guo *et al.,* 2003, 2009) and public buildings (Lee *et al.,* 1999; Kim *et al.,* 2001; Loh *et al.,* 2006; Eklund *et al.,* 2008)**.** Air quality in educational institution facilities is considered to be of particular importance (Norback, 1995; Lee *et al.,* 1999a; Daisey and Angell, 2003; Godwin and Batterman, 2007).

Increasing interest in indoor air quality in housing buildings, office buildings, schools, hospitals, etc. has resulted in the subject being discussed also in relation to industrial practice. World literature presents studies on VOC emissions and air pollution in industrial practice only to a limited extent, including also different sectors of wood industry. The studies concerning wood industry have discussed mainly VOC emissions from wood, lacquer coatings and finished products (Salthammer, 1997; Risholm-Sundman *et al.,* 1998; Salthammer *et al.,* 1999; Brown, 1999; Baumann *et al.,* 2000; Guo and Murray, 2001; Kim *et al.,* 2006; Roffael, 2006; Ohlmeyer *et al.,* 2008, Kirkeskov *et al.,* 2009).

Such pollution occurs first of all during the process of lacquering of furniture elements.

For this reason the aim of this study was to determine the effect of application methods of lacquer products used in the furniture industry on the microclimate of facilities, in which the finishing operations were performed on surfaces of furniture items.

The scope of the study included quantitative and qualitative analyses of compounds emitted to the air.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Characteristics of wood finishing plants
2.1. Obilježja pogona za površinsku obradu proizvoda

In order to determine the effect of lacquer product application methods on the emission of volatile organic compounds, investigations were conducted in three furniture manufacturing plants located in Poland, producing case furniture.

Production in these plants is based on modern technological solutions, both in rough wood processing and secondary processing as well as surface finishing. All the plants selected for the study in the finishing process use only lacquer systems based on waterborne binders, which were applied on the surface of furniture elements using different lacquer application methods and machines. The parameters of lacquer products used in the production process are presented in Table 1.

In the plant 1, the process of furniture surface finishing was based on:

- An automated finishing line (1) for lacquer application and drying, consisting of a belt sanding machine, a dust suction device and an oscillating spray machine with the electronic control unit for panel dimensions reading, a belt conveyor and the lacquer recovery system and a drying tunnel, composed of the following segments: heating (to a temperature of 30 °C – 40 °C), drying using IR radiators (at a temperature of 60 °C) and conditioning to ambient temperature.

Incoming air by means of the air pressurization unit moves overspray to the filtering system and is then carried to the exhaust fan. Suction system composed of a double set of dry filters.

Table 1 Technical parameters of lacquer products used in plants selected for the study
Tablica 1. Tehnički parametri lakova upotrebljavanih u pogonima odabranim za istraživanje

Parameters / *Parametri*	**Lacquers** / *Lakovi*		
	Plant 1 *Pogon 1.*	**Plant 2** *Pogon 2.*	**Plant 3** *Pogon 3.*
Binding agent / *Vezno sredstvo*	acrylic dispersion / *akrilna disperzija*		
Solvents / *Otapala*	water		
Non-volatile contents / *Sadržaj nehlapljivih tvari*, %	43	33	48
Density / *Gustoća*, g/cm^3	1.18	1.07	1.25
Working viscosity at a temp. of (22±1) °C *Radni viskozitet pri temp. (22±1)°C*, s* Spraying / *Prskanje* Curtain coater / *Uređaj za lakiranje sa zavjesom*	55 -	68 -	23 45
Colour / *Boja*	white / *bijela*	blue / *plava*	white / *bijela*
Other information / *Druge informacije*	multilayer product *višeslojni proizvod*	multilayer product *višeslojni proizvod*	undercoating product *zaštitni proizvod*
Information on ingredients / *Informacija o sastavu*	2-butoxyethanol *2-butoksietanol*	2-butoxyethanol *2-butoksietanol*	2-butoxyethanol 1,2-propanodiol *2-butoksietanol* *1,2-propanodiol*

* Value measured using a Ford's cup No. 4 / *Vrijednost izmjerena uporabom Fordova uređaja broj 4*

- An automated vertical spray machine, equipped with two spray guns. The spraying was performed in a spraying booth.

The lacquering booth consisted of two rooms, i.e. a painting room of 4.9 x 3.9 m (*L* x *W*) and a drying room of 7.6 x 4.9 m (*L* x *W*). Pure air was supplied to the booth through the filter ceiling. The air filtration process consisted of preliminary and final filtration stages. Dusted air was discharged through a filtering water curtain.

In turn, in the plant 2, the furniture surface finishing process was performed using:

- An automated finishing line (2) for lacquer application and drying, equipped with a standing belt machine, a reading line with photocells to identify dimensions of processed elements, a drying tunnel with IRM lamps, an automated spray machine with six spray guns, a drying tunnel composed of the following zones: the drying zone using microwave electromagnetic radiation energy (the *Microwaves Operating System* - MOS), the drying zone with hot air injection in a nozzle tunnel with IRM lamps, the conditioning zone adjusting the temperature to ambient temperature.

Air purity in the lacquering chamber was provided by two fans coupled with filters. The unit is supplied with ambient air using an electric fan. Overspray is sucked in by two pipes mounted on an elevator using an exhaust fan and passes through the system of two filters: a prefilter and an after filter.

- Manual pneumatic guns in spray booths with dry filters.

The lacquering unit was equipped with the supply-exhaust ventilation system. The ventilation system was equipped with two filters: a cardboard pleated filter and a Paint-Stop filter mat.

In turn, the plant 3 was equipped with:

- A 1-headed curtain coater.

The curtain coater was located in the hall equipped with a mechanical supply-exhaust ventilation system, meeting requirements of the current technical and legal requirements concerning the operation of the plant. It was confirmed by the positive results of environmental analyses conducted at the plant on a regular basis. The lacquering stand was not equipped with a local exhaust ventilation.

- Lacquer application booths with dry filters with manual pneumatic guns.

Spray booths were equipped with the supply-exhaust ventilation system. Contaminated air was purified in a single stage process: using a cardboard pleated filter.

2.2 Adsorption of volatile organic compounds
2.2. Adsorpcija hlapljivih organskih spojeva

The air for analyses was collected to glass tubes filled with a Tenax TA solid sorbent at 120 mg (35/60 mesh, Alltech). Each time, five parallel air samples were collected using a pump (FLEC Air Pump 1001, Chematec).

The analyses were performed at the lacquer application zone at a distance of approx. 0.5 m from the lacquer application machines. The samples were collected at a height of 1.5 m above floor level.

The volume of 500 ml air was transferred by the sorbent at a rate of 50 ml/min.

2.3 Chromatographic analysis
2.3. Kromatografska analiza

The volatile organic compounds adsorbed on the Tenax TA were released in a thermal desorber and next, they were determined by gas chromatography combined with mass spectrometry following the procedure presented in Table 2.

Table 2 Operating conditions of the TD/GC/MS
Tablica 2. Uvjeti rada uređaja TD/GC/MS

Elements of the system *Elementi sustava*	**Parameters** / *Obilježja*
Thermal desorber *Toplinski desorber*	
Injector / *injektor*	Thermal desorber connected to a sorption microtrap / *toplinski desorber spojen na sorpcijski mikrotrap* Purging gas / *plin za čišćenje*: argon at 20 $m^3 \cdot min^{-1}$ Purge time / *vrijeme čišćenja*: 5 min
Microtrap / *mikrotrap*	Sorbent / *sorbent*: 80 mg Tenax TA/30 mg Carbosieve III Desorption temperature / *vrijeme desorpcije*: 250 °C during 90 s.
Gas chromatograph *Plinska kromatografija*	TRACE GC, Thermo Quest.
Column / *kolona*	RTX – 624 Restek Corporation, 60 m x 0.32 mm ID D_f – 1.8 μm: 6% cyanopropylophenyl, 94% dimethylopolysiloxane
Detector / *detektor*	Mass spectrometer / *maseni spektrometar* (SCAN: 10 – 350)
Injector / *injektor*	Thermal desorber connected with a sorption microtrap / *toplinski desorber spojen na sorpcijski mikrotrap* Rinsing gas / *plin za ispiranje*: argon 20 $m^3 \cdot min^{-1}$ Rinsing time / *vrijeme ispiranja*: 5 min.
Microtrap / *mikrotrap*	Sorbent / *sorbent*: 80 mg Tenax TA/30 mg Carbosieve III; Desorption temperature / *temperature desorpcije*: 250 °C during 90 s.
Carrier gas / *plin*	Helium / *helij*: 100 kPa, ~2 $cm^3 \cdot min^{-1}$.
Temperature setting / *postavka temperature*	40 °C during 2 min, 7 °C·min^{-1} to 200 °C, 10 °C·min^{-1} to 230 °C, 230 °C during 20 min

2.4 Qualitative and quantitative analyses
2.4. Kvalitativna i kvantitativna analiza

The compounds were identified by comparing the recorded mass spectra with the spectra contained in the NIST MS Search library – program ver. 1.7 and confirmed by referring the mass spectra and retention times of identified compounds to the spectra and retention times of appropriate standards.

Quantitative analysis of volatile organic compounds emitted from investigated surfaces was conducted by adding a reference standard 1-bromo-4-fluorobenzene (Supelco).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figures 1 to 4 and Tables 3 to 5 present testing results concerning the effect of different lacquer application technologies on the levels of volatile organic compound emissions. These results make it possible to compare the effect of technologies used to apply products based on waterborne binders, in recent years used with increasing frequency in the furniture industry. These comparisons may be made only within individual plants, since the finishing process in each of these plants was performed using different waterborne lacquer products (Table 1).

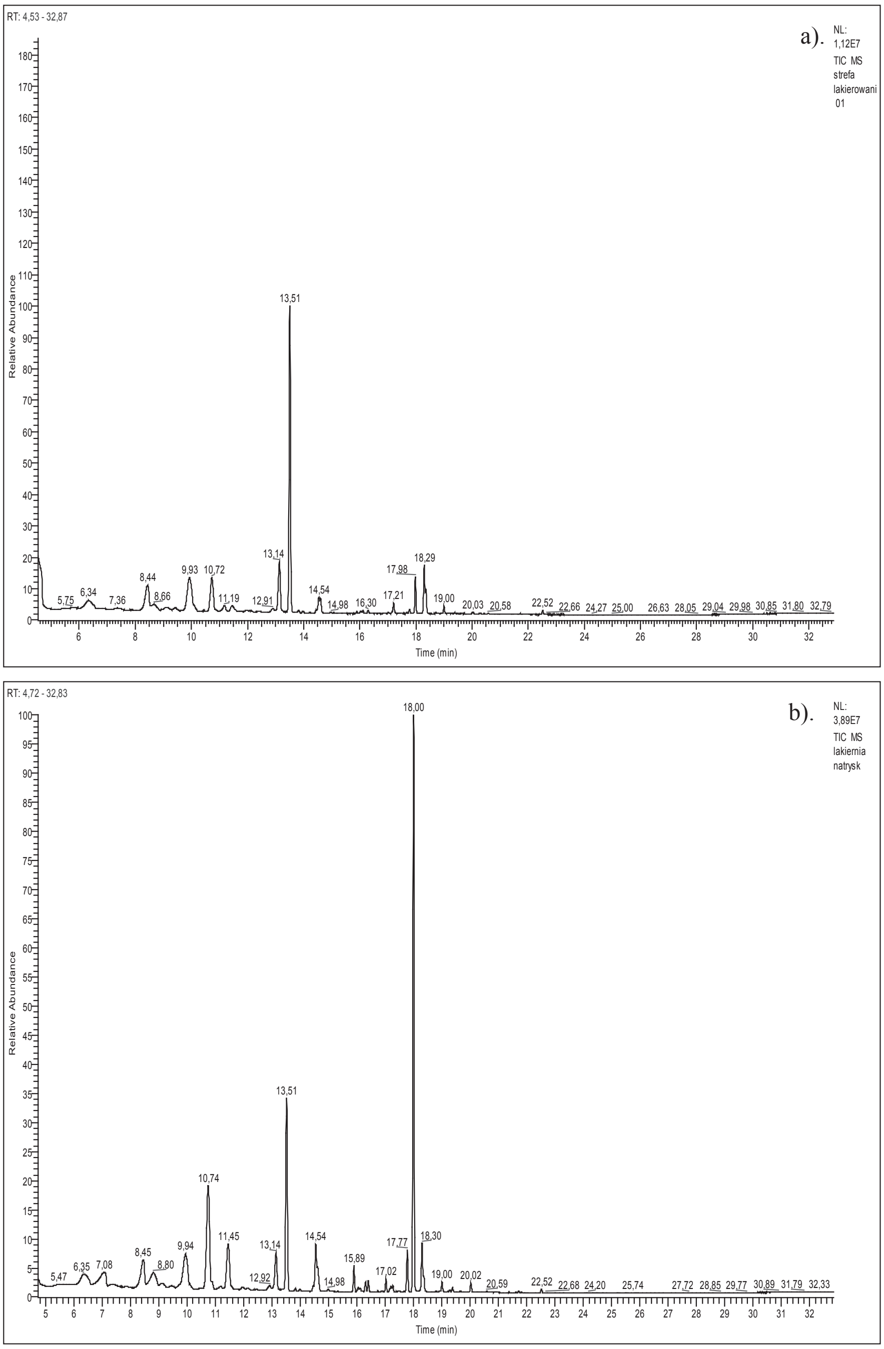

Figure 1 Chromatogram of VOCs emitted during surface lacquering in the plant 1: a) on a finishing line (1), b) using an automated vertical spray machine
Slika 1. Kromatogram hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda u pogonu 1: a) na liniji za površinsku obradu (1), b) primjenom automatskih vertikalnih uređaja za prskanje

Table 3 Concentration of VOCs during surface lacquering on a finishing line (1) and an automated vertical spray machine in the plant 1
Tablica 3. Koncentracije hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda na liniji za površinsku obradu i primjenom automatskih vertikalnih uređaja za prskanje u pogonu 1

Compounds / *Spojevi*	**RT** min	**Concentration, μg·m⁻³** / *Koncentracija, μg·m⁻³*	
		finishing line (1) *linija za površinsku obradu (1)*	**automated vertical spray machine** / *automatski vertikalni uređaj za prskanje*
1-butanol / *1-butanol*	10.72-10.74	721.1	2075.8
Toluene / *toluen*	13.14	768.6	547.3
Butyl acetate / *butil acetat* Hexanal / *heksanal*	14.53-14.55	181.9 147.1	501.0 268.1
n-butyl ether / *n-butil eter*	15.89	-	210.8
m.p-xylene / *m.p-ksilen*	16.29	-	81.9
1-methoxy-2-propyl acetate / *1-metoksi-2-propil acetat*	16.40	-	86.9
Propanoic acid. butyl ester / *propanoik acid. butil ester*	17.02	-	100.6
o-xylene / *o-ksilen*	17.21	29.9	-
ά-pinene / *ά-pinen*	17.77	43.3	373.0
2-butoxyethanol / 2-*butoksietanol*	17.98-18.00	293.9	4737.1
3-carene / *3-karen*	20.02	20.7	78.1
Limonen / *limonen*	20.59	-	8.4
Σ unidentified compounds / Σ *nedefinirani spojevi*		80.6	329.0
TVOC		2287	9398

The detailed results concerning the effect of surface finishing technologies applied in the plant 1 are presented in Figures 1 and in Table 3.
In the plant 1 equipped with a modern finishing line (1) and an automated vertical spray machine, the concentration of all volatile organic compounds at the lacquer application zone was in a very broad range of values from 2287 μg/m^3 to 9398 μg/m^3.

In the air, collected from the lacquer application zone on the finishing line (1) the detected compounds included particularly toluene, 1-butanol and 2-butoxyethanol at 768.6 μg·m^{-3}, 721.1 μg·m^{-3} and 293.9 μg·m^{-3}. Moreover, the presence of the following compounds was also detected: n-butyl acetate, hexanal and terpenes, mainly α-pinene and 3-carene.

In the course of lacquer application on furniture elements using an automated vertical spray machine, a broader spectrum of compounds was noted than that recorded at the application by the finishing line (1). When using the automated vertical spray machine, 2-butoxy-

Table 4 Concentration of VOCs during surface lacquering on a finishing line (2) and with the use of manual pneumatic guns in the spray booth in plant 2
Tablica 4. Koncentracije hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda na liniji za površinsku obradu (2) i primjenom ručnoga pneumatskog pištolja u kabini za prskanje u pogonu 2.

Compounds / *Spojevi*	**RT** min	**Concentration, μg·m⁻³** / *Koncentracija, μg·m⁻³*	
		finishing line (2) *linija za površinsku obradu (2)*	**manual pneumatic guns** *ručni pneumatski pištolj*
Acetone / *aceton*	6.42	299.0	-
1-butanol / *1-butanol*	10.77-10.79	226.3	944.5
Penatanal / *penatanal*	11.49	142.9	-
Toluene / *toluen*	13.17	401.7	68.7
Tetrachloroethylene / *tetrakloretilen*	14.14	48.1	-
Butyl acetate / *butil acetat*	14.57-14.58	134.1	700.1
Hexanal / *heksanal*	14.64	231.6	258.6
n-butyl ether / *n-butil eter*	15.92-15.93	15.9	110.6
Ethylbenzene / *etilbenzen*	16.08-16.09	54.0	57.1
m.p-xylene / *m.p-ksilen*	16.33-16.34	135.0	102.1
o-xylene / *o-ksilen*	17.19-17.20	43.5	31.9
Styrene / *stiren*	17.25	170.10	-
ά-pinene / *ά-pinen*	17.80-17.81	72.3	26.8
2-butoxyethanol / *2-butoksietanol*	18.04-18.03	1264.9	1970.5
1-butoxy-2-propanol / *1-butoksi-2-propanol*	18.74	23.3	-
3-carene / *3-karen*	20.06	-	10.8
Limonen / *limonen*	20.62	29.7	-
Σ unidentified compounds *Σ nedefinirani spojevi*		448.8	277. 1
TVOC		3741	4559

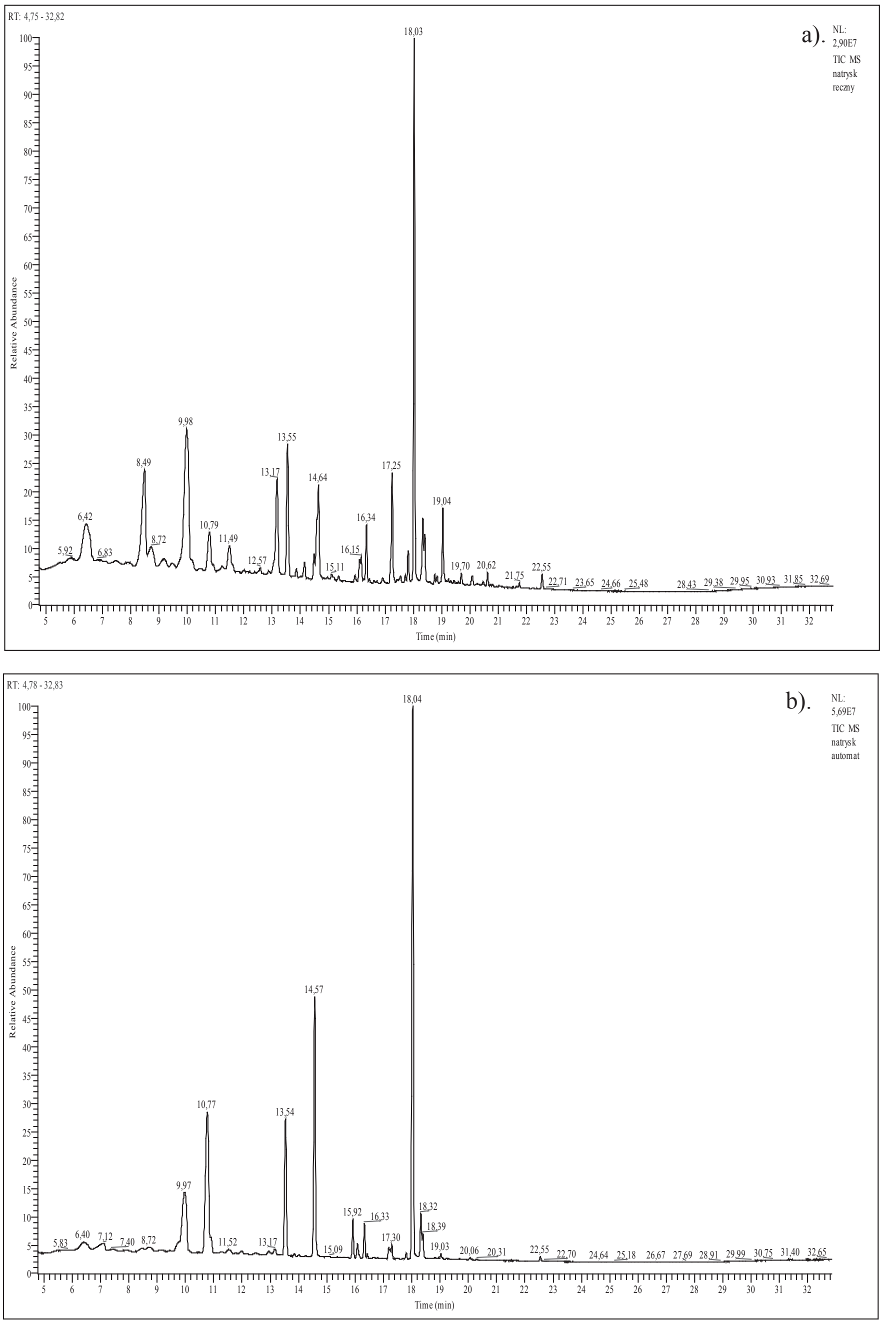

Figure 2 Chromatogram of VOCs emitted during surface lacquering in the plant 2: a) on a finishing line (2), b) with the use of a manual pneumatic gun in the spray booth

Slika 2. Kromatogram hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda u pogonu 2.: a) na liniji za površinsku obradu (2), b) primjenom ručnoga pneumatskog pištolja u kabini za prskanje

ethanol was emitted in the greatest amounts. Concentration of the compound amounted to 4737.1 μg·m^{-3}. i.e. almost 50 % total concentration of all compounds found in the analyzed air. High emissions were also recorded for 1-butanol (2075.8 μg·m^{-3}), toluene (547.3 μg·m^{-3}) and butyl acetate (501.0 μg·m^{-3}).

Large differences in the total amount of all compounds released into the air are primarily the result of the increased concentration of 2-butoxyethanol and 1-butanol in the spray booth. Glycol concentration in the lacquer application zone, when automated vertical spraying was used, was over 16-times higher and that of alcohol was almost 3-fold higher than at the lacquer application zone on the finishing line.

Successive figures (Fig. 2) and Table 4 present results concerning the effect of surface lacquering processes on air quality in the plant 2.

The concentration of the volatile organic compounds at the finishing line (2) amounted on an average to 3741 μg/m^3 and it was lower than when applying coatings with manual spray guns in the lacquer application booth, equipped with dry filters, where it amounted to 4559 μg/m^3.

In the tested air collected near the lacquer application zone on the finishing line (2) considerable amounts were detected for 2-butoxyethanol at 1264.9 μg/m^3, toluene at 401.7 μg/m^3, acetone at 299.0 μg/m^3, 1-butanol at 226.3 μg/m^3 and hexanal at 231.6 μg/m^3. The above mentioned compounds jointly accounted for over 64 % of the total emission. The other substances emitted in smaller amounts included e.g. pentanal, butyl acetate, ethylbenzene, m,p-xylene, as well as terpene compounds. i.e. ά-pinene. It needs to be stressed that in the air collected at the finishing line (2) the presence of styrene was detected at 170.10 μg/m^3. Lacquer application on furniture surface in the finishing line (2) additionally caused by the emission of such compounds as acetone, pentanal, tetrachloroethylene and 1-butoxy-2-propanol, whose presence was not detected in the air collected from the spray booth (2).

In the air samples collected from a spray booth, in which manual spraying was applied, a smaller spectrum of compounds was detected than in the case of the finishing line (2). 2-butoxyethanol was the compound released in the greatest amount, at a concentration of 970.5 μg/m^3. Lacquer application by manual pneumatic guns caused the emission of large amounts of 1-butanol (944.5 μg/m^3) and butyl acetate (700.1 μg/m^3).

Emissions of 2-butoxyethanol, 1-butanol and butyl acetate accounted for over 80 % of all the released compounds.

The measurements taken in the plant 3 made it possible to compare the technology of surface finishing using curtain coater with manual spray pneumatic guns. The results of these measurements are presented in Figures 3 and 5.

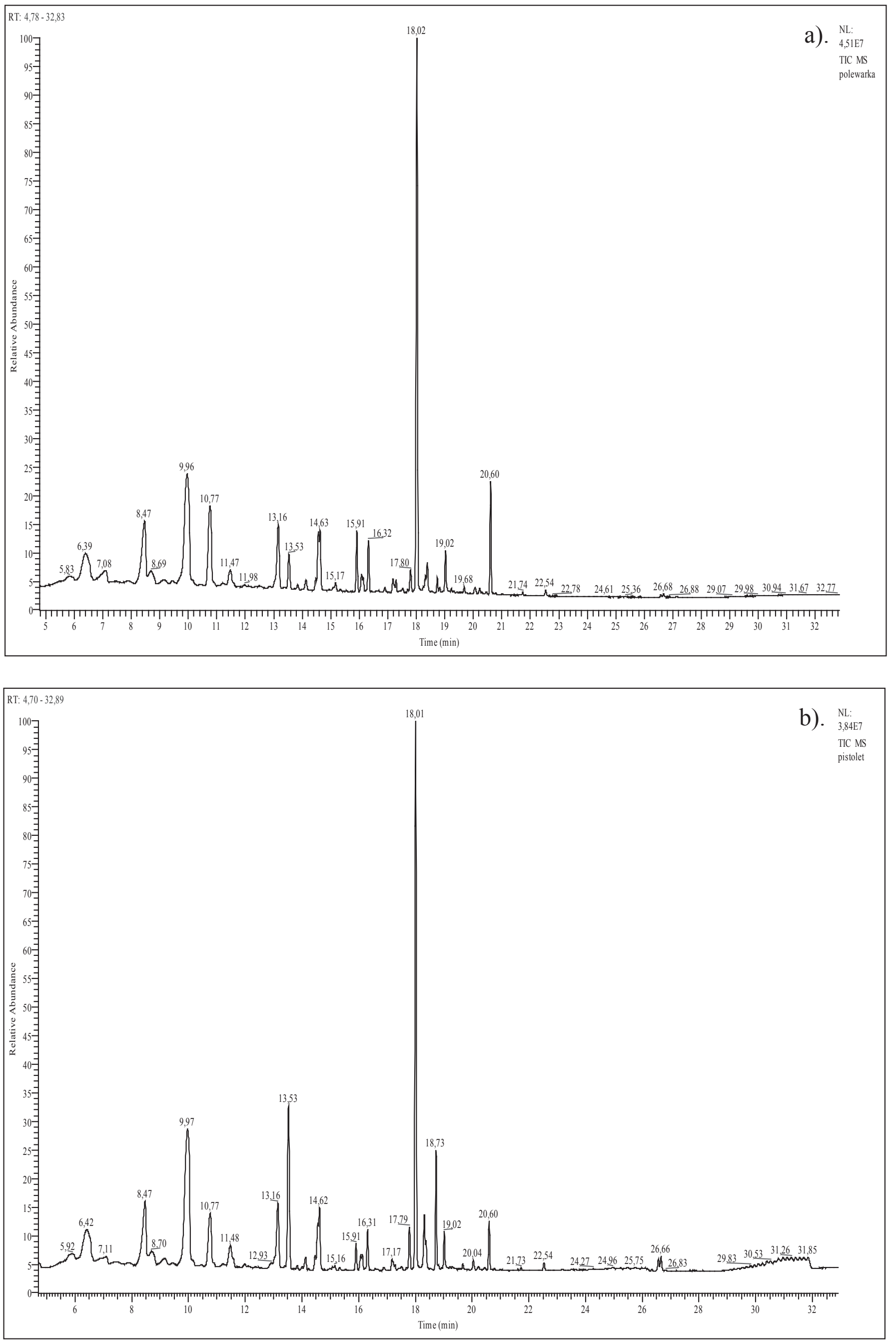

Figure 3 Chromatogram of VOCs emitted during surface lacquering in plant 3: a) with a curtain b coater, b) with the use of a manual pneumatic gun in the spray booth
Slika 3. Kromatogram hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda u pogonu 3.: a) uređajem za nanošenje laka sa zavjesom, b) primjenom ručnoga pneumatskog pištolja u kabini za prskanje

Table 5 Concentration of VOCs during surface lacquering with the use of a curtain coater and of manual pneumatic guns in the spray booth in plant 3
Tablica 5. Koncentracije hlapljivih organskih spojeva emitiranih tijekom lakiranja proizvoda primjenom uređaja sa zavjesom i primjenom ručnoga pneumatskog pištolja u kabini za prskanje u pogonu 3.

Compounds / *Spojevi*	**RT** min	**Concentration, μg·m⁻³** / *Koncentracija, μg·m⁻³*	
		curtain coater *uređaj za lakiranje sa zavjesom*	**manual pneumatic guns** *ručni pneumatski pištolj*
Acetone / *aceton*	6.39-6.42	377.1	440.3
1-butanol / *1-butanol*	10.77	1306.5	502.6
Penatanal / *penatanal*	11.47-11.48	146.4	215.3
Toluene / *toluen*	13.16	498.1	447.5
Tetrachloroethylene / *tetrakloretilen*	14.13	51.3	67.4
Butyl acetate / *butil acetat*	14.56	349.9	215.2
Hexanal / *heksanal*	14.63	193.7	274.9
n-butyl ether / *n-butil eter*	15.91	515.9	100.7
Ethylbenzene / *etilbenzen*	16.08	89.2	62.7
m.p-xylene / *m.p-ksilen*	16.32-16.31	262.1	168.9
o-xylene / *o-ksilen*	17.18-17.17	66.9	40.5
ά-pinene / *ά-pinen*	17.80-17.79	75.2	181.6
2-butoxyethanol / *2-butoksietanol*	18.02-18.01	2829.6	2207.3
1-butoxy-2-propanol / *1-butoksi-2-propanol*	18.73	50.9	408.6
3-carene / *3-karen*	20.05-20.04	30.8	47.0
Limonen / *limonen*	20.60	405.5	168.3
Σ unidentified compounds / *Σ nedefinirani spojevi*		357.2	362.5
TVOC		7606	5911

They showed that lower air pollution is caused by manual spray guns in a lacquer application booth than by a curtain coater. The concentration of volatile organic compounds near the lacquer application zone in the curtain coater was 7606 μg/m^3, while at the lacquer application workstation with the use of manual pneumatic guns it was lower amounting on an average to 5911 μg/m^3.

In the plant 3, where during the study, the undercoating product was applied, a spectrum of compounds was found similar to those detected in the two other plants. The compound released in the greatest amount turned out to be 2-butoxyethanol. Finishing of furniture elements by curtain coating caused emission of this compound at 2829.6 μg/m^3, while lacquer application with the use of manual guns resulted in emission at 2207.3 μg/m^3. In the tested air, high concentrations were also detected for acetone, 1-butanol, toluene and 1-butoxy-2-propanol. Lower amounts were recorded for pentanal, n-butyl acetate, hexanal, m,p-xylene as well as terpenes, i.e. ά-pinene, 3-carene and limonene.

Tested air samples collected from the furniture element lacquer application zones contained such compounds as aldehydes, ketones, aromatic hydrocarbons, alcohols, glycols and terpenes. Sources of their emissions included both finished furniture elements and applied lacquer systems. Wood species were sources of emissions of aldehydes, pentanal and hexanal. These compounds are formed through oxidation reactions of unsaturated fatty acids found in wood (Risholm-Sundman *et al*., 1998). Pentanal is formed as a result of oxidation of linoleic acid, while pentanal is the product of oxidation of linolenic acid (Salthammer *et al*., 1999). Terpene compounds (α-pinene, 3-carene, limonene) are also emitted by various wood species, particularly softwood iglaste (Roffael, 2006; Risholm-Sundman *et al.,* 1998; Manninen *et al.,* 2002). Acetone is a compound detected during analyses of emissions of volatile organic compounds from different wood species, wood-based materials and lacquer systems (Brown, 1999; Risholm-Sundman *et al.,* 1998; Kirkeskov *et al.,* 2009).

2-butoxyethanol was an important component released by all lacquer systems applied in the plants. Analyses of water-borne systems conducted by Salthammer (1997) and Stachowiak-Wencek and Prądzyński (2011) showed that 2-butoxyethanol is a characteristic compound emitted by such lacquer systems. Moreover, chamber tests conducted by Stachowiak-Wencek and Prądzyński (2011) also showed that waterborne systems, apart from glycols, may emit to air several other compounds. Air collected from furniture element lacquer application zones in the analyzed plants was found to contain aromatic hydrocarbons (toluene, ethylbenzene, m-, p- and o-xylene, styrene) and esters (butyl acetate, 1-methoxy-2-propyl acetate and propanoic acid butyl ester).

It is rather difficult to explain the presence of styrene in air collected from the lacquer application zone at lacquering line 2. Available literature contains practically no information on emission of styrene from aqueous systems. Moreover, this compound was not detected during the application using spray guns. Emission of styrene is possible from waterborne products cured using UV irradiation. Styrene is used for copolymerization of UPE-systems. A study by Salthammer *et al.* (1999) showed that UV-cured aqueous products based on unsaturated polyester (UPE) may be sources of styrene emission. In the analyzed lacquering line (2) both aqueous products and UV-cured aqueous products may be applied alternately. It may be assumed that sty-

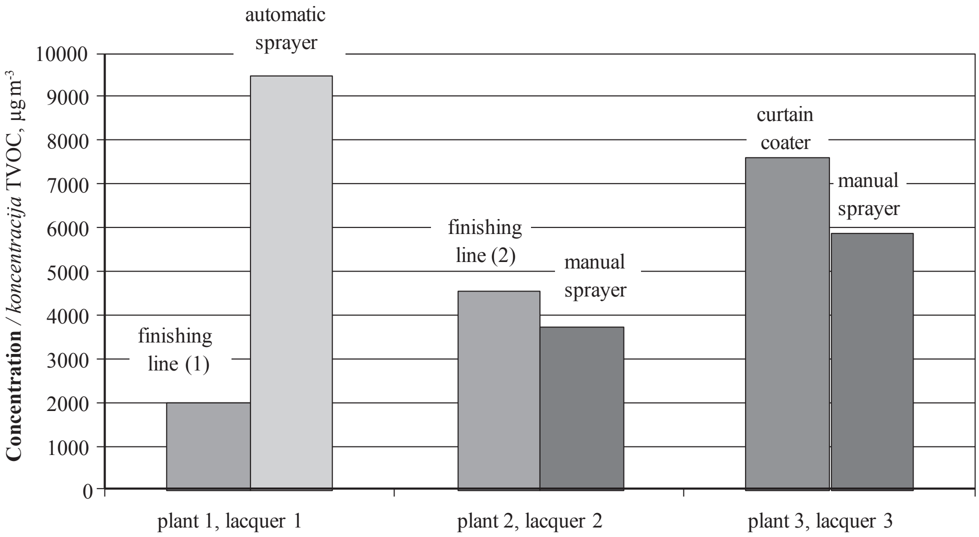

Figure 4 Comparison of TVOC emissions from lacquer application zones using individual lacquer application machines
Slika 4. Usporedba emisije ukupnih hlapljivih organskih spojeva pri primjeni različitih uređaja za lakiranje

rene detected in the lacquer application zone at lacquering line (2) did not originate from the analyzed systems, but rather from the UV-cured aqueous products applied earlier at the same line.

On the basis of the conducted tests, it was found that in the analyzed plants emissions of volatile organic compounds varied and to a considerable extent depended on the type of the used lacquer application machine or device. A comparison of TVOC emissions from the lacquer application zones in individual lacquer application machines is presented in Figure 4.

The highest TVOC content was detected in the air collected from the lacquer application zone with automated spraying amounting to 9398 µg/m^3, while the level for the use of a curtain coater was 7606 µg/m^3. Automated finishing lines proved to be superior in comparison to the other machines. Concentration of VOCs was 2287 and 3741µg/m^3. In the case of manual spraying, the level of emission from the lacquer application zone was varied ranging from 4559 5911 µg/m^3 to 5911 µg/m^3.

When comparing technologies of lacquer product application, in which identical lacquer products were applied, it needs to be stated that VOCs emissions in the plant 1 were 4-fold higher when using automated spraying than in the case of surface finishing of furniture on the finishing line. In turn, in the plants 2 and 3 these differences were less marked. The finishing line installed in the plant 2 in the lacquer application zone caused air pollution with volatile compounds by 20 % higher than the lacquer application with the use of manual pneumatic guns. In turn, in the plant 3, surface finishing with the use of a curtain coater contributed to VOC air contamination higher by 28 %.

4 CONCLUSION
4. ZAKLJUČAK

1. It was found out that surface finishing of furniture with waterborne lacquer products causes air pollution in production halls with volatile organic compounds.
2. A broad spectrum of volatile compounds was found in the air collected from the lacquer application zones. A characteristic component of emissions, irrespective of the type of the applied waterborne product, was 2-butoxyethanol, whose concentration ranged from 293.9 µg/m^3 to 4737.1 µg/m^3 and accounted for 12 % up to 79 % of the total amount of all released volatile compounds.
3. It was determined that not only the type of the applied lacquer product influenced the amount and type of VOCs emitted during the finishing process, but a significant role was also played by the type of the used lacquer application machine.
4. The use of automated finishing lines in surface finishing of furniture elements leads not only to an increase in efficiency of the finishing process, but has a positive effect on the microclimate in the facilities in which these machines are used.

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Modelling of Experimental Tests of Wooden Specimens from Scots Pine (*Pinus sylvestris*) with the Help of Anisotropic Plasticity Material Model

Modeliranje eksperimentalnih ispitivanja uzoraka izrađenih od drva običnog bora (*Pinus sylvestris*) uz pomoć modela za anizotropno-plastične materijale

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ABSTRACT • *In order to describe the behaviour of wood when calculating wooden elements and structures with the use of the finite element method, orthotropic material model in combination with non-interactive (maximum stress criterion) or interactive failure criteria (Hoffman and Tsai-Wu criterion) is used. Another option is to use a general anisotropic plasticity material model complemented with a non-interactive failure criterion – maximum stress criterion, which allows to describe wood failure by brittle failure in tension. The presented general material model was used in combination with the idealization of annual rings by cylindrical surface for the modelling of wood specimen tests form Scots pine (Pinus sylvestris). The obtained results show good agreement between the results of numerical analysis and experimental testing of wood specimens. The use of the anisotropic material model can also be seen in cases when the level of the applied load is higher than the level when the failure of wooden material occurs.*

Key words: *Scots pine (Pinus sylvestris), FEA, numerical modelling, elastic constants, material constants, anisotropic plasticity*

SAŽETAK • *Radi objašnjenja ponašanja drva pri proračunima drvnih elemenata i konstrukcija primjenom metode konačnih elemenata, upotrijebljen je model ortotropnog materijala u kombinaciji s neinteraktivnim kriterijem (kriterij maksimalnog naprezanja) ili interaktivnim kriterijima loma (Hoffmanov i Tsai-wuov kriterij). Druga je mogućnost upotrijebiti opći model za anizotropno-plastične materijale dopunjen neinteraktivnim kriterijem loma – kriterijem maksimalnog naprezanja, koji omogućuje objašnjenje lomljivosti drva pri naprezanju. Predstavljeni opći model materijala u kombinaciji s idealizacijom godova kao cilindričnih površina upotrijebljen je za modeli-*

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ranje uzoraka izrađenih od drva običnog bora (Pinus sylvestris). Dobiveni rezultati pokazuju dobru podudarnost rezultata numeričke analize i rezultata eksperimentalnih ispitivanja uzoraka drva. Model anizotropnog materijala primjenjiv je i kada je opterećenje veće od onoga pri kojemu dolazi do loma drvnog materijala.

Ključne riječi: *obični bor (Pinus sylvestris), FEA, numeričko modeliranje, elastične konstante, materijalne konstante, anizotropna plastičnost*

1 INTRODUCTION
1. UVOD

Despite the high abundance of Scots pine (*Pinus sylvestris*) in mild and colder Eurasia climate (Úřadníček *et al.*, 2001; 2012a), few literature sources contain information on elastic and material constants of this tree species, which could be used for an analysis with the use of anisotropic plasticity material model. Anisotropic plasticity material model defined by 9 elastic and 18 material constants is described by Moses and Prion (2004) as a general material model, which allows to define different bilinear elasto-plastic behaviour with possible hardening of material in three perpendicular directions, including the definition of different behaviour in these directions in tension, compression, and shear.

Elastic and material constants are predominantly specified for Loblolly pine (*Pinus taeda*) (Bergman *et al.*, 2010; Bodig and Goodman, 1973; Morais *et al.*, 2001; Jeong *et al.*, 2010) and for Douglas fir (*Douglas fir*) (Bergman *et al.*, 2010; Bodig and Goodman, 1973; Winandy, 1994; Nairin, 2007; Kim and Harries, 2010).

Elastic constants for Scots pine (*Pinus sylvestris*), shown by Bodig and Goodman (1973) and Martin and Berger (2001), are based on a special report produced by R. F. S. Hearmon (Hearmon, 1948). Elastic constants for Scots pine used for the modelling of a section of a wooden string staircase and stair joints are also presented by Pousette (2006). Elastic and material constants of Scots pine are shown by Danielsson and Gustafsson (2013), who used these constants for the modelling of a double cantilever beam (DCB) and end-notched beams. According to Danielsson and Gustafsson (2013), the specified constants are in compliance with the values for Norway spruce (*Picea abies*). The values of elastic and material constants of Scots pine are shown in the papers of Matovič (1993) and Požgaj *et al.* (1997; 2004).

For the purpose of the numerical analysis of a prefabricated suspended staircase from Scots pine (Pěnčík, 2013), elastic and material constants of the Scots pine were selected with the use of results presented in the papers of Matovič (1993) and Požgaj *et al.* (1997; 2004). The constants are shown in Table 1, where E is modulus of elasticity in material directions (longitudinal L – E_L, radial R – E_R and tangential T – E_T), G is shear modulus in material planes (G_{RT}, G_{LT}, G_{LR}), ν Poisson's ratio (ν_{RT}, ν_{LT}, ν_{LR}), f_{Lt}, f_{Rt}, f_{Tt} are strengths in tension and f_{Lc}, f_{Rc}, f_{Tc} are strengths in compression in material directions L, R and T, f_{LR}, f_{LT}, f_{RT} are shear strengths in material planes.

The elastic constants (Table 1) were selected taking into account the meeting of criteria presented in relation (1) (Gillis, 1972; Hallai, 2008) and in relation (2) (Xavier, 2007), which express their inter-relation.

$$E_L > E_R > G_{LR} \approx G_{LT} > E_T > G_{RT} \quad (1)$$

$$E_L \gg E_R > E_T,\ G_{LR} > G_{LT} \gg G_{RT},\ \nu_{LR} > \nu_{LT} > \nu_{RT} \quad (2)$$

The verification of elastic and material constants (Table 1) was performed by a numerical modelling of experimental testing with the use of finite element calculation using software ANSYS (ANSYS, 2012a).

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Experimental testing
2.1. Eksperimentalno ispitivanje

Wooden specimens made of Scots pine (*Pinus sylvestris*) were prepared in compliance with ČSN EN 408. The dimensions of the cross section – width (b) and height (h) and length (L) of specimens were selected in compliance with the requirements of ČSN EN 408; $b \times h \times L = 25 \times 25 \times 475$ mm. Before the testing, the specimens were conditioned in a standard environment at the temperature of 20 ± 2 °C and relative

Table 1 Elastic and material constants of Scots pine (*Pinus sylvestris*) in MPa
Tablica 1. Elastične konstante i materijalne konstante drva običnog bora (izražene u MPa)

Elastic constant for orthotropic and anisotropic plasticity material model *Elastične konstante za model ortotropnoga i anizotropnoga plastičnog materijala*								
E_L	E_R	E_T	G_{RT}	G_{LT}	G_{LR}	ν_{RT}	ν_{LT}	ν_{LR}
14300	700	545	500	800	1230	0.380	0.040	0.030
Material constant / *Materijalne konstante*								
f_{Lt}	f_{Lc}	f_{Tt}	f_{Tc}	f_{Rt}	f_{Rc}	f_{LR}	f_{LT}	f_{RT}
103.0	48.5	3.5	7.6	5.4	5.2	7.5	7.3	2.3
R_b	E_b	ρ						
86	12800	505						
Adjusted material constant for anisotropic plasticity material model *Prilagodba materijalnih konstanti za model anizotropnoga plastičnog materijala*								
f_{Lt}	f_{Lc}	f_{Tt}	f_{Tc}	f_{Rt}	f_{Rc}	f_{LR}	f_{LT}	f_{RT}
101.0	43.0	4.927	5.4	5.4	5.2	7.5	7.3	2.3

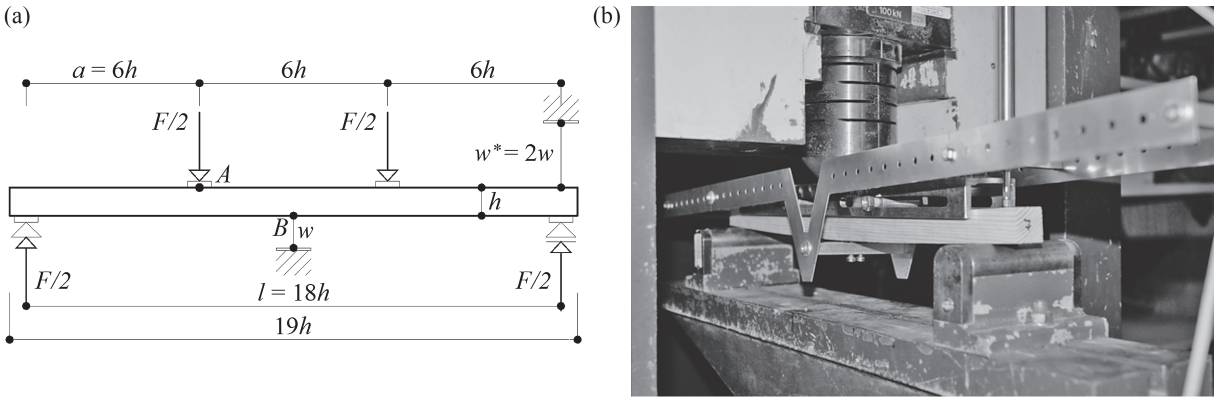

Figure 1 Arrangement of the test in compliance with ČSN EN 408 (a) and specimen No. 7 with a steel V-shape fixture (b)
Slika 1. Skica ispitivanja u skladu s normom ČSN EN 408 (a) i uzorak broj 7 čeličnim učvršćenjem V-oblika (b)

humidity of 65 ± 2 % until reaching constant weight (Kuklík and Vídeňský, 2005). In total, 10 specimens were prepared.

The specimens were simply supported during the experimental testing. The specimens were loaded by four-point bending (Fig. 1). The distance between supports was 450 mm ($18 \cdot h$). The testing set was complemented with a developed steel V-shape fixture (Fig. 1), which prevented transversal displacement of the tested specimens, while allowing their bending.

For the purpose of the monitoring of vertical displacement w^* (Fig. 1), testing specimens were fitted on the right support at their upper surface, with an inductive standard displacement transducer HBM WA-T/50 mm (HBM, 2012), with the measuring range of 0 – 50 mm and accuracy of 0.001 mm. The vertical displacement w at midspan was converted with the use of the measured vertical displacement w^* ($w = w^*/2$). The load was derived from the mechanical testing press FPZ100. The magnitude of the loading force was recorded by a calibrated resistance load cell. All sensors were connected to an 8-channel measuring data logger HBM Spider 8 (HBM, 2006). The data were recorded with the recording frequency of 2 Hz, i.e. in the time interval of 0.2 s.

2.2 Results of experimental testing
2.2. Rezultati eksperimentalnog ispitivanja

The relation of applied load F on vertical load w (load – displacement diagram $F – w$) for the whole interval of loading and all specimens is shown in Fig. 2. The load displacement diagram for individual specimens is shown in Fig. 5. The average value of limit load F_{max} is 2.693 kN (Table 2). The regression analysis and the determination of modulus of elasticity in bending used the part of graph in the interval $0.1 \cdot F_{max}$ to $0.4 \cdot F_{max}$, i.e. the part with linear relationship between load F and displacement w (Fig. 2) with the value of reliability R^2 higher than 0.99 (Kuklík and Vídeňský, 2005).

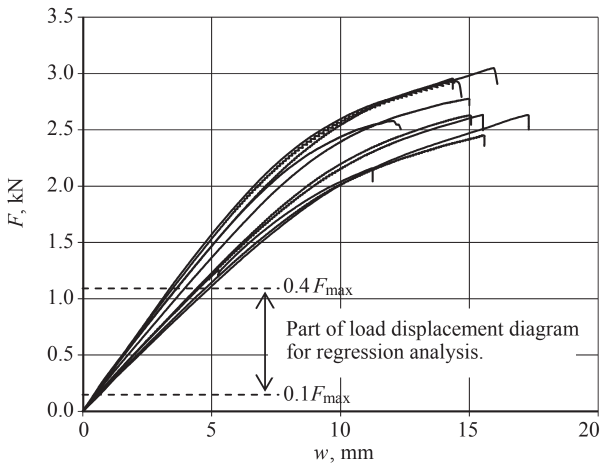

Figure 2 Load displacement diagram ($F – w$) for the whole loading interval
Slika 2. Dijagram opterećenje – pomak ($F – w$) za cijeli interval opterećenja

Table 2 Experimentally measured values for individual specimens
Tablica 2. Eksperimentalno dobivene vrijednosti za pojedine uzorke

Specimen No. *Uzorak br.*	m	ρ	F_{max}	w*	w	E_b	R_b	w_1	w_2	R^2
	g	kg/m³	kN	mm	mm	MPa	MPa	mm	mm	
1	152.3	513.0	2.643	34.6188	17.3094	10624.0	74.5	1.14592	4.83916	0.9999
2	150.8	508.0	2.458	31.4688	15.7344	11070.0	69.2	1.13983	4.68429	0.9998
3	165.8	558.5	2.979	28.7375	14.3688	15738.0	83.9	0.83749	3.33063	1.0000
4	169.6	571.3	2.579	27.1000	13.5500	14414.0	72.6	0.86025	3.5824	0.9995
5	155.5	523.8	2.777	37.8688	18.9344	13157.6	78.2	0.91057	3.89265	1.0000
6	162.5	547.4	3.062	32.3875	16.1938	14510.4	86.3	0.89047	3.59453	0.9995
7	150.5	506.9	2.171	22.5063	11.2531	11518.3	61.2	1.03163	4.43813	0.9991
8	153.9	518.4	2.936	30.4813	15.2406	14785.6	82.7	0.78059	3.43433	1.0000
9	165.1	556.1	2.639	31.0688	15.5344	11710.7	74.3	1.06821	4.41875	0.9994
10	159.7	537.9	2.684	30.1625	15.0813	11825.1	75.6	1.03245	4.35058	1.0000
Average *Prosječno*	158.6	534.1	2.693	30.6400	15.3200	12935.4	75.9			

2.3 Evaluation of modulus of elasticity in bending
2.3. Određivanje modula elastičnosti pri savijanju

Modulus of elasticity in bending E_b (MPa) (Table 2) was determined with the use of relation (3) according to ČSN EN 408, where l – free sample length, m, b – width of cross-section, m and h – height of cross-section, m, and a – distance of load from support (6·h), m (Fig. 1). The difference ($F_2 - F_1$) and ($w_2 - w_1$) shows the growth of loading and vertical displacement on the linear part of the load – displacement diagram. The values F_1, F_2, w_1 and w_2 were determined with the use of load–displacement diagram in Fig. 2; F_1 = 0.269 kN and F_2 = 1.077 kN. The measured values are arranged in Table 2, where m – weight, g, F_{max} – limit load, kN, w^* – measured vertical displacement, mm, w – converted vertical displacement at midspan, mm and R^2 – value of reliability.

$$E_b = \frac{l^3 \cdot (F_2 - F_1)}{b \cdot h^3 \cdot (w_2 - w_1)} \cdot \left[\left(\frac{3 \cdot a}{4 \cdot l} \right) - \left(\frac{a}{l} \right)^3 \right] \tag{3}$$

2.4 Evaluation of bending strength
2.4. Određivanje čvrstoće na savijanje

Bending strength R_b (MPa) (Table 2) was determined with the use of the relation (4) according to ČSN EN 408, where b – width of cross-section, m, and h – height of cross-section, m, a – distance of load from support (6·h), m and F_{max} – limit load of specimen.

$$R_b = \frac{3 \cdot F_{max} \cdot a}{b \cdot h^2} \tag{4}$$

2.5 Numerical analysis of experimental testing
2.5. Numerička analiza eksperimentalnog ispitivanja

When modelling wood by the finite element method (Bathe, 2006; Tankut *et al.*, 2014), several approaches to wood modelling can be used. The approaches are based on simplifications of the real natural material. The modelling idealizes the real trunk of generally cone shape as a cylindrical object (Bodig and Jayne, 1993), idealizes annual rings as constant shape, thickness and curvature, local failures (knots, cracks), variable structure of material, and differences between earlywood and latewood.

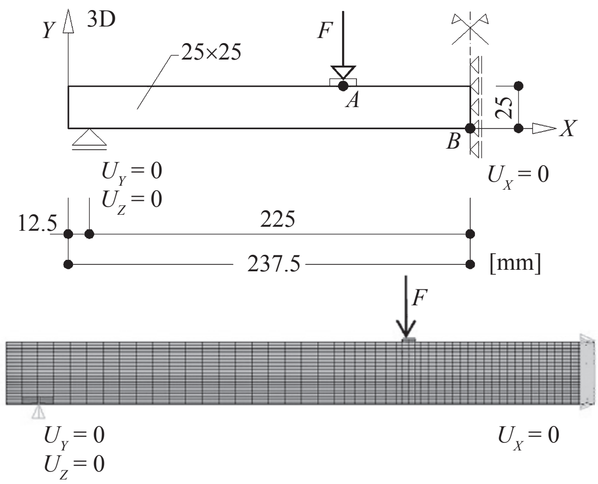

Figure 3 Geometry and 3D numeric model of wooden specimens in the calculation system ANSYS
Slika 3. Geometrijski i numerički 3D model drvnih uzoraka u računalnom sustavu ANSYS

The numerical modelling of experimental testing of specimens idealized annual rings of individual specimens as cylindrical surfaces (Fig. 4) and the behaviour of wood was described with the use of anisotropic plasticity material model (Moses and Prion, 2004). The model was described with elastic and material constants shown in Table 1. The material constants were adjusted in order to meet the conditions of plasticity incompressibility and closed surface plasticity of elliptical shape mentioned by Moses and Prion (2004) and ANSYS (2012a). The material model was complemented with non-interactive failure criterion – maximum stress criterion (Vinson and Sierakowski, 2002), in order to allow the description of wood failure by brittle failure in tension. Neither the hardening of material, nor the limitation concerning the plasticity reserve was considered for compression.

Ten 3D numerical models of specimens were made in the calculation system ANSYS version 14.0 (ANSYS, 2012a). The models were created with the

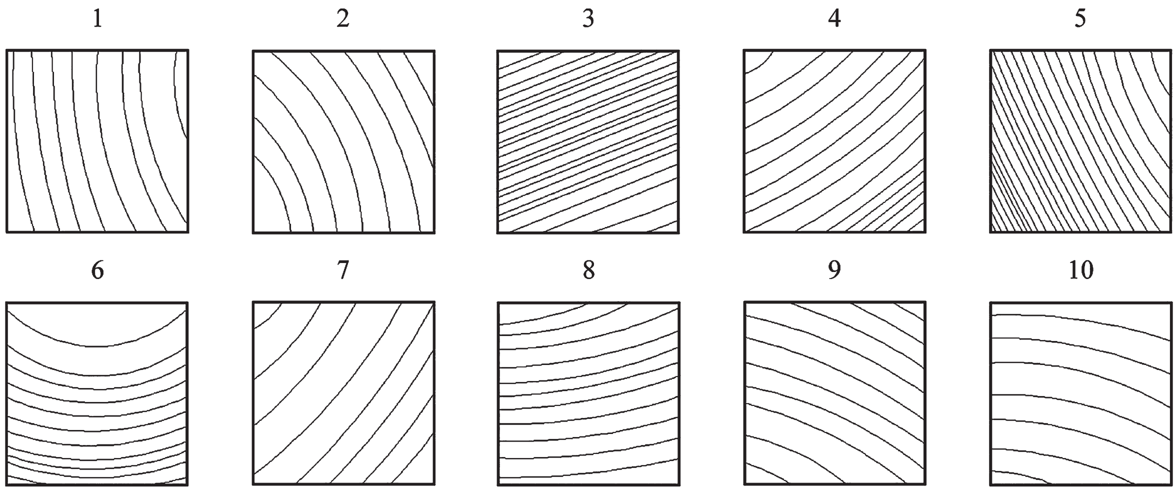

Figure 4 Idealised annual ring characteristics found from the characteristics of annual rings at the specimen front
Slika 4. Idealizirani godovi na poprečnom presjeku uzoraka

use of solid finite elements of SOLID45 and SURF154 type (ANSYS, 2012a).

In order to reduce the time demanding nature of calculations, symmetric boundary conditions were considered (Cook *et al.*, 2001), i.e. specimen halves were modelled of a size of 25 × 25 × 237.5 mm (Fig. 3). In the transversal direction, the line load (line *A*) was distributed on specimens with the use of a distribution board (Fig. 3).

The cross sections of numerical models considered the characteristics of annual rings. The modelling of the characteristics of annual rings was based on one of two front views of specimens. General cone shape of the trunk, as well as the spiral arrangement of grains along the whole length of the trunk, was neglected. The characteristics of annual rings in the front were replaced with cylindrical surfaces, and the specimens were expected to have constant curvature along the length. The cross sections of specimens are shown in Fig. 4.

The calculations were made in steps, taking into account material non-linearity. In addition, the effect of large displacements and rotations of finite elements, i.e. geometric non-linearity, was taken into account.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Results of experimental testing
3.1. Rezultati eksperimentalnog ispitivanja

On average, the failure of tested specimens occurred under the force of 2.693 kN (Table 2). The minimum force of 2.171 kN at the failure was measured when testing specimen No. 7. In contrast, the maximum force of 3.062 kN at the failure was measured when testing specimen No. 6. The experimentally measured variation strength coefficient at failure is 9.83 %.

The average value of the modulus of elasticity in bending E_b, determined by experimental testing of 10 specimens, is 12935.4 MPa. The measured values of the modulus of elasticity in bending ranged within the interval of 10624.0 MPa (min; specimen No. 1) to 15738.0 MPa (max; specimen No. 3). The experimentally measured variation coefficient of the modulus of elasticity in bending is 14.0 %, which is a lower value than that of 22 % mentioned by Bergman *et al.* (2010) and Jírů (1970).

The average value of bending strength R_b is 75.9 MPa. Minimum and maximum values of bending strength do not correspond to the same samples used for measuring modulus of elasticity in bending. The measured values of bending strength ranged within the interval of 61.2 MPa (min; specimen No. 7) to 86.3 MPa (max; specimen No. 6). The experimentally measured variation coefficient of bending strength is 9.8 %, which is again a lower value than that of 16 % mentioned by Bergman *et al.* (2010) and Jírů (1970).

The value of modulus of elasticity in bending E_b and bending strength R_b depends on the orientation and density of annual rings (Table 2 and Fig. 4). Higher values E_b and R_b were shown by samples with higher density of annual rings and specimens, whose annual rings were convex when looking at the specimen front.

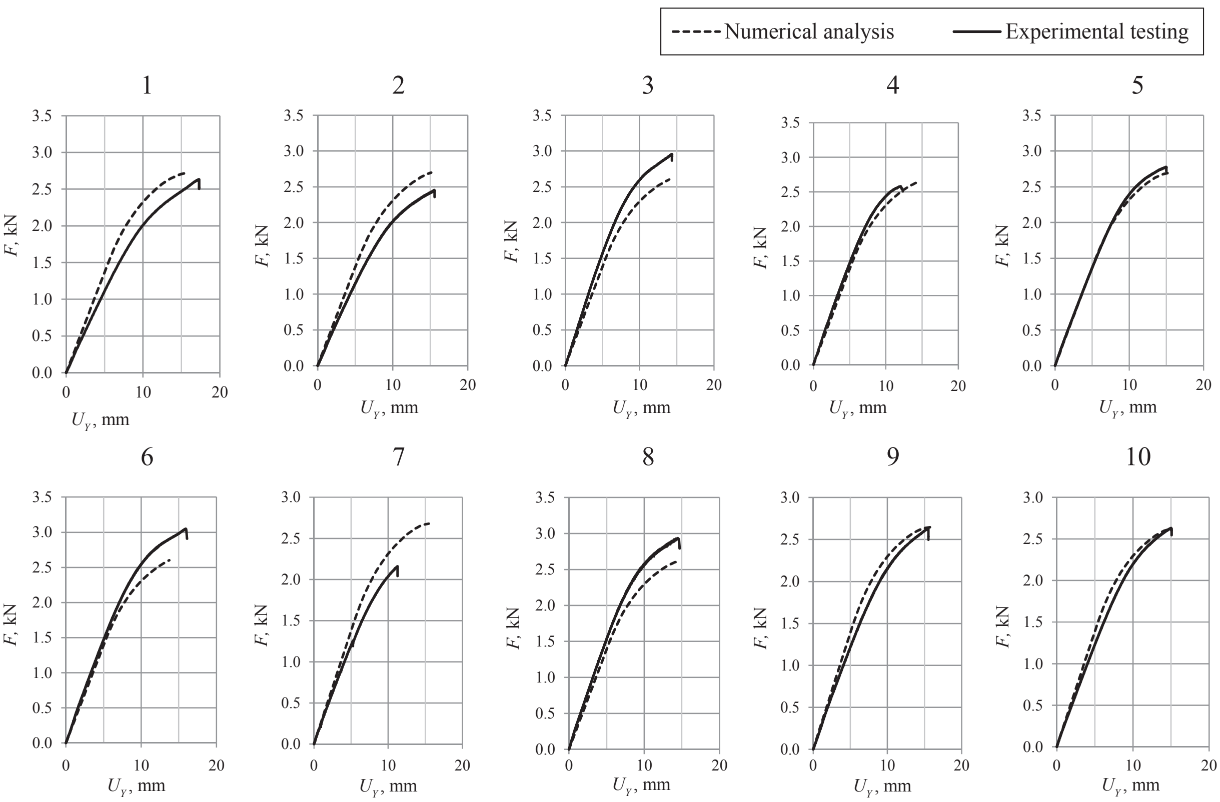

Figure 5 Load displacement diagrams ($F - U_Y$) of specimens determined by numerical analysis and experimental testing
Slika 5. Dijagram opterećenje – pomak za ispitivane uzorke određen numeričkom analizom eksperimentalnog ispitivanja

Table 3 Results of experimental measurement of strength at the failure limit *F* (kN) and vertical displacement U_Y at point B at midspan with numerically determined values
Tablica 3. Rezultati eksperimentalnog mjerenja čvrstoće pri maksimalnom opterećenju *F* (kN) i vertikalnom pomaku U_Y u točki B u sredini raspona s numerički utvrđenim vrijednostima

Specimen No. *Uzorak br.*	w	F_{max}	U_Y	$F_{max,NA}$	w / U_Y	$F_{max} / F_{max,NA}$
	mm	kN	mm	kN	%	%
	Experimental testing *Eksperimentalni podaci*		Numerical analysis *Numerička analiza*			
1	17.3094	2.643	15.9896	2.723	-8.25	2.91
2	15.7344	2.458	15.1248	2.698	-4.03	8.90
3	14.3688	2.979	13.9851	2.601	-2.74	-14.53
4	13.5500	2.579	14.2121	2.631	4.66	1.98
5	18.9344	2.777	15.4661	2.696	-22.42	-2.99
6	16.1938	3.062	13.7368	2.601	-17.89	-17.74
7	11.2531	2.171	15.4568	2.678	27.20	18.96
8	15.2406	2.936	14.5737	2.610	-4.58	-12.51
9	15.5344	2.639	15.9157	2.647	2.40	0.32
10	15.0813	2.684	14.8208	2.618	-1.76	-2.52
Average	15.3200	2.693	14.9282	2.650	-	-

3.2 Results of numerical analysis of experimental testing
3.2. Rezultati numeričke analize eksperimentalnog ispitivanja

The load curves $F - U_Y$ at point B (Fig. 3) are shown in Fig. 5. Very good conformity between experimental tests and numerical analysis was reached with the specimen No. 4, 5, 6, 9 and 10. Regarding the specimen No. 1, 2 and 7, the hardness values of the numerical and material model, respectively, were higher than those of wood specimens. Load curves of specimen No. 3 and 8 are located under the experimentally determined load curves, indicating lower rigidity of the numerical and material model, respectively.

The average strength at the failure limit determined by experimental testing (2.693 kN) differs from the average strength at the failure limit determined by numerical modelling (2.650 kN) by –1.62 % (Table 3). The difference of the average measured vertical displacement at midspan (15.32 mm) and numerically determined values (14.93 mm) is –2.61 %.

4 CONCLUSIONS
4. ZAKLJUČAK

The determined value of average modulus of elasticity in bending E_b 12935.4 MPa by experimental testing differs from the values stated in literature for Scots pine (*Pinus sylvestris*) 12800 MPa (Table 1) by 1.05 %. The average bending strength R_b 75.9 MPa determined with the use of the same group of specimens differs by 11.74 % from the published value of 86.0 MPa. The determined average values E_b and R_b confirm the values of these constants mentioned in the paper of Matovič (1993) and Požgaj *et al.* (1997, 2004). The partial results of experimental testing of specimens show that constants E_b and R_b are dependent on the orientation and density of annual rings.

The use of anisotropic plasticity material model (Moses and Prion, 2004) for wood modelling with elastic and material constants according to Table 1, while taking into account non-interactive failure criterion and the idealisation of the annual rings characteristics, showed good agreement between the results of numerical analysis and experimental testing of wood specimens. The difference between experimentally and numerically determined results is on average up to 2.7 %. Numerically determined load curves follow the load curves determined by experimental testing. The use of anisotropic plasticity material model can be seen on examples of load test modelling, numerical determination of load bearing capacity, i.e. in cases when the level of the applied loading is higher than the load when the material failure occurs. Otherwise, the above described approach can be replaced by a simpler, orthotropic material model with elastic constants according to Table 1 and interactive failure criteria – Hoffman (Hoffman, 1967) and Tsai-Wu criterion (Tsai and Wu, 1971).

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Morphological and Thermal Properties of Cellulose Nanofibrils Reinforced Epoxy Nanocomposites

Morfološka i toplinska svojstva epoksidnih nanokompozita ojačanih celuloznim nanofibrilima

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ABSTRACT • *Epoxy resins have gained attention as important adhesives because they are structurally stable, inert to most chemicals, and highly resistant to oxidation. Different particles can be added to adhesives to improve their properties. In this study, cellulose nanofibrils (CNFs), which have superior mechanical properties, were used as the reinforcing agent. Cellulose nanofibrils were added to epoxy in quantities of 1 %, 2 % and 3 % by weight to prepare nanocomposites. Morphological characterization of the composites was done with scanning electron microscopy (SEM). Thermal properties of the nanocomposites were investigated with Thermogravimetric Analyzer (TGA/DTG) and Differential Scanning Calorimeter (DSC). SEM images showed that the cellulose nanofibrils were dispersed partially homogenous throughout the epoxy matrix for 1 % CNF. However, it was observed that the cellulose nanofibrils were aggregated (especially for 2 and 3 % CNFs) in some parts of the SEM images, and the ratios of the aggregated parts increased as the loading rate of the cellulose nanofibrils increased. The TGA curve showed that DTG and decomposition temperature of pure epoxy was higher than that of the nanocomposites. The DSC curve showed that the glass transition temperature (T_g) value of pure epoxy was found to be similar with Tg of the nanocomposites.*

Keywords: *Epoxy nanocomposites, cellulose nanofibrils, morphological and thermal analysis*

SAŽETAK • *Epoksi smole smatraju se važnim ljepilima jer su strukturno stabilne, inertne na većinu kemikalija i vrlo otporne na oksidaciju. Ljepilima se za poboljšanje njihovih svojstava mogu dodati različite čestice U ovom istraživanju, kao sredstvo za ojačanje kompozita upotrijebljeni su celulozni nanofibrili (CNFs), koji imaju izvrsna mehanička svojstva. Celulozni su nanofibrili dodani epoksi smoli u količini od 1 , 2 i 3 % mase radi izrade nanokompozita. Morfološka karakterizacija kompozita napravljena je skenirajućim elektronskim mikroskopom (SEM). Toplinska svojstva nanokompozita istražena su termogravimetrijskim analizatorom (TGA/DTG) i diferencijalnim skenirajućim kalorimetrom (DSC). SEM slike pokazale su da su celulozni nanofibrili raspršeni djelomično homogeno u matrici od epoksidne smole s 1 % CNFs-a. Međutim, uočeno je da su celulozni nanofibrili agregirani (pogotovo za 2 i 3 % CNFs-a) u nekim dijelovima SEM slike, a udjel agregiranih dijelova povećava se s udjelom celuloznih nanofibrila. TGA krivulja pokazala je da su DTG i temperatura raspadanja čiste epoksi smole veće od*

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temperature raspadanja nanokompozita. DSC krivulja pokazala je da je temperatura staklastog prijelaza (T_g) čiste epoksi smole slična vrijednosti T_g za nanokompozite.

Ključne riječi: *epoksidni nanokompoziti, celulozni nanofibrili, morfološka i toplinska analiza*

1 INTRODUCTION
1. UVOD

Generally, epoxy adhesives have been used because they have good physical properties and high bonding strength. Epoxies have many applications, ranging from electronic technologies to the development of new materials (Kozma and Olefjord, 1987). Their properties can be tailored for the desired end use, *e.g.*, they can be filled or foamed, flexible or rigid, high or low modulus materials, a conductor or an insulator, a fire retardant, and resistant to chemicals. Epoxy systems basically contain two main components, *i.e.*, the resin and a hardener. The hardener initiates the chemical reaction, which converts the epoxy resin into a solid material that has a cross-linked network of chains of molecules. Epoxies are said to be 'thermosetting' because, when they are cured, they are irreversibly rigid and relatively unchanged by heat. Curing of epoxies begins when a hardener is added. The curing of epoxy resins generally is an exothermic reaction, which causes the temperature of the process to increase (Petrie, 2006). Epoxies are used extensively in many applications to bond the substrates of different materials (Lapique and Redford, 2002). In recent years, it has been shown that the addition of nanoparticles and nanofibrils to adhesives is an economical and environmentally friendly way to improve the various properties of a polymer. Nano-sized materials have superior properties, such as increased chemical activities, increased aspect ratios, and enhanced physical properties (Auer and Frenkel, 2001). Thus, many researchers (Zhai *et al.,* 2007; Masoodi *et al.,* 2012) have shown important progress in obtaining significant improvements in performance, such as enhanced physical, mechanical, thermal, and surface properties, by mixing low concentrations of nanoparticles or nanofibrils with epoxy.

Cellulose nanofibrils (CNFs), which are natural fibrils that occur at the nano scale, were selected for use in producing nanocomposites. The cellulose chains are held together by hydrogen bonds between hydroxyl groups. Therefore, cellulose chains have high strength and stiffness. They have begun to receive additional attention as a reinforcement material because of reductions in the energy requirements for breaking down cellulose fibrils in nanofibrils (Siro and Plackett, 2010). Previous studies on reinforced epoxy, an adhesive that is not used extensively in the wood industry, showed that the addition of different fillers improved the toughness of the adhesive bond (Kinloch and Lee, 2003; Stewart *et al.,* 2007).

In this study, cellulose nanofibrils were selected because of their sustainability, industrial ecology, eco-efficiency, inexpensive cost, green chemistry, and abundance in nature. Cellulose nanofibrils have a high reinforcing effect and can improve the properties of the matrix (Sain and Oksman, 2005). Epoxy was chosen as the matrix due to its good physical properties and excellent bonding strength. Thermal properties of the composites prepared with epoxy and cellulose nanofibrils at different loadings (1 %, 2 %, and 3 % by weight) were investigated with thermogravimetric analysis (TGA/DTG) and differential scanning calorimeter (DSC). Morphological structure of the obtained composites was characterized with scanning electron microscopy (SEM).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Cellulose nanofibrils (CNFs) used in this study were a commercial product, ARBOCEL MF40-10 at 10 wt % from J. Rettenmaier & Söhne (JRS), Germany. The SEM images of CNFs are given in Fig. 1.

The CNFs were used to prepare the epoxy nanocomposites. A commercially available Technobond 3000 adhesive epoxy with two components, *i.e.*, a resin and a hardener, was obtained from Techno Structural Chemicals, Turkey. The density of the epoxy adhesive was 1.15 g/cm^3. The flammable point of the epoxy was 180 °C, and the curing time was 45 min.

Different quantities (1 %, 2 %, and 3 % wt) of cellulose nanofibrils were added to the epoxy resin, and the mixture was blended mechanically with a mechanical stirrer at 1500 rpm for 20 min to obtain even

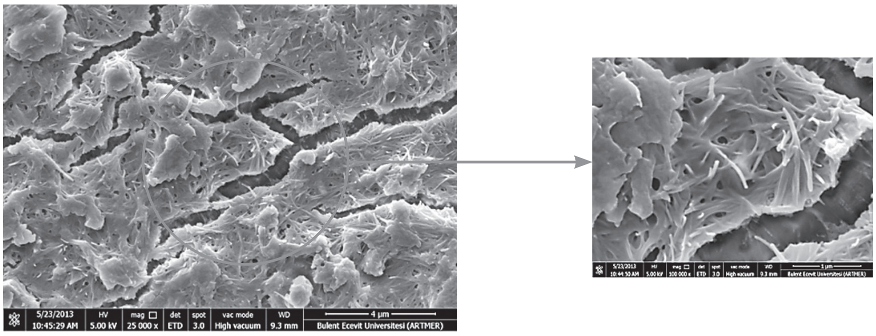

Figure 1 SEM images of cellulose nanofibrils
Slika 1. SEM slike celuloznih nanofibrila

dispersion. Then, an equal amount of hardener was added to the mixture, which was mixed mechanically again for 10 min. The hardener was mixed homogenously throughout the adhesive by mechanical dispersion. An epoxy adhesive without cellulose nanofibrils was also prepared using equal amounts of resin and hardener, which were mixed mechanically until the mixture was homogeneous. The prepared adhesives were cast in aluminum molds, and the molds were cured for 1 day at 50 °C in an oven having ±3 °C sensitivity and working without air circulation.

The morphology of the surfaces of the epoxy films was observed with an environmental scanning electron microscope (ESEM) (Phillips Electroscan 2020) with an accelerating voltage of 5 kV. The surfaces of all samples were sputter-coated with gold using a Denton sputter coater for enhanced conductivity. The thermal stability of the nanocomposites reinforced with cellulose nanofibrils was investigated using thermogravimetric analysis (TGA/DTG) (Perkin Elmer, TA Instruments, USA). The samples were heated from 25 °C to 600 °C with a heating rate of 10 °C/min and a nitrogen flow of 100 mL/min. The differential scanning calorimeter (DSC) tests were performed on a DSC 2920 (Perkin Elmer, TA Instruments, USA) at a heating rate of 5 °C/min under a nitrogen atmosphere. The samples that were used weighed about 10 mg.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The SEM was an effective method for investigating the morphological characteristics of the composites. Fig. 2 shows the distribution of CNFs in the epoxy matrix. The SEM results showed that the CNFs were dispersed throughout the epoxy matrix. The dispersion of CNFs changed as the loading rates of the CNFs were increased from 1 % to 3 %. Fig. 2 shows that clumping occurred for the 2 % and 3 % loadings of CNFs due to the strong affinity for hydrogen bonding or insufficient mixing. For the case of low loading, *i.e.*, 1 %, the dispersion of CNFs was partially homogenous (Fig. 2a and 2b), but this condition was found to deteriorate as the loading was increased (Fig. 2c, 2d, 2e, and 2f). The poor dispersion can be said to occur due to increasing of viscosity. There were mechanically weak locations in the epoxy due to inadequate dispersion and poor bonding of the cellulose nanofibril domains. Therefore, the poor dispersion can be the cause of decreased mechanical performance.

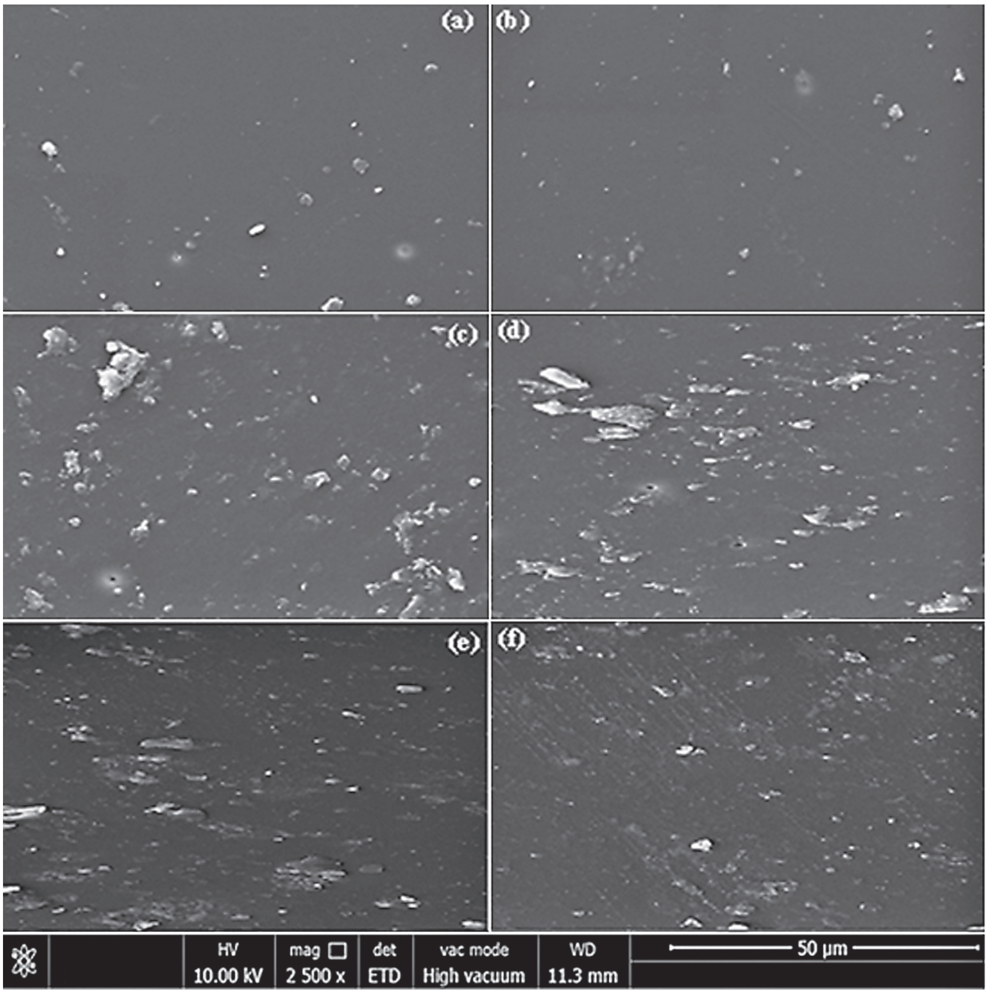

Figure 2 SEM images of cellulose nanofibrils reinforced epoxy nanocomposites: (a) and (b) 1 % CNF; (c) and (d) 2 % CNF; (e) and (f) 3 % CNF
Slika 2. SEM slike epoksidnih nanokompozita ojačanih celuloznim nanofibrilima: a) i b) uz 1 % CNFs-a; (c) i (d) uz 2 % CNFs-a; (e) i (f) uz 3 % CNFs-a

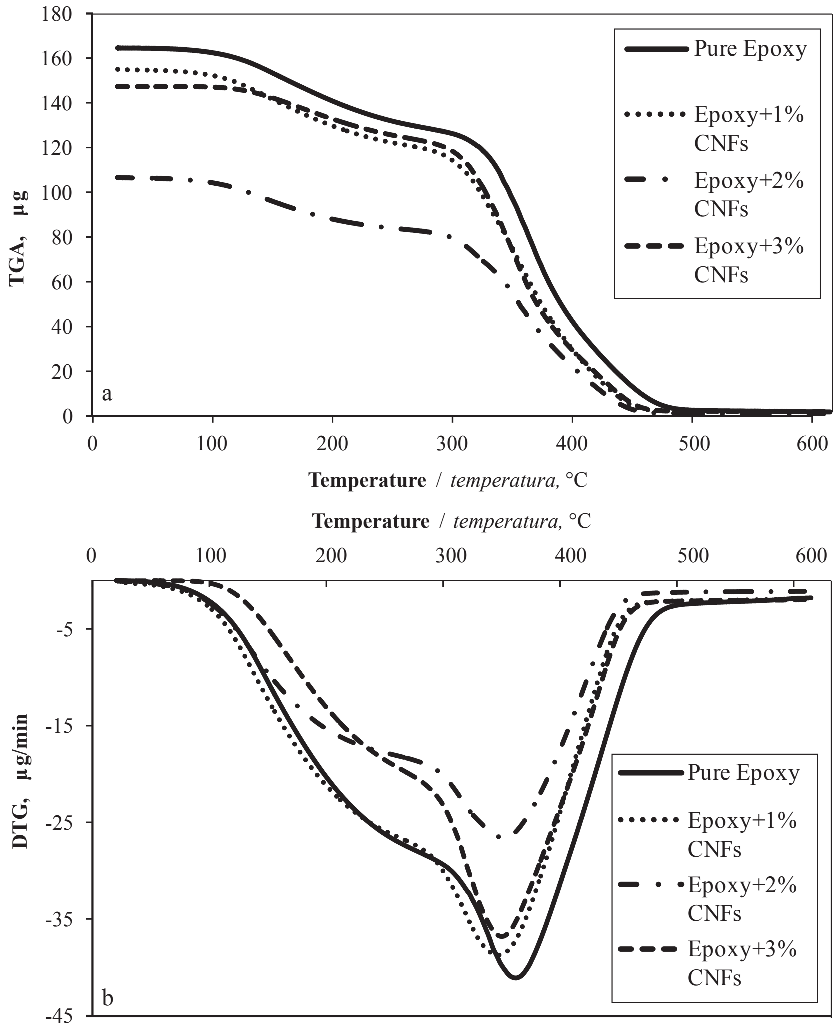

Figure 3 TG/DTG curves of CNF-reinforced epoxy nanocomposites
Slika 3. TG/DTG krivulje epoksidnih nanokompozita ojačanih celuloznim nanofibrilima

Lu *et al.* (2008) reported the surface modification of micro-fibrillated cellulose for epoxy composite applications. The SEM results showed that there was a non-uniform phase morphology that constituted many granular domains for all of the composites that were prepared. This was possibly because of poor mechanical mixing or faster cross-linking nature of the surface molecules, which formed a particulate structure (Nair and Dufresne, 2003).

Alamri and Low (2012) studied hybrid epoxy composites using cellulose and nano-SiC. The results showed that the dispersion of cellulose nanofibrils (1 %) was essentially homogenous, but the dispersion for 3 % was found to deteriorate, and many agglomerations were observed at this loading. Fig. 3 shows the thermal stability of the epoxy nanocomposites.

Three degradation steps for the samples were determined from the weight changes in TGA and the derivatives of the weight loss curves in Fig. 3a and Fig. 3b. At the first degradation point, pure epoxy and cellulosic nanocomposites exhibited mass losses due to the evaporation of moisture at around 50 °C to 100 °C. Other decomposition points were determined in the DTG curves. A different decomposition point was

Table 1 Summary data of thermal stability of CNF-reinforced epoxy composites
Tablica 1. Sažeti podaci toplinske stabilnosti epoksidnih nanokompozita ojačanih celuloznim nanofibrilima

Samples *Uzorci*	**DTG_{max}**	**$T_{10\%}$**	**$T_{50\%}$**	**Maximum decomposition** *Najveća dekompozicija*	
				Residue / *Ostatak*	Mass loss / *Gubitak mase*
	°C	°C	°C	%/min	%
Pure epoxy / *čista epoksidna smola*	362.7	170.1	362.1	0.5	99.5
1 % CNF + epoxy / *1 % CNF + epoksidna smola*	358.1	161.5	347.4	1.8	98.2
2 % CNF + epoxy / *2 % CNF + epoksidna smola*	355.8	168.9	350.5	1.9	99.1
3 % CNF + epoxy / *3 % CNF + epoksidna smola*	351.4	169.5	350.7	1.9	99.1

Legend: DTG_{max} shows maximum degradation point of the composites; $T_{10\%}$ and $T_{50\%}$ show the degradation temperature at 10 % and 50 % weight losses, respectively. / *Legenda: DTG_{max} pokazuje najveću temperaturu degradacije kompozita; $T_{10\%}$ and $T_{50\%}$ označava temperature degradacije pri gubitku mase od 10 i 50 %.*

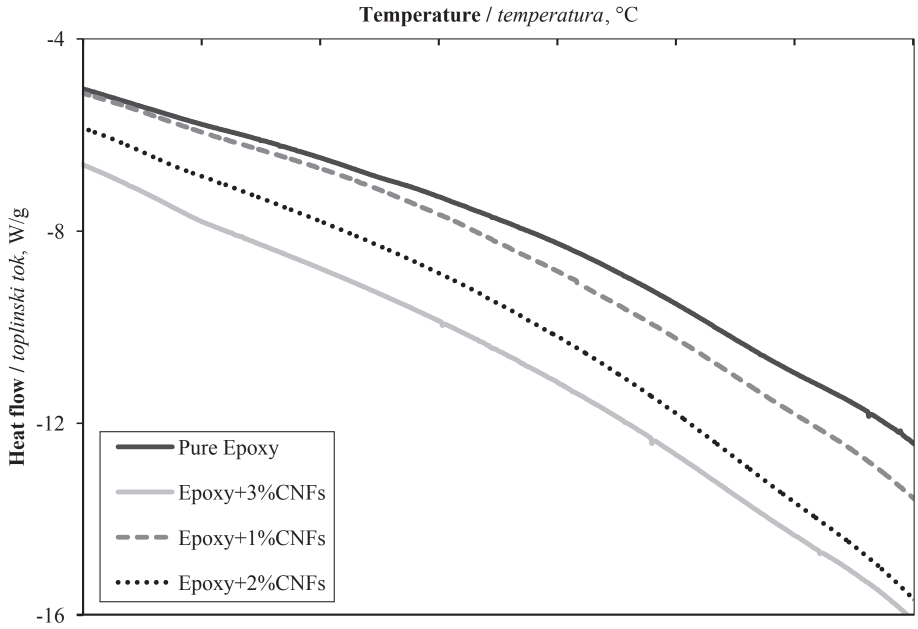

Figure 4 DSC curves of pure epoxy and cellulosic epoxy nanocomposites
Slika 4. DSC krivulje čiste epoksidne smole i celuloznih epoksidnih nanokompozita

found due to the presence of cellulose nanofibrils. The third point is shown at $T_{50\%}$ (Tab. 1). DTG peaks showed that the peak and degradation temperatures of all composites were similar to that of pure epoxy. It was, however, found that the composites had shoulders (2^{th} degradation point between 150 °C and 250 °C) in DTG curves due to the presence of CNFs.

It was found that the thermal stability of the composites was not improved by the addition of CNFs. When CNFs were added, the curves of DTG_{max} (Tab. 1) were found to range from 362.7 °C to 351.4 °C. The DTG values do not have a positive effect in raising the loading rate. The TGA curves decreased as the particle loadings increased. The highest residue of composites was found to be 1.9 % for 2 % and 3 % additions of the cellulose nanofibrils. The maximum mass loss was calculated to be 99.5 % for pure epoxy. Alamri and Low (2012) studied the thermal stability of epoxy nanocomposites. Their results showed that, at low temperatures (< 200 °C), epoxies with 1 % and 2 % CNFs had better thermal stability than pure epoxy and those with 3 % CNFs. Lu *et al.* (2008) worked with micro-fibrillated cellulose epoxy composites. The results showed that the decomposition of neat epoxy occurs between 325 °C and 450 °C, and the degradation of micro fibrillated cellulose (MFC) starts at 280 °C, which is lower than the temperature at which epoxy starts to degrade. Thus, the thermal stability of the composite was decreased slightly by the addition of 5 % MFC, and MFC does not have any significant effect on the thermal stability of the resulting composite, although the residual weight following decomposition increased slightly. Fig. 4 shows DSC thermograms of the neat epoxy and the nanocomposites prepared with cellulose nanofibrils. The T_g values of the nanocomposites showed no appreciable changes among each other compared with their increase over neat epoxy. Isik *et al.* (2003) also observed that the glass transition temperatures of epoxy slightly increased with increasing clay content. This status explained this behavior in terms of the restricted mobility of polymer chains due to the interaction between the particles and the polymer.

4 CONCLUSIONS
4. ZAKLJUČAK

The morphologies of epoxy nanocomposites that were prepared with cellulose nanofibrils were characterized and investigated for their thermal properties. The results showed that cellulose fibrils were found to have some effects on the morphological and thermal properties of epoxy. When the cellulose loading rate of nanofibrils in the epoxy was increased to 3 %, some clumping was observed on the SEM photographs. The thermal stability of epoxy was decreased by the addition of cellulose fibrils, and the highest DTG_{max} was found at 362.7 °C for neat epoxy, whereas DTG_{max} was decreased to 351.4 °C when the cellulose loading was increased.

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Process Characteristics of Horizontal Log Band Saw in Cutting Frozen Beech

Obilježja procesa obrade na horizontalnoj tračnoj pili trupčari pri piljenju zamrznute bukovine

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ABSTRACT • *The paper presents the research results of process characteristics during cutting beech prisms on horizontal log band saw type Mebor HTZ–1000. The band saw blades were equipped with swaged teeth and stellited teeth. The power consumption, tool wear resistance, surface roughness and variation of board thickness during 6000 m sawn prism length were studied. All studied parameters were monitored during the tool life-circle (from sharpening to loosing its sawing capability). Wearing process was monitored as a function of cutting length. The cutting edge modification, i.e. its wearing affecting energetic demands during sawing process as well as the surface quality and dimension accuracy of produced work piece was monitored, too.*
Based on cutting edge wear process and its effect on the above mentioned sawing process parameters, the optimal period of saw band replacement with a new or sharpened one was determined. Based on measured parameters, it was possible to determine which type of band saw tooth is recommended for cutting frozen beech.

Key words: *horizontal log band saw, band saw blade, stellite teeth, swaged teeth, cutting wedge wear, cutting power, surface quality*

SAŽETAK • *U radu se iznose rezultati istraživanja obilježja procesa piljenja bukovih prizmi na horizontalnoj tračnoj pili trupčari proizvođača Mebor, model HTZ-1000. Za piljenje su primijenjeni listovi pila sa stlačenim i stelitiranim zubima. Proučavana je snaga potrebna za piljenje, postojanost alata, hrapavost obrađene plohe i odstupanje debljine piljenica od nominalne dimenzije, i to tijekom piljenja prizmi ukupne duljine 6000 m. Svi proučavani parametri praćeni su tijekom vremena postojanosti pojedinog lista pile. Proces trošenja zubi lista pile promatran je kao funkcija duljine puta zahvata tijekom piljenja. Također je analiziran utjecaj postupnog zatupljivanja zubi lista pile na energiju potrebnu za piljenje, na kvalitetu obrađene plohe i na odstupanje dimenzija piljenica s obzirom na nominalne vrijednosti.*
Uzimajući u obzir proces zatupljivanja zubi lista pile i utjecaj na promatrane parametre obrade, određeno je optimalno vrijeme zamjene lista pile. Na temelju izmjerenih parametara zaključeno je koji je način pripreme zubi pile preporučljiv za piljenje zamrznute bukovine.

Ključne riječi: *horizontalna tračna pila trupčara, list tračne pile, stelitirani zubi, stlačeni zubi, trošenje oštrice alata, snaga rezanja, kvaliteta obrađene plohe*

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1 INTRODUCTION
1. UVOD

Log band saw is one of the main sawmilling machines designed to saw leafy hardwood species with large diameters. Csanády *et al*. (2011) defined the sawing process on log band saw as wood splitting by evenly moving tool, during which feed force vector acts across the saw band. As it was presented by Detvaj (2003) and Siklienka (2006), it is an individual method of cutting, the principle of which is based upon qualitative and geometrical characteristics of hardwood logs (Gejdoš *et al*., 2014; Suchomel *et al*., 2010). These logs often require specific cutting layout during the sawing process. The advantage of band saws is that there is no need to classify and sort logs into large number of categories in regard to variance of log cross-section (Lisičan *et al*., 2000).

The sawing process on a log band saw is considerably influenced by numerous parameters. The season of the cutting process (summer/winter) also affects the process. Frozen wood changes its mechanical properties and it has different impact on the cutting tool. The consequence is the reduction of the dimensional accuracy of sawn products as well as production economics effects (Fryková *et al*., 2010). Frozen wood is more fragile than unfrozen wood and according to Lustrum (2001) and Gaff *et al*. (2010) there is less variance of surface unevenness due to lower saw band plate friction. Orlowský *et al*. (2006) as well as Fryková *et al*. (2010) allege that sawing frozen wood is energetically more demanding than sawing unfrozen wood.

In practice, it is very important to saw with minimal energetic input demands at the same time attempting to achieve the best output quality of sawing products. As mentioned by Wasilewski *et al*. (1999) and also Siklienka *et al*. (2005), suitable tool selection, tool geometry and cutting conditions can lower the costs of the cutting process and increase the performance and accuracy of cutting.

Surface quality of wooden sawing products is mostly characterized by their unevenness. Siklienka (2004) and Sandak *et al*. (2005) present 4 classes of surface unevenness: form variance, washboarding, roughness and micro-roughness.

During sawing on band saws, the quality of workpieces is monitored and evaluated on the basis of the surface unevenness parameter (P_z – the difference between height mean value of five highest points and mean value of five lowest points of primary profile) in accordance to STN EN ISO 4287 and on the basis of deviation of trimmed layer thicknesses. Both parameters are monitored in dependence of the indicated chip length (ICL). This quality monitoring method was also used by Fryková *et al*. (2010) and Silienka *et al*. (2008, 2011).

The indicated chip length (ICL) is the tool effective edge trajectory through the workpiece during cutting. An important influencing factor that affects energy demands as well as the quality of cutting surface is the wear of the cutting edge. Wearing is caused by the resistance of the machined material (Očkajová, 2002). This resistance is based on wood stiffness, bend deformation, chip friction on teeth cutting face and friction of the teeth back as well as machined surface (Hájnik *et al*., 2008).

The aim of this article is to describe the effect of cutting wedge wearing on energy demands and qualitative indicators of the sawing process by sawing frozen beech prisms on horizontal log band saw type Mebor HTZ-1000. The practical result of this article are references that should enable choosing the suitable saw band plate in accordance with the cutting wedge wear, cutting process energy demands and the quality of machined surface.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

The sawing of beech prisms was carried out on horizontal log band saw type Mebor HTZ-1000 (Fig. 1), installed in VDL TU in Zvolen.
Technical data:
- wheel diameter: D = 1000 mm,
- band blade width: B = 95 mm,
- cutting speed: v_c = 30 m·s^{-1},
- feed rate: v_f = (0 ÷ 40) m·min^{-1} (adjustable)
- max. log diamater: 800 mm,
- main electromotor output power: P_{EM} = 22 kW.

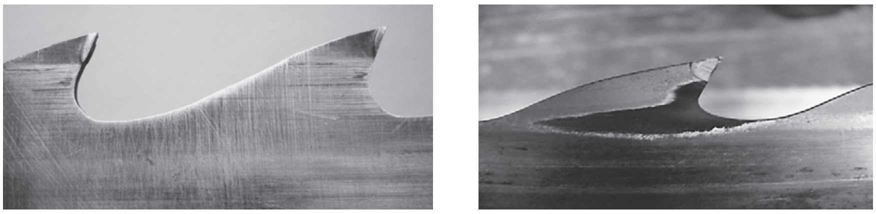
2.1 Characteristics of sample work pieces
2.1. Parametri uzoraka

Beech prisms – European beech (*Fagus sylvatica* L.) were used for the experimental measurement. The prisms humidity was over the point of fibers saturation, in the range (53÷56) %. The logs were transported from the Budča area – provided by the University forest enterprise (ŠLP) TU Zvolen. The cutting of beech prisms was done under the following conditions:
- feed rate v_f =10 m·min^{-1},
- cutting height h = 300 mm,
- band saw blade with stellited teeth and band saw blade with swaged teeth
- thickness of trimmed sample = 3 mm
- frozen prisms – prisms were placed in ambient temperature -15 °C for at least 48 hours.

Figure 1 Horizontal log band saw Mebor HTŽ -1000
Slika 1. Horizontalna tračna pila trupčara Mebor HTŽ-1000

Table 1 Geometry parameters of the band saw blade
Tablica 1. Geometrijski parametri lista tračne pile

Parameter *Parametar*	Symbol *Simbol*	Value *Vrijednost*	Parameter *Parametar*	Symbol *Simbol*	Value *Vrijednost*
Clearance angle, ° / *leđni kut,* °	α	15	Blade thickness, mm / *debljina lista, mm*	a	1.1
Sharpness angle, ° / *kut oštrice,* °	β	50	Tooth height, mm / *visina zuba, mm*	h_z	10
Rake angle, ° / *prednji kut,* °	γ	25	Tooth spacing, mm / *korak zuba, mm*	t_z	45
Cutting angle, ° / *kut rezanja,* °	δ	65	Swage set, mm/ *ispon zuba, mm*	e	0.35 ± 0.05
Band width, mm / *širina lista, mm*	B	100			



a) b)

Figure 2 Swaged tooth a), and tooth with stellite b) used in experimental cutting
Slika 2. Detalj listova pila primijenjenih u eksperimentu: a) sa stlačenim zubima i b) sa stelitiranim zubima

2.2 Saw band characteristics
2.2. Parametri lista pile

For the purpose of the experiment, band saw blades made by UHB 15 (Uddeholm, 2000) with hardness 38 – 44 HRc, supplied by KLI Produkt s.r.o were used. Geometry parameters of band saw blades (PP) are shown in Table 1 for both types of teeth.

Band saw blade with a swaged, i.e. a stellited tooth used in experimental cutting are shown in Fig. 2.

2.3 The experiment procedure
2.3. Tijek eksperimenta

At the beginning of the experiment, the initial cutting wedge wear on the band saw blade with sharpened swaged teeth was measured. Two initial cuts with sharpened saw band were made. Samples for the unevenness test were removed and at the same time the input cutting power was measured. The cutting was performed with the same band saw blade up to 50 m ICL. The samples for the unevenness test were removed periodically. Before that, input cutting power and cutting wedge wear were measured. This testing procedure was repeated every 500 m ICL until the machined surface has shown defects of quality visible with the naked eye. The same test procedure was applied for both types of teeth.

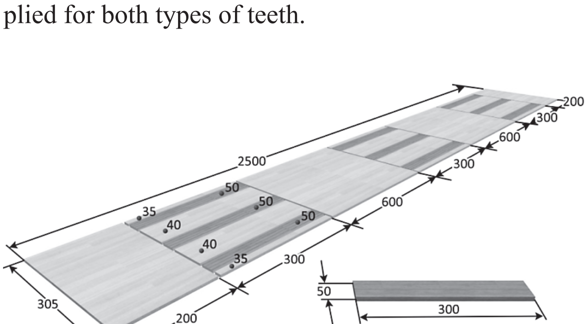


Figure 3 Sample selection for surface unevenness measurement
Slika 3. Shema uzimanja uzoraka od piljenica za određivanje kvalitete obrađene plohe

Surface unevenness was measured on samples of 300x50x3 mm. The samples were cut-out following the cutting layout shown in Fig. 3.

The surface unevenness was measured with a laser measuring equipment, Type LPM-4, which was assembled and installed at the Department of Woodworking at the Technical University in Zvolen in cooperation with the Kvant Ltd. Company. The measuring chain (Fig. 4) was assembled of the following components: a profile meter LPM-4 was installed on the height adjustable console; the recording and evaluation unit was equipped with a LPM-View software. LPM uses the triangulation principle of laser profile meter. The image of the laser line was scanned with a digital camera. The interpreted profile was scanned from the image cross section (Siklienka *et al*., 2001). The principle of the laser profile meter is shown in Figure 5.

Surface unevenness was evaluated according to the actual woodworking standard STN EN ISO 4288 on the length of 80 mm. The surface unevenness of the tested specimen was measured in feed speed direction during cutting. The surface unevenness was evaluated based on the maximum height of primary profile P_z.

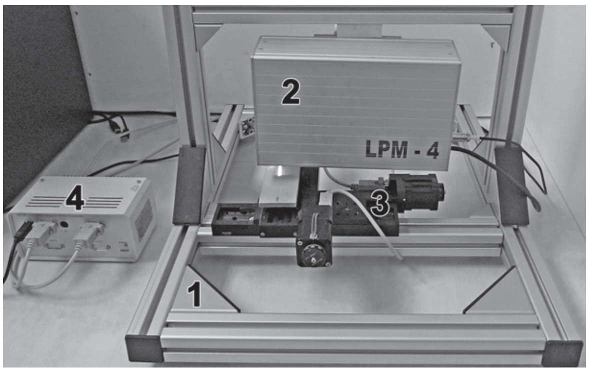


Figure 4 Surface roughness measuring chain
Slika 4. Mjerni lanac za određivanje hrapavosti piljene plohe

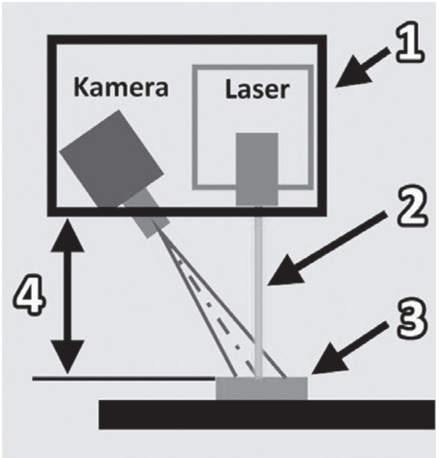


Figure 5 Principle of laser profile meter LPM 4 (1 – camera, 2 – laser, 3 – tested specimen, 4 – distance between LPM and measured object)
Slika 5. Shematski prikaz načela mjerenja uz pomoć laserskog profilometra LPM 4 (1–kamera, 2 – laser, 3 – uzorak, 4 – udaljenost između lasera i mjernog objekta)

Cutting input power was measured using the measuring device designed for analyzing the electrical power network quality. The Metrel Power Q Plus MI 2392 device was installed into the electric network before connecting the separate phases into the main machine electromotor.

The measuring principle was based on the changes of power demand of the main electromotor of the log band saw from the power network (Siklienka *et al*., 2011). For the calculation of the electromotor input power, the Metrel Power Q scans the changes of current demand (I), actual voltage (U) and power factor ($\cos \varphi$). The values were recorded in intervals of 1 second. All values were measured with the frequency of 1024 Hz. The measuring values were averaged in periods of 1 second. These averaged values were the base for the power consumption evaluation. The power measuring device was connected to the computer via RS 232 interface. Values were downloaded with the Power Q Link 2.1 software (Hajník, 2008).

Cutting wedge wear was measured using microscopic method based on measuring the increase of cutting edge radius (r_n). The increase of the wedge radius is a consequence of cutting during certain effective time (Fig. 6). The measurements were carried out according to the internal methodology at the Department of Woodworking at the Technical University in Zvolen. As Hajník *et al*. (2008) stated, it is a method of evaluation with the help of a digital camera and a microscope. Digital photography of the cutting wedge (Fig. 6/c) is graphically analyzed using AutoCAD software.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Cutting wedge radius
3.1. Radijus zaobljenosti oštrice

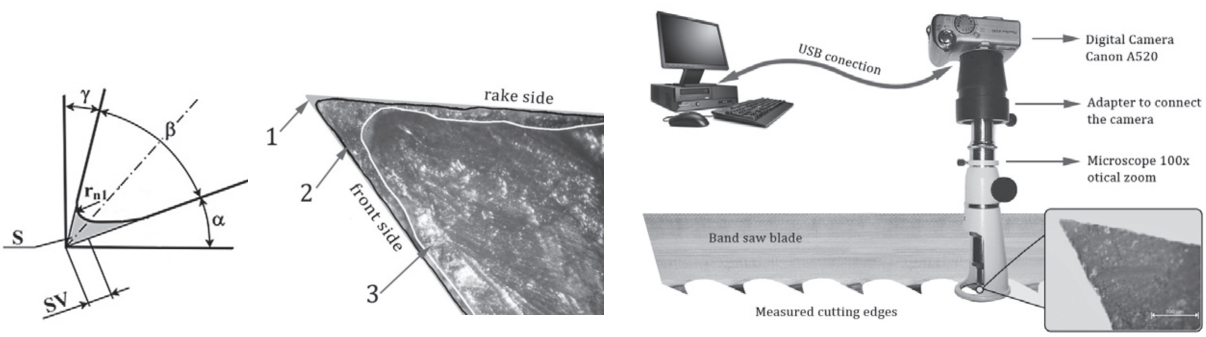
Increase of the cutting wedge radius of saw bands swaged teeth and stellited teeth at sawing frozen beech prisms are given in Table 2.

The data obtained with the experimental cutting given in Table 3 were analyzed and fitted with the polinomal regression. The results are shown in Fig. 7a) and 7 b).

Stellited teeth have shown evidently higher wear resistence in comparison with swaged teeth in cutting frozen beech prisms. Catastrophic wear was observed on swaged teeth after cutting length of 2500 m. In the

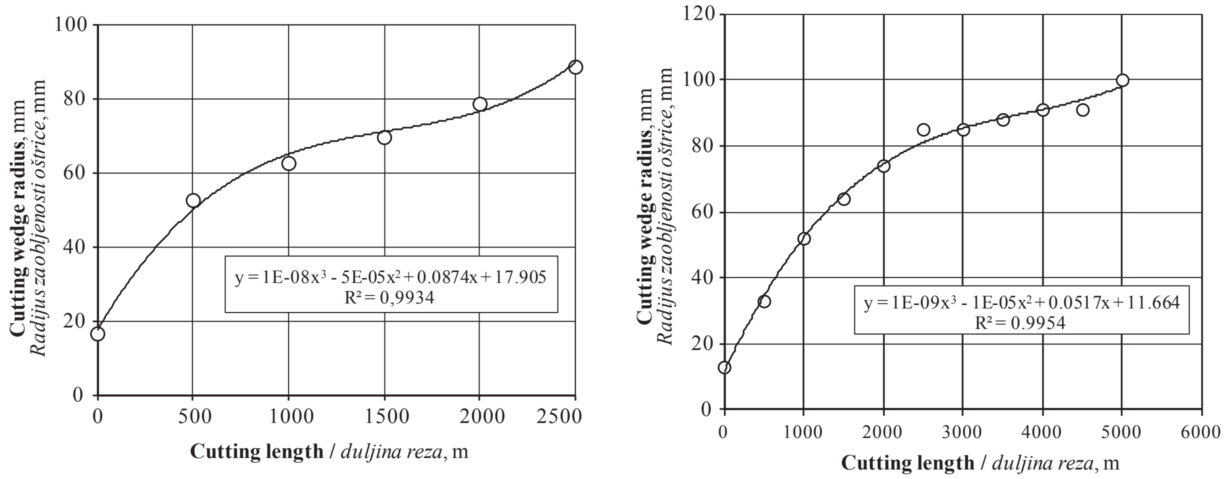
Table 2 Change of the cutting wedge radius during cutting for swaged teeth and stellited teeth as a function of cutting length
Tablica 2. Promjena radijusa zaobljenosti oštrice za stlačene i stelitirane zube kao funkcija duljine puta zahvata

ICL, m	**Cutting wedge radius, μm** *Radijus zaobljenosti oštrice, μm*	
	Swaged teeth *Stlačeni zubi*	Stellited teeth *Stelitirani zubi*
0	17	13
500	53	33
1000	63	52
1500	70	64
2000	79	74
2500	89	85
3000	-	85
3500	-	88
4000	-	91
4500	-	91
5000	-	100



a) b) c)

Figure 6 a) Wear of cutting edge (SV), b) real wear of cutting wedge, c) measuring apparatus for measuring SV with microscopic method
Slika 6. a) Trošenje rezne oštrice (SV), b) prikaz stvarnog trošenja oštrice i c) mjerni lanac za određivanje zatupljenosti oštrice uz pomoć mikroskopa



a) b)

Figure 7 Cutting wedge radius in relation to cutting length: a) swaged teeth and b) stellited teeth
Slika 7. Promjena radijusa zaobljenosti oštrice kao funkcija duljine puta zahvata: a) za stlačene zube i b) za stelitirane zube pile

same cutting conditions, catastrophic wear was observed on the stellited teeth at the double cutting length as clearly shown in Fig. 7 a) and 7 b). Vasilka *et al*. (2009) came to the same conclusion. The increase of the radius of the cutting wedge as a result of the ICL increase was also confirmed in the works of Lisičan *et al*. (1996), Očkajová (2001), Javorek *et al*. (2006) and Siklienka *et al*. (2007).

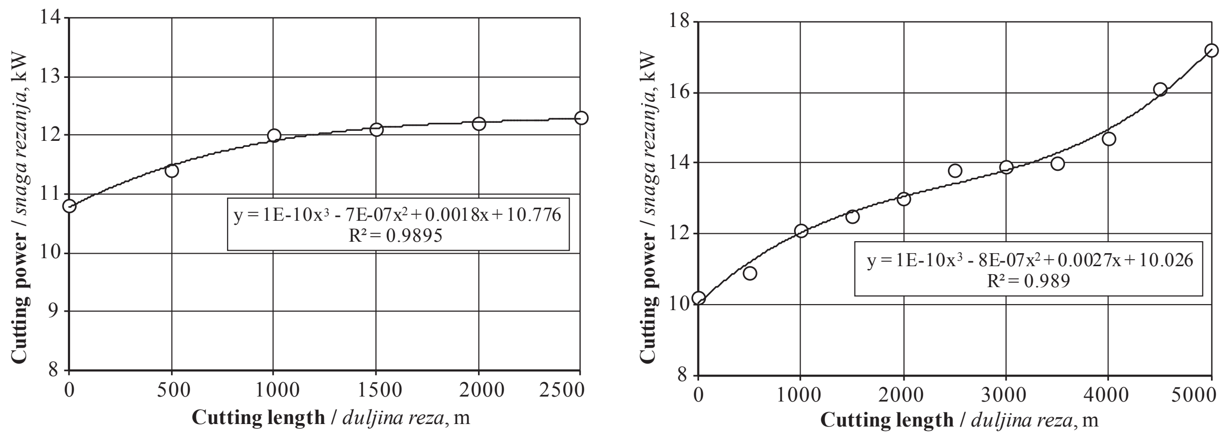
3.2 Cutting input power
3.2. Snaga rezanja

Cutting power was measured periodically in the same intervals as tool wedge radius during cutting with the swaged teeth and stelitted teeth. The results obtained during power measurements are given in Table 3. The data for cutting with swaged teeth are graphically presented in Fig. 8 a), and for cutting with stellited teeth in Fig. 8 b).

Fig. 8 a) cleary shows that the power required for cutting frozen beech prisms with sharpened teeth intensively increases at the start until approximately 1000 m of cutting length. After that, the power con-

Table 3 Power consumption in cutting frozen beech prism with swaged and stellited teeth
Tablica 3. Snaga potrebna za piljenje bukovih prizmi primjenom lista pile: a) sa stlačenim zubma i b) sa stelitiranim zubima

ICL, m	**Power consumption, kW** *Snaga piljenja, kW*	
	Swaged teeth *Stlačeni zubi*	Stellited teeth *Stelitirani zubi*
0	10.8	10.2
500	11.4	10.9
1000	12.0	12.1
1500	12.1	12.5
2000	12.2	13.0
2500	12.3	13.8
3000	-	13.9
3500	-	14.0
4000	-	14.7
4500	-	16.1
5000	-	17.2



a) b)

Figure 8 Power consumption during sawing frozen prisms in relation to total cutting lenght: a) swaged teeth, and b) stellited teeth
Slika 8. Snaga potrebna za piljenje zamrznutih prizmi u ovisnosti o ukupnoj duljini piljenja: a) za stlačene zube i b) za stelitirane zube

sumption increases lineary until the period in which catastrophic tool wear occurs. The power consumption curve follows the changes of the tool wedge radius over the whole interval of cutting length. The same comment applies to the changes in the level of power consumption in different periods when cutting with stellited teeth. It corresponds to the conclusion of Javorek (1995) and Holopírek (2004), who state that the cutting power input increases with the increase of the cutting surface, cutting time and cutting wedge wear. Similar trends were presented in the works of Siklienka *et al*. (2011) and Hajník (2008).

3.3 Sawing surface quality
3.3. Kvaliteta obrađene plohe

The tool influence on the cutting surface quality is usually evaluated by measuring surface roughness, i.e. maximum height of the primary profile (P_z). Another quality indicator, called thickness deviation, was also used in this study.

a) Surface roughness

The data obtained in measuring surface roughness are given in Table 4. The surface roughness was measured at the same time intervals as the increase of tool wedge radius and power consumption. The surface roughness in relation to cutting length for swaged teeth is graphically presented in Fig. 9a). The relation between the surface roughness and cutting length for stellited teeth is shown in Fig. 9b). The data obtained in measuring the surface roughness were statistically analyzed and fitted with linear equations. The results are also given in Fig. 9a) and b). The regression coefficients show very strong correlation between surface roughness and cutting length.

From the point of view of the machined surface quality (Table 5, Fig. 9a) and b)), it is obvious that sawing frozen beech prism using stellite tipped band saw blades leads to better surface quality. This observation corresponds with Okai's *et al*. (2006) and Lustruma's (2001) research results. The surface roughness measurement has shown that roughness of machined surface increases with the increase of cutting length as a result of cutting wedge wear (Table 3). The same conclusion was reached by Siklienka (2004), Wilkowski *et al*. (2006) and Carpa *et al*. (2006).

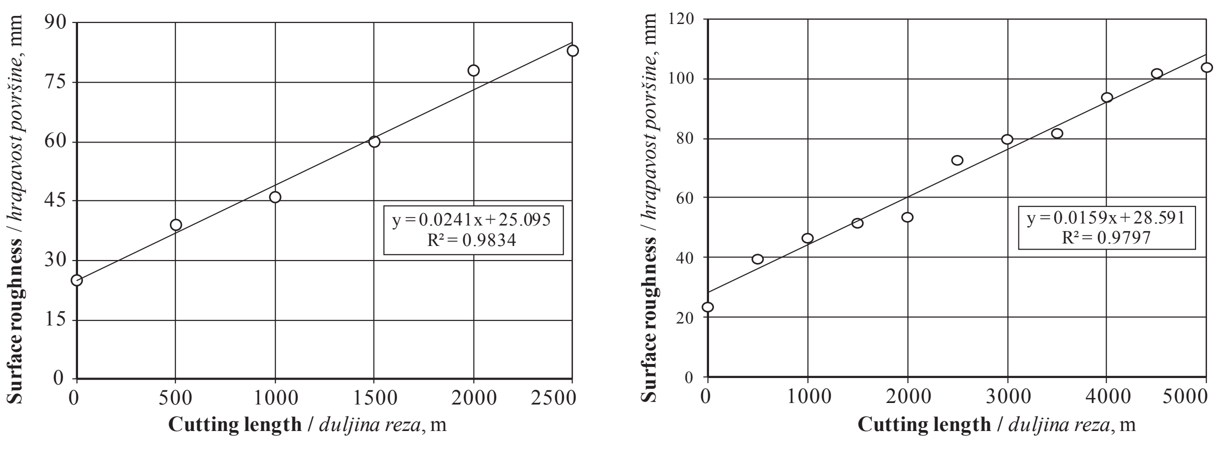
Table 4 Machined surface quality in cutting frozen beech prism with swaged and stellited teeth
Tablica 4. Kvaliteta obrađene plohe nakon piljenja zamrznutih prizmi od bukovine uz pomoć lista pile sa stlačenim i sa stelitiranim zubima

ICL, m	**Surface roughness, μm** *Hrapavost površine, μm*	
	Swaged teeth *Stlačeni zubi*	Stellited teeth *Stelitirani zubi*
0	25	24
500	39	40
1000	46	47
1500	60	52
2000	78	54
2500	83	73
3000	-	80
3500	-	82
4000	-	94
4500	-	102
5000	-	104

b) Thickness deviation

Table 5 shows the results of measurement of thickness deviations. The data are graphically presented in Fig. 10 a) and b). The data obtained by measurement were analyzed with the help of mathematical statistics and fitted with polynomial curves. The results are also shown in Fig. 10 a) and b).

Fig. 10 clearly shows that the height deviation is greater in samples sawed with the swaged teeth. The increase of the height deviation ratio on the surfaces sawed with swaged teeth is very intensive in the cutting length interval from the start to approximately 1300 m and nearly constant in the interval from 1300 m to 2300 m. After that period, the height deviation dramatically increases. The 4th degree polynomial regression very well fits the changes of the height increase of the surface sawn with swaged teeth with a very high correlation coefficient. The height deviations



a) b)

Figure 9 Surface roughness during sawing frozen prisms in relation to total cutting lenght: a) swaged teeth and b) stellited teeth
Slika 9. Ovisnost hrapavosti obrađene plohe pri piljenju zamrznutih bukovih prizmi o ukupnoj duljini puta zahvata: a) za stlačene zube i b) za stelitirane zube

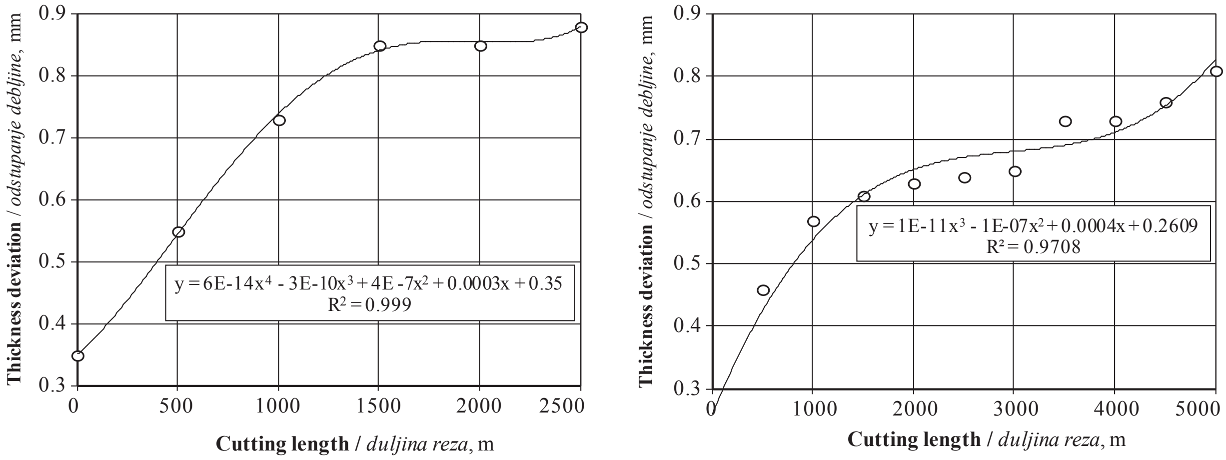


Figure 10 Thickness deviation of the surface in relation to cutting length: a) for swaged teeth, b) for stellited teeth
Slika 10. Promjena odstupanja debljine ispiljenih uzoraka od nominalne dimenzije s obzirom na duljinu puta zahvata alata: a) za stlačene zube i b) za stelitirane zube

Table 5 Surface height deviation in cutting frozen beech prism with swaged and stellited teeth
Tablica 5. Odstupanje debljine ispiljenih uzoraka od nominalne dimenzije pri piljenju zamrznutih bukovih prizmi primjenom lista pile sa stlačenim i sa stelitiranim zubima

ICL, m	**Thickness deviation, mm** *Odstupanje debljine, mm*	
	Swaged teeth *Stlačeni zubi*	Stellited teeth *Stelitirani zubi*
0	0.35	0.23
500	0.55	0.46
1000	0.73	0.57
1500	0.85	0.61
2000	0.85	0.63
2500	0.88	0.64
3000		0.65
3500		0.73
4000		0.73
4500		0.76
5000		0.81

of the surfaces sawn with stellited teeth are significantly lower. The intensive increase of height deviation could be viewed in the interval from the start to 2000 m. After that the increase ratio is approximately linear until 4000 m of cutting length. Finally, in the last section from 4000 m to 5000 m, the surface height deviation drastically increases. The changes in surface height deviation in relation to cutting length were fitted with the 3rd degree polynomial regression with very high correlation coefficient as shown in Fig. 10.

4 CONCLUSION
4. ZAKLJUČAK

Sawing frozen beech prisms on the horizontal band saw with swaged and stelitted teeth has shown some interesting results. The following conclusions could be drawn:

- Stellited teeth have shown significantly higher wear resistance in comparison to swaged teeth. Catastrophic wear was observed on swaged teeth after 2500 m of sawing length. The stellited teeth have shown near double wear resistance. The catastrophic wear was observed after approximately 4800 m of cutting length
- According to the wear characteristics of the two different types of teeth, the power consumption during tool life period has not shown the expected results. Power consumption during the first 2500 m of cutting length was comparable for both types of teeth. After that period, due to the unacceptable quality of the cutting surface, cutting with the swaged teeth was stopped.
- During sawing with the swaged teeth, the surface roughness has increased to the unacceptable level after 2500 m. That was the reason why cutting has been stopped. Quite the opposite, the surface quality with stellited teeth remained acceptable until 5000 m of cutting length.
- The results of measurement of sample height deviation are the same. The increase of height deviation ratio on the surfaces sawed with swaged teeth is very intensive in the cutting length interval from the start to approximately 1300 m and nearly constant in the interval from 1300 m to 2300 m. After that period, the height deviation dramatically increases. Height deviation of the surfaces sawn with stellited teeth is significantly lower. Intensive increase of height deviation could be observed in the interval from the start to 2000 m. After that, the increase ratio is approximately linear until 4000 m of cutting length. Finally, in the last period from 4000 m to 5000 m, the surface height deviation drastically increases.

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Laccase Application for Upgrading of Lignocellulose Fibers

Primjena lakaze za dogradnju lignoceluloznih vlakanaca

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ABSTRACT • *Laccases have the ability to oxidize both phenolic and trough mediators non-phenolic lignin related compounds. When reacting on lignin, they can display both ligninolytic and polymerizing (cross-linking) abilities, which makes them very useful for their application in industries based on lignocellulose material. Most of the published papers and applications of laccase and laccase-mediator systems on lignocellulose material relate to the pulp, paper and textile industry. Recent research has been done in terms of laccase assisted biografting of phenols and other compounds on wood surface and use of laccase for adhesion enhancement in fiberboard production. They can be introduced to wood technology as environmentally friendly enzymes. The paper reviews the application of laccases in industries based on lignocellulose material and discusses the future outlook and development in the above mentioned fields.*

Key words: *laccase, laccases mediators, lignocellulose material, lignin functionalization*

SAŽETAK • *Enzimi lakaze imaju sposobnost oksidacije fenolnih spojeva uz pomoć medijatora i nefenolnih spojeva lignina. Kada reagiraju na lignin, mogu pokazati i ligninolitičke i polimerizacijske (unakrsno povezujuće) sposobnosti, što ih čini vrlo korisnima za primjenu u industriji utemeljenoj na lignoceluloznim materijalima. Većina objavljenih radova i primjena enzima lakaze i posredničkih lakaza-sustava na lignoceluloznim materijalima odnose se na celulozu, papir i proizvode tekstilne industrije. Nedavno su provedena istraživanja o kalemljenju fenola i drugih spojeva uz pomoć lakaza na površinu drva i o primjeni lakaza za poboljšanje adhezije u proizvodnji ploča vlaknatica. Lakaze se mogu upotrijebiti u drvnoj tehnologiji kao ekološki prihvatljivi enzimi. U radu se analizira primjena enzima lakaze u industriji utemeljenoj na lignoceluloznim materijalima i razmatraju se buduće perspektive i razvoj na spomenutim područjima.*

Ključne riječi: *lakaze, posrednici lakaze, lignocelulozni materijal, primjena lignina*

1 INTRODUCTION
1. UVOD

Laccases (EC 1.10.3.2., p-diphenol:dioxygen oxidoreductase) belong to the multicopper oxidases family and are also called blue enzymes. They are widely distributed in many plant and fungal species (Riva, 2006). An enzyme of this group was first described by Yoshida (1883) at the end of the 19th century as a component of the resin ducts of the lacquer tree *Rhus vernicifera* (Yoshida, 1883). The physiological function of these biocatalysts is different in various or-

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ganisms but they all catalyze polymerization or depolymerization processes. It has been suggested that laccases are involved in cuticle sclerotization in insects and in the assembly of UV-resistant spores in *Bacillus* species. In plants, they are involved in cell wall formation and, together with peroxidases, in lignification (Mayer and Staples, 2002). In white rot fungi, the laccases are among the main enzymes involved in delignification process (Tavzes *et al*., 2009).

Meeting the challenges of reducing formaldehyde emissions from the adhesives and improving product recyclability, calls for innovative approaches to minimize the amount of binder while ensuring product quality. Enzymatic treatment of wood fibers or other wood particles before their pressing into composite boards, such as medium density fibreboards (MDF), has been investigated by Felby, Kharazipour and coworkers since 1997. For example, laccase has been shown to greatly improve the internal bond (IB) of fiber boards (Felby *et al*., 1997; Kharazipour *et al*., 1997; Hüttermann *et al.,* 2001; Felby *et al*., 2002; Felby *et al*., 2004). This effect may be explained by the fact that laccase oxidizes the phenolic structures in lignin, which leads to relatively stable free radicals that may participate in fiber bonding by subsequent radical coupling (Fackler *et al*., 2008).

Others, like Widsten (2008b), made research for combining boards without petroleum-derived wood adhesives. Furthermore, an important topic related to wood products is the chemical modification of their surface properties to improve their resistance. Enzyme technology offers an environmentally friendly method for modifying solid wood, pulp, or other lignocellulosics by biografting of phenols and other molecules on their surfaces. Properties such as antimicrobial, antifungal, UV- and weathering stability, and fire retardancy have been or can potentially be imparted to lignocellulosic substrates (Widsten *et al*., 2008a).

2 DISTRIBUTION, STRUCTURE AND MECHANISMS OF LACCASE
2. DISTRIBUCIJA, STRUKTURA I MEHANIZMI ENZIMA LAKAZE

Laccases are common enzymes in nature. The first laccase was reported in *Rhus vernicifera*, the Japanese lacquer tree (Reinhammar, 1984). Subsequently laccases have been discovered in numerous plants. The majority of laccases characterized so far have been from wood decay fungi especially from white-rot basidiomycetes (Fig. 1) that are efficient lignin degraders. Well-known laccase producers also include fungi belonging to the ascomycetes, deuteromycetes and basidiomycetes (Sharma *et al*., 2007).

The first report of prokaryotic laccase is from the rhizospheric bacterium *Azospirillum lipoferum* (Givaudan *et al.,* 1993). The best-studied bacterial laccase is the CotA, the endospore coat component of *Bacillus subtilis*. The CotA gene codes for a 65-kDa protein belonging to the outer spore coat. CotA participates in the biosynthesis of the brown spore pigment, which mu-

Figure 1 White-rot caused by basidiomycetes *Oudemansiella mucida* (photo by Franc Pohleven, 2011)
Slika 1. Bijela trulež uzrokovana basidio gljivicama *Oudemansiella mucida* (foto: Franc Pohleven, 2011)

tants in the gene encoding CotA lost the ability to produce. The protein, which was over expressed in E. coli, has a molecular mass of 65 kDa, an isoelectric point of 7.7 and is highly thermo stable (Martins *et al*., 2002). Fungal laccases molecular mass ranges from 50 to 100 kDa with a 10 to 45 % covalently linked carbohydrate molecules. For the catalytic activity, a minimum of four copper atoms per protein unit are needed, and they are divided in three Types (T1, T2, and T3). T1 is a paramagnetic copper with absorbance at 610 nm and confers the blue color to the multicopper proteins, which results from the intense electronic absorption caused by the covalent copper-cysteine bond. It is also the site where substrate monoelectronic oxidation takes place. It has a high redox potential of +790 mV. On the other hand, T2 copper shows no absorption in the visible spectrum but reveals paramagnetic properties in Electron Paramagnet Resonance (EPR) studies. It is positioned close to the T3, a binuclear center spectroscopically characterized by an electron adsorption at 330 nm. T2 and T3 copper form a trinuclear cluster, where reduction of molecular oxygen and release of water take place. The oxidation of substrates (p-diphenols) creates reactive radicals that can undergo nonenzymatic reactions like cross-linking of monomers, degradation of polymers and ring cleavage of aromatic compounds (Claus, 2003; 2004) (Fig. 2).

Because of their redox potential of around ≤0.8 V, their action is restricted to the oxidation of the phenolic lignin moiety, whereas non-phenolic substrates having redox potential above 1.3 V cannot be oxidized by laccases directly (Cañas and Camarero, 2010).

For catalyzing the oxidation of non-phenolic substrates, laccase requires the presence of a mediator. A mediator is a small molecule in the medium that behaves like an "electron shuttle" between laccase and substrate. They act as redox mediators and oxidize other compounds that are not substrates of laccase (Sharma *et al*., 2007). In 1990, the first artificial mediator 2,2'-azino bis-(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS) was used in the laccase mediator systems (LMS) for pulp delignification (Bourbonais *et al*.,

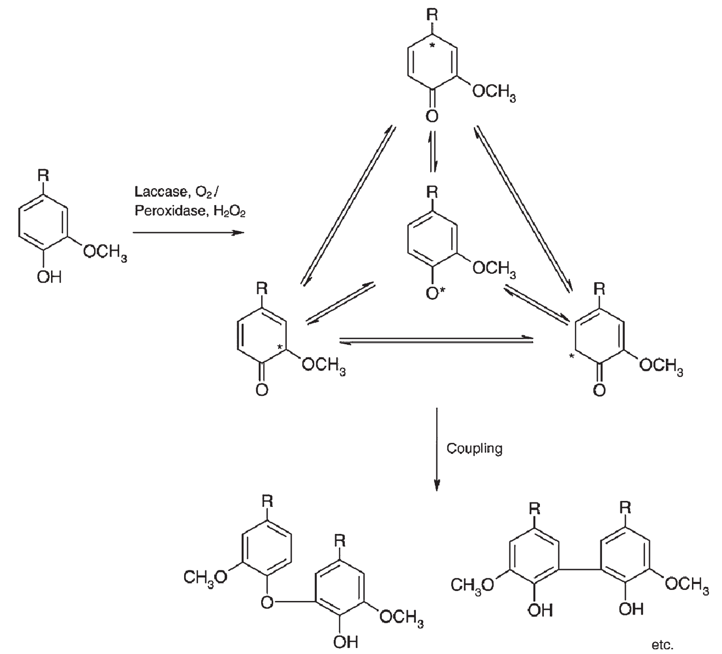

Figure 2 Coupling reactions of phenoxy radicals on lignocellulosic substrates treated with phenol-oxidizing enzymes (Widsten and Kandelbauer, 2008b)
Slika 2. Reakcija fenoksi radikala na lignoceluloznim podlogama tretiranim fenol-oksidacijskim enzimima (Widsten i Kandelbauer, 2008b)

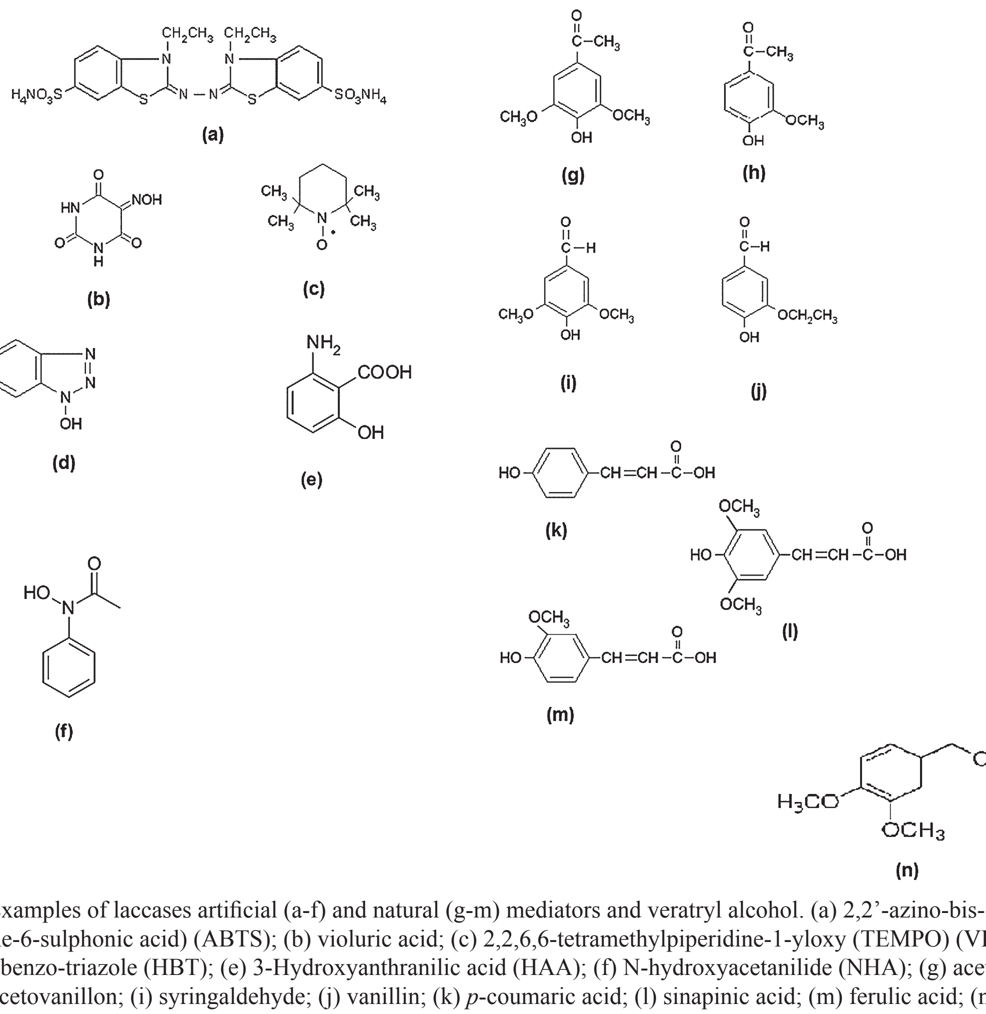

Figure 3 Examples of laccases artificial (a-f) and natural (g-m) mediators and veratryl alcohol. (a) 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS); (b) violuric acid; (c) 2,2,6,6-tetramethylpiperidine-1-yloxy (TEMPO) (VLA); (d) N-hydroxybenzo-triazole (HBT); (e) 3-Hydroxyanthranilic acid (HAA); (f) N-hydroxyacetanilide (NHA); (g) acetosyringone; (h) acetovanillon; (i) syringaldehyde; (j) vanillin; (k) *p*-coumaric acid; (l) sinapinic acid; (m) ferulic acid; (n) 3,4-dimethoxybenzyl alcohol (VA) (Riva, 2006; Kunamneni et al., 2008)
Slika 3. Primjeri umjetnih (a-f) i prirodnih (g-m) posrednika lakaze i veratril alkohola (n): (a) 2,2'-azino-bis (3-etilbenzotiazolin-6-sulfonska kiselina) (ABTS); (b) violurična kiselina; (c) 2,2,6,6-tetrametilpiperidin-1-iloksi (TEMPO) (VLA); (d) N-hidroksibenzo-triazol (HBT); (e) 3-hidroksiantranilna kiselina (HAA); (f) N-hidroksiacetanilid (NHA); (g) acetosiringon; (h) acetovanilon; (i) siringaldehid; (j) vanilin; (k) p-kumarinska kiselina; (l) sinapinska kiselina; (m), ferulična kiselina; (n) 3,4-dimetoksibenzil alkohol (VA) (Riva, 2006; Kunamneni *et al.*, 2008.)

1995). Since then, more than hundred other compounds have been tested for their ability to oxidize lignin or lignin models (Fig. 3). Riva and coworkers (2006) proved the most effective mediators for lignin degradation to be the N – heterocycles bearing N – OH groups (Fig. 3 b, d, f, i).

The cost and toxicity of synthetic mediators tend to be prohibitive for implementation in industry. This has generated interest in natural mediators obtainable from plants, fungi or as industrial by-products. Potentially cost-effective lignin derived natural mediators like p-coumaric acid, syringaldehyde and acetosyringone have been investigated by Camarero et al. (2007). Not only organic compounds have been investigated as laccase mediators, but also inorganic polyoxometalate and other transition metal complexes (Widsten and Kandelbauer, 2008a).

3 LIGNOCELLULOSE MATERIAL AS LACCASE SUBSTRATE
3. LIGNOCELULOZNI MATERIJAL KAO PODLOGA LAKAZE

Lignin is an amorphous polymer; it comprises approximately 20–32 % of dry wood mass and functions as a cementing material in wood cells. Lignin consists of p-hydroxyphenyl, guaiacyl and syringyl-type phenylpropane units in which the aromatic units bear 1, 2 or 3 free or etherified hydroxyl groups. The phenylpropane units are linked together by alkyl aryl ether (α-O-4, β-O-4), aromatic ether (4-O-5') bonds and carbon-carbon bonds (5-5' or β-5) in condensed structures (Fig. 4). A good understanding of lignin structure and chemistry is helpful in the development of laccase based treatment technology for wood (Widsten and Kandelbauer, 2008a).

Adhesion improvement of lignocellulosic products, such as medium-density fiberboard and particleboard, by enzymatic bonding methods are well summarized in a paper by Widsten and Kandelbauer (2008b). They mention two approaches; one is to improve the self-bonding properties of the particles by oxidation of their surface lignin before they are fabricated into boards. Another method involves using enzymatically pre-treated lignins as adhesives for boards and laminates.

Fackler *et al*. (2008) functionalized spruce wood particles by fungal laccase combined with 4-hydroxy-3-methoxybenzylamine (HMBA) or 4-hydroxy-3 methoxybenzylurea (HMBU). The expectation was cross-linked with urea-formaldehyde (UF) resins in subsequent bonding processes, which should improve strength properties of particle boards (Fig 5). Mechanical testing and multivariate data analysis revealed an

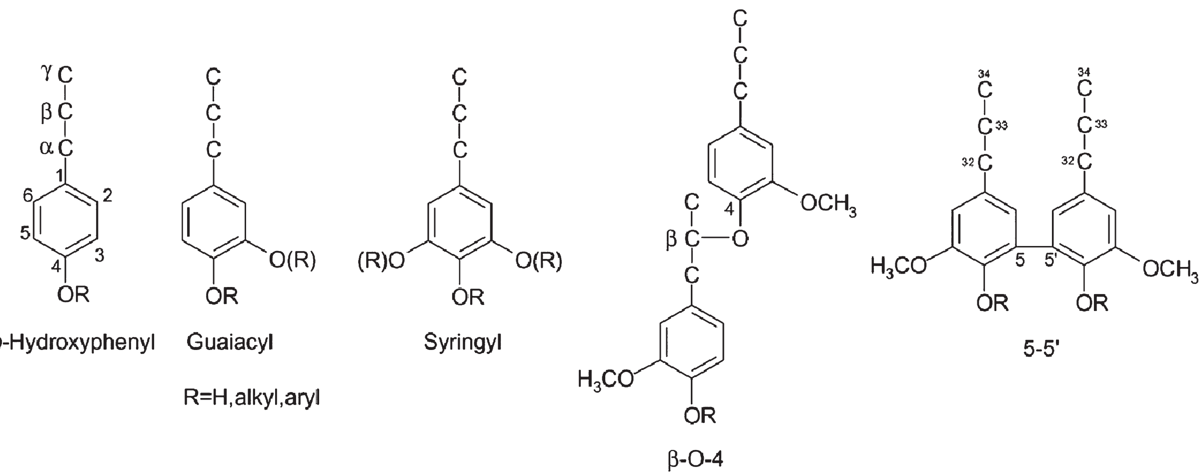

Figure 4 Lignin model compounds (p-Hydroxyphenyl, Guaiacyl, Syringyl);a β-O-4 ether linkage; an example of condensed lignin structures, a biphenyl 5-5' lignin substructure (Widsten and Kandelbauer, 2008a)
Slika 4. Modeli spojeva lignina (p-hidroksifenil, Guajacil, Siringil); β-O-4 eter veza; primjer kondenziranih ligninskih struktura, bifenil 5-5' ligninska podstruktura (Widsten i Kandelbauer, 2008a)

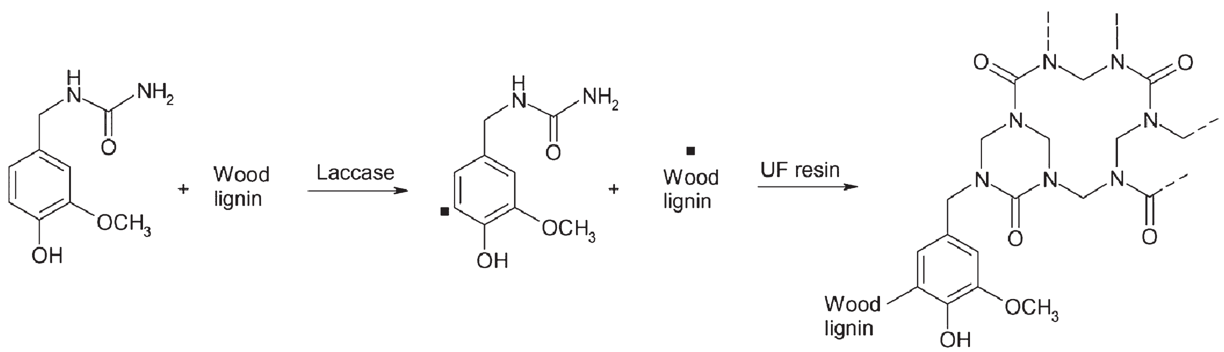

Figure 5 Functionalization of lignin with laccase and 4-hydroxy-3-methoxybenzylurea (HMBU), and cross-linking of functionalized lignin and urea-formaldehyde (UF) resin in particleboards (Fackler *et al.*, 2008)
Slika 5. Funkcionalizacija lignina primjenom enzima lakaze i 4-hidroksi-3-metoksibenzilurea (HMBU) te umreženje funkcionaliziranog lignina i urea-formaldehidne (UF) smole u pločama ivericama (Fackler *et al.*, 2008.)

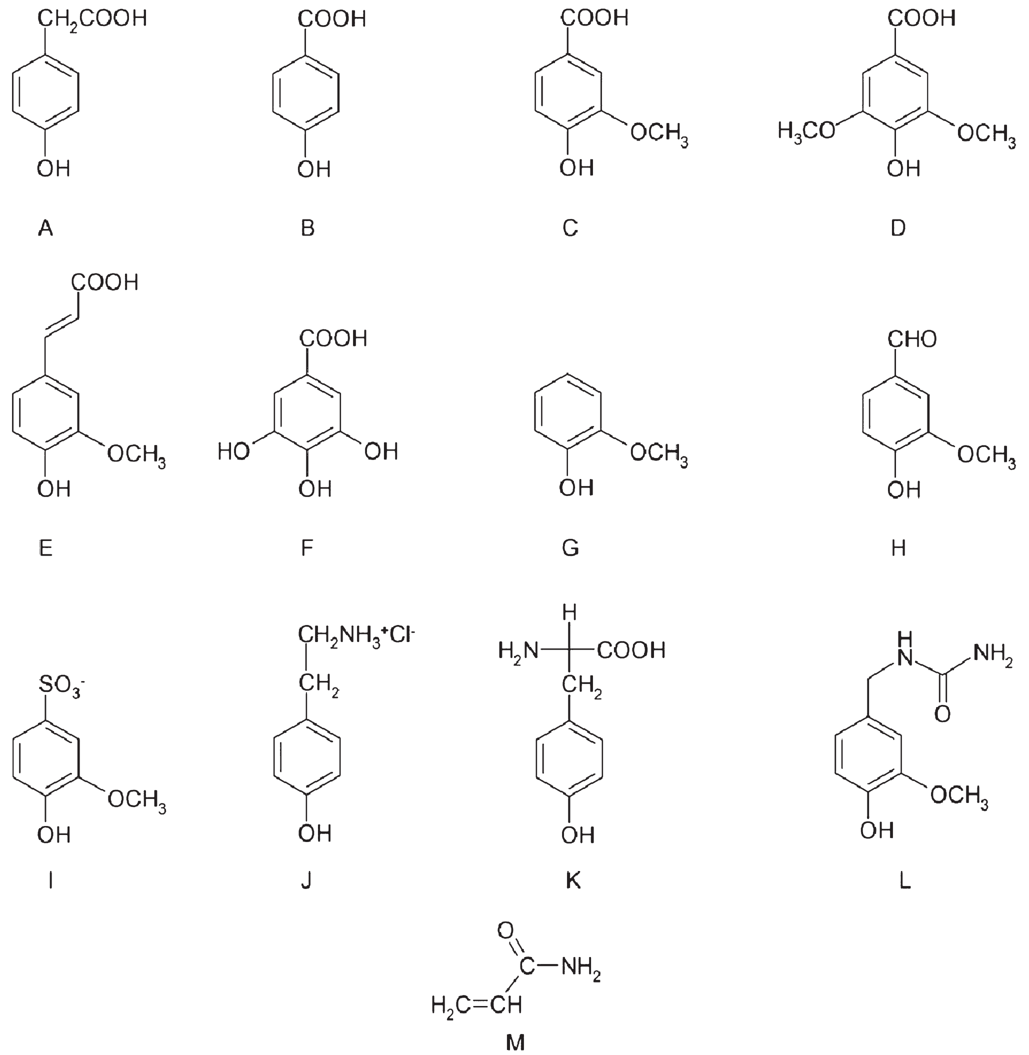

Figure 6 Examples of low-molecular weight compounds biografted to lignocellulosic materials with the aid of laccase: (A)4-hydroxyphenylacetic acid; (B)4-hydroxybenzoic acid; (C) vanillic acid; (D) syringic acid; (E) ferulic acid; (F) gallic acid; (G) guaiacol; (H) vanillin; (I) guaiacol sulfonate; (J) 3-hydroxytyramine hydrochloride; (K) tyrosine; (L) 4-hydroxy-3 methoxybenzylurea; (M) acrylamide (Widsten in Kandelbauer, 2008a)

Slika 6. Primjeri spojeva male molekularne težine kalemljeni na lignocelulozne materijale uz pomoć enzima lakaze: (a) 4-hidroksifeniloctena kiselina; (B) 4-hidroksibenzojeva kiselina; (C) vanilična kiselina; (D) siringijska kiselina; (E) ferulična kiselinu; (F) galna kiselina; (G) gvajakol; (H) vanilin; (I) gvajakol sulfonat; (J) 3-hidroksitiramin hidroklorid; (K) tirozin; (L) 4-hidroksi-3 metoksibenzilurea; (M) akrilamid (Widsten u Kandelbauer, 2008a)

increase of internal bond (IB) as a result of functionalization with HMBU. HMBA showed no significant increase of IB.

Biografting is a method for tailoring the surface of lignocellulose material (LM) under mild conditions and usually without harmful solvents. Series of reactions result in the introduction of new functional groups that may alter the physicochemical properties of LM in a desired way. Laccase may act as a catalyst for the covalent binding of compounds with low-molecular weight to lignin in wood and pulp fibers (Chandra *et al.,* 2002, 2004a,b; Grönqvist *et al.,* 2006). Examples of grafted molecules are shown in Figure 6.

Kudanga *et al*. (2010b) showed for the first time the mechanistic evidence of a laccase-catalyzed method of covalently grafting hydrophobicity enhancing fluorophenols onto *Fagus sylvatica* veneers. Coupling was made of fluorophenols (4-fluoro-2-methylphenol, 4-[4-(trifluoromethyl)phenoxy] phenol and 4-(trifluoromethoxy)phenol) onto complex lignin model compounds guaiacylglycerol β-guaiacyl ether and syringylglycerol β-guaiacyl ether (Fig 7). The covalent bonding was demonstrated by LC–MS, NMR and XPS analysis.

Furthermore, they report of laccase-mediated grafting of long chain alkylamines onto LMs and how it can be potentially exploited for improving their hydrophobicity (Kudanga *et al*. (2010a). Concomitantly the grafting of dihexylamine (DHA) or dodecylamine (DA) onto beech veneers resulted in a 53.8 % and 84.2 % increase in hydrophobicity, respectively when compared to simple adsorption (Kudanga *et. al*., 2010a). The advantage of laccase-mediated covalent binding of molecules onto wood surface is that the grafted molecules are not easily released into the environment.

Schubert (2013) represented laccase-catalysed iodination of wood as an efficient method for wood protection. The enzymatic oxidation of iodide (I-) to

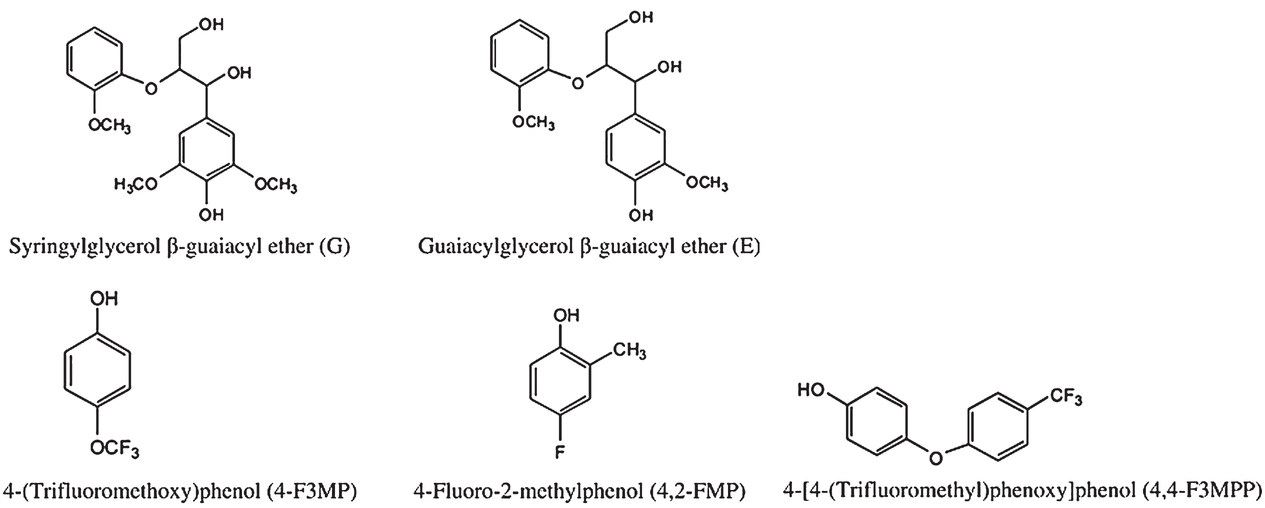

Figure 7 Chemical structures of the lignin model compounds and fluorophenols used in the coupling reactions in an attempt to achieve higher surface hydrophobicity. (Kudanga *et. al.*, 2010b)
Slika 7. Kemijske strukture spojeva lignina i fluorofenola koji se upotrebljavaju u kondenzacijskim reakcijama kako bi se postigla veća hidrofobnost (Kudanga *et al*., 2010b)

iodine (I_2) in the presence of wood led to an enhanced resistance of the wood surface against all microorganisms, even after exposure to leaching.

4 SUCCESSFUL APPLICATION OF LACCASE ON OTHER LM
4. USPJEŠNA PRIMJENA LAKAZE NA DRUGIM LIGNOCELULOZNIM MATERIJALIMA

In textile industry, laccase is used to bleach textiles and even to synthesize dyes. In 1996 Novozyme from Denmark launched a new industrial application of laccase enzyme in denim finishing called DeniLite®. It is the first industrial bleaching enzyme acting with the help of mediator molecule. In 2001, the company Zytex from India developed the formulation based on a laccase mediator system (LMS) Zylite® capable of degrading indigo. Due to laccases potential to degrade dyes of diverse chemical structure, it seems an attractive solution for removal of dyes from industrial effluents (Couto *et al*., 2006).

Production of chemical pulp paper requires separation and degradation of lignin in wood pulp, pretreatments of wood pulp with ligninolytic enzymes provides milder and cleaner strategies than polluting chlorine-based procedures. In pulp and paper industry, laccase and LMS are used for a variety of processes like biopulping, biobleaching, deinking, pitch control by pulp treatment, enhancing paper strength properties, mill process water and effluent treatment (Widsten and Kandelbauer, 2008a). LMS have also found commercial applications in paper industry such as Lignozym® - process (Couto *et al*., 2006).

Tavzes et al. (2009) tested the chemical changes induced in melanin as a result of treatment with laccase and 1-hydroxybenzotriazole (HBT). Since melanin is a black pigment produced by moulds and various blue-staining fungi which also infest many art objects, the implication of these findings can be applied in art conservation science (Tavzes *et al*., 2009).

5 FUTURE OUTLOOK
5. POGLED U BUDUĆNOST

Mayer and Staples (2002) titled their paper "Laccases: New Functions for an Old Enzyme" and almost ten years later we are discovering new functions and possible applications for this "old" enzyme. Not only can we use it for new wood technological processes, but we can also use it for bioremediation of old wood preservatives that were used for wood protection in the past, such as lindan (gamma-hexachlorocyclohexane) and PCP (pentachlorophenol). Ulčnik (2012) demonstrated that white rot fungi can degrade lindan. With the use of enzymes, wood industry has the potential to become part of many fields in biotechnology and modern environmentally friendly technologies. Who knows what else the future holds for these "old eco-friendly" enzymes.

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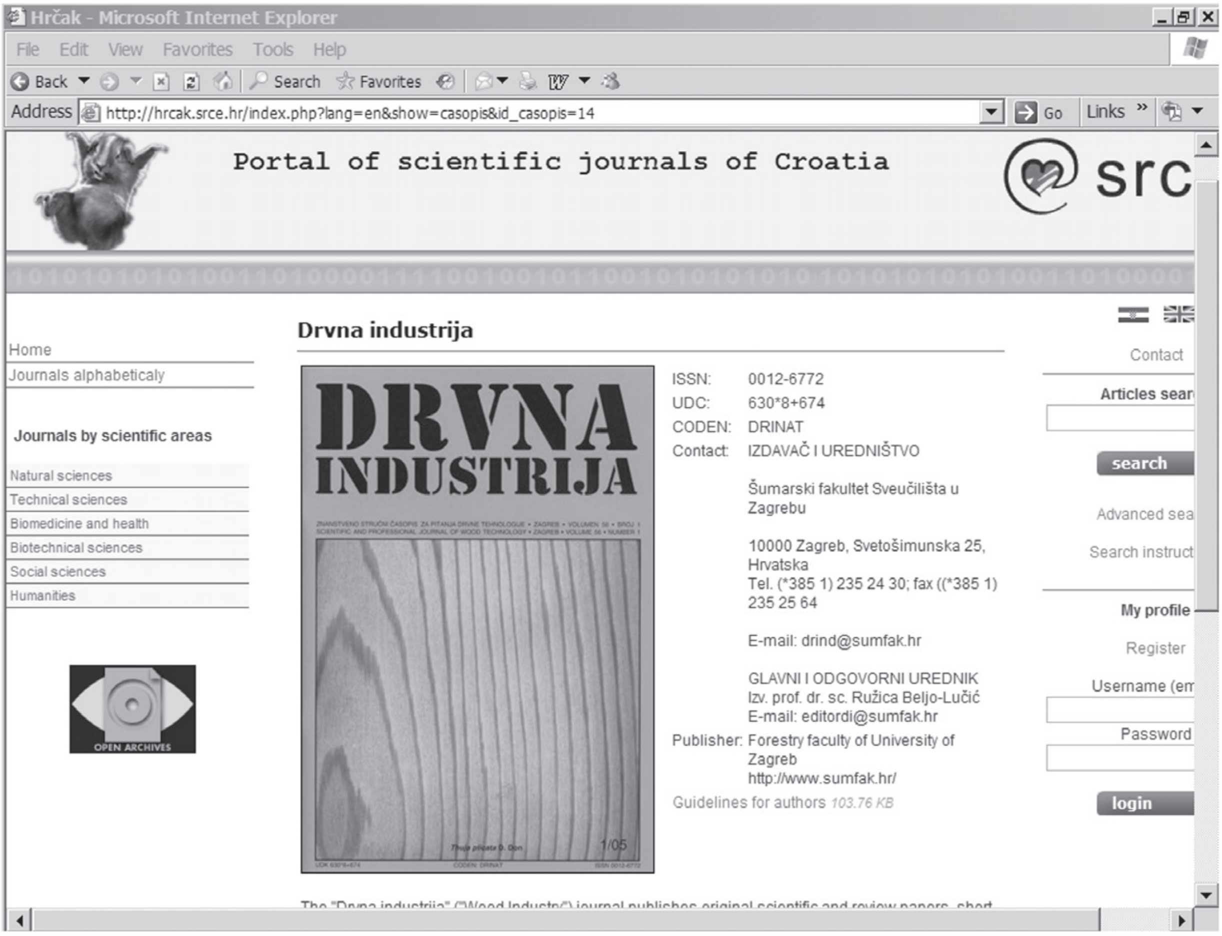

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Fabian Wulf, Karsten Schulz, Lukas Brösel, Alexander Pfriem[1]

Mineralized Wood Particle Reinforced Concrete as Stiffening Elements with Reduced Density

Armirani beton s mineraliziranim česticama drva kao element za ukrućenje smanjene gustoće

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ABSTRACT • *The aim of the cooperative research project was the development of a wood-cement in-situ concrete used as local filler and stiffening element in wooden ceiling elements. For further processing, only water should be added to the mineralized particles, whereby the amount of added water is relevant to the adjustment of the consistence and flowing characteristics. Portland cement was used as binding component. Particle residues of Scots Pine (Pinus sylvestris L.) and spruce (Picea abies (L.) Karst.) from sanding with 60 grit paper, as filling components, were supplied by Lignotrend GmbH, an industrial manufacturer of solid wood structural elements (cross laminated timber) and project partner. The mineralization of these wood particles has also been studied. Three different ways to accelerate the hydration of the cement and therefore to counteract the effect of the so called cement poisons were examined. Moreover, the compressive strength of hardened concrete had to be set to not less than 3.2 N/mm², which was also examined.*

Key words: *wood concrete compound, mineralization, compressive strength*

SAŽETAK • *Cilj zajedničkog istraživanja bio je proizvesti beton od drva i cementa koji će se upotrebljavati kao punilo i kao element za ukrućivanje drvnih stropnih elemenata. Za daljnju obradu mineraliziranim česticama drva treba samo dodati vodu, pri čemu je količina dodane vode relevantna za prilagodbu konzistencije i svojstva tečljivosti betona. Kao vezivna komponenta upotrijebljen je portlandski cement, a kao punilo drvne čestice nastale brušenjem drva običnog bora (Pinus sylvestris L.) i smreke (Picea abies (L.) Karst.), i to brusnim papirom granulacije 60. Drvne čestice dobavljene su od tvrtke Lignotrend GmbH, industrijskog proizvođača strukturnih elemenata od masivnog drva (unakrsnoga lameliranog drva), koja je ujedno i partner u projektu. Mineralizacija čestica drva također je dio istraživanja. Istražena su tri različita načina ubrzavanja hidratacije cementa, a istraženi su i tim procesima suprotni učinci, tzv. otrovi cementa, kao i tlačna čvrstoća otvrdnutog betona, koja ne smije biti manja od 3,2 N / mm².*

Ključne riječi: *spoj drvo – beton, mineralizacija, tlačna čvrstoća*

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1 INTRODUCTION
1. UVOD

Since the use of wood particles is considered attractive for the reinforcement of cement (Campbell and Coutts, 1980), their application leads to various challenges due to wood components like water soluble carbohydrates (e.g. sugars, starch, hemicellulose and pectin) and due to resins, oils, waxes and fats - depending on wood species (Schubert *et al.*, 1990). Those substances react with cement and cause delays in hardening. Miller and Moslemi investigated the effects of wood components like glucose, quercetin, xylan and acetic acid on cement regarding hydration characteristics and tensile splitting strength. They discovered that glucose decreased the cement tensile strength by nearly 50 % (Miller and Moslemi, 1991). By differential calorimetric analysis, Kühne and Meier showed that cement hydration is inhibited by galactomannan and especially xylan hemicelluloses, as well as by glucose (Kühne and Meier, 1990). Cong *et al.* (2007) have conducted experiments to reduce the hydration retarding sugar in the wood by microorganisms and enzymes (Cong *et al.*, 2007). Alpar *et al.* applied an additive combination of montmorillionite and polydiallyldimethylammonium chloride to Portland cement to improve the bending strength of cement bonded poplar wood (*Populus* spp*.)* composite. Bending strength could be increased above 20 % (Alpár *et al.*, 2012). Wei *et al.* suggested to eliminate the so called cement poisons (Sandermann and Brendel, 1956) by using alkali salts, for example calcium chloride, as setting accelerators (Wei *et al.*, 2000). Alpár and Rácz claimed that the use of calcium-chloride and calcium-formate with poplar clone (*Populus x euramericana cv. „I 214“*) for the production of cement-bonded particleboards leads to a significantly reduced price by improved physical and mechanical properties of boards compared to those made with conventional water-glass (Alpár and Rácz, 2009). On the other hand, the increased corrosion of ferrous materials (for example various fasteners like nails or screws) by leachable chlorides is disadvantageous for later use. Del Menezzi *et al.* (2007) replaced Portland cement with silica fume (SiO_2) to reduce the inhibitory effects of wood (*Pinus taeda* L.) on the setting of cement in the wood-cement board production. They showed that a replacement of cement with 10 % of SiO_2 not only improved mechanical properties but also eliminated the inhibitory effect of wood on cement setting.

In the context of a scientific study, it had to be found out which kind of mineralization is meaningful for the present use and which concentrations are useful. Furthermore, it was examined how much of the wood particles can be inserted into the concrete in order to achieve a maximum reduction in density, simultaneously maintaining the required consistency, and to keep a compressive strength of hardened wood concrete over the minimum compressive strength of Scots pine (*Pinus sylvestris* L.), since the material should be able to bring stability to wooden ceiling elements. This compressive strength transverse to the fibre $f_{c,90,k}$ of softwood for the highest strength class C50 is described in the standard DIN EN 338:2010-02 with 3.2 N/mm².

In a preliminary experiment, the following mineralizers, which are mentioned in various patents and have been successfully used there, were examined: cement, water glass, magnesium hexafluorosilicate, silica, calcium chloride, aluminium sulphate. Another aspect of the treatment is the reduction of the water uptake of the timber to minimize the total water requirement. The first four of the just mentioned substances should prevent the leaching of wood components, producing a better adhesion and reducing the water absorption of the particles. The latter two substances are salts to accelerate the hydration of the cement - and hence, counteracting the effect of cement poisons.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

It is known that the particle size fraction can be influenced by the sanding direction (Očkajová *et al.*, 2008). In this research however, Scots Pine (*Pinus sylvestris* L.) and spruce (*Picea abies* (L.) Karst.) particles, generated by both perpendicular and longitudinal sanding, were used as fillers in the wood concrete compound. They were produced by the project partner Lignotrend Produktions GmbH using 60 grit paper. For mineralisation, the particles have been treated with:

- 31.2 % aqueous sodium silicate solution (Na_2O x SiO_2), thinned to 10 % (“WG 10 %”),
- Sodium silicate solution 10 %; after drying, the particles were powdered with cement (“WG 10 % / Cement powdered”)
- Cement mixed with moistened particles were additionally powdered (“Cement powdered”)
- Cement; after drying, the mixture has been separated from cement dust (“cement dust reduced”).

Pantarhit PC160 PLV from the Ha-Be Betonchemie GmbH & Co. KG was used as plasticizing agent. It is based on a polyacrylic acid derivative. 146 different mixing ratios and recipes were tested in total. In the preliminary series, wood particles were mineralized and then mixed with cement. The mass gain after mineralization, miscibility and consistency were determined as well as the water/cement ratios whenever water was added to the dry mixture. After 20 hours. the setting and curing behaviour was examined.

As a result of preliminary series, concrete with a wood/cement ratio of 15 mass % kiln dry could be produced. Concrete with a higher wood particle level did not set after 20 hours. Based on the results of the preliminary series, five recipes were selected for the main experiment. Due to the findings of the preliminary tests, following recipes were considered for the production of wood concrete in the main test (Table 1):

1. Filling material: wood particles soaked in sodium water glass (10 %); wood/cement ratio of 15 mass %; binder: sodium silicate water glass.
2. Filling material: wood particles soaked in sodium water glass (10 %); powdered with cement; wood/

Table 1 Mixtures for the production of pressure test specimens
Tablica 1. Smjese za proizvodnju uzoraka za tlačni test

Sample ID *Oznaka uzorka*	**Filler** / *Punilo*				**Cement** *Cement*	**Plasticizing agent** *Sredstvo plastifikacije*	**Water** *Voda*	**Miscibility** *Miješanje*	**Consistency** *Konzistentnost*	**Comment** *Komentar*
	batch / *serija*	composition / *sastav*								
	short name *skraćeni naziv*	wood particle kiln dry *suhe drvne čestice*	mineralization agent *sredstvo mineralizacije*	water *voda*						
		g	g	g	g	g	g			
A	pure cement *čisti cement*	---	---	---	9501.02	---	3800.90	---	watery *vodenast*	
B	WG 10%	541.20	232.28	28.91	3607.95	9.02	3635.92	good *dobro*	crumbling dividing *mrvi se, dijeli se*	
C	WG 10%/ cement powdered *cement u prahu*	523.28	483.31	72.80	3488.58	---	3416.34	bad *loše*	crumbling *mrvi se*	
D	cement powdered *cement u prahu*	529.10	212.43	7.57	3527.73	---	3540.87	bad *loše*	crumbling *mrvi se*	
E	cement dust reduced *smanjena cementna prašina*	409.40	310.59	12.47	2730.38	---	2736.88	bad *loše*	crumbling *mrvi se*	did not set *nije postavljena*
F	cement dust reduced *smanjena cementna prašina*	410.00	337.86	8.04	2733.60	---	2979.62	bad *loše*	crumbling *mrvi se*	did not set *nije postavljena*

cement ratio of 15 mass %, binder: sodium silicate water glass and Portland cement.

3. Filling material: moistened wood particles; powdered with cement; wood/cement ratio of 15 mass %, binder: Portland cement.
4. Filling material: wood particles soaked in 25 % cement / 75 % water slurry, then after drying separated from cement dust; wood/cement ratio of 15 mass %; binder: Portland cement.

As consistency has great influence on certain properties like pumpability, the flow spread was measured with a flow table according to DIN EN 12350-5. For pressure testing, five cube-shaped specimens with a side length of 100 mm (nominal) of each recipe (Table 1) were prepared according to DIN EN 12390-1:2001-02, DIN 1048-5:1991-06 and DIN EN 12390-2:2009-08.

When producing specimens for the pressure test based on the results of the preliminary tests, it was found that the dust reduced specimens (sample ID E and F) did not solidify. Thus, only the sample rows B, C and D were examined further and compared with the samples consisting of pure cement (sample row A). Water-resistant plywood, coated with phenolic resin, was used for the mould. After 20 hours, the test specimens were removed from the mould and then stored in sealed bags, where they were kept for two weeks at 21 °C. Subsequently, they were removed from the bags and preserved for a further two weeks with the prevailing ambient laboratory climate (21 °C / RH 35 %) to prepare the pressure test. For a better load transmission, the specimens were ground plane and parallel, and a compensating layer of quick-setting cement was also applied on pure cement specimens (Figure 1).

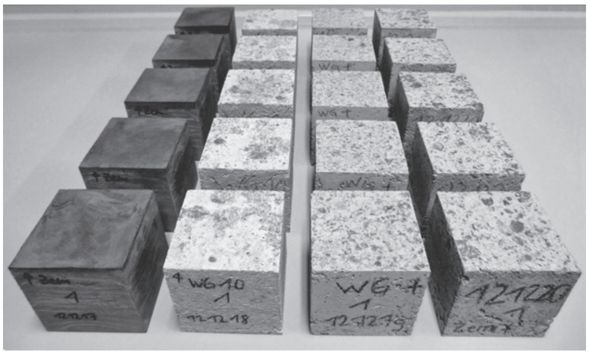

Figure 1 Specimens for compressive strength testing
Slika 1. Uzorci za ispitivanje tlačne čvrstoće

After a total of 28 days, the pressure test was carried out in compliance with DIN EN 12390-3:2009-07 using a WPM 600 testing machine equipped with a 650 kN load cell for the pure cement series (sample row A) and a Zwick 4084 universal testing machine equipped with a 200 kN load cell for the sample rows B, C and D.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

A consistency that allows the concrete to be processed with a spatula could only be created with a max-

Table 2 Moisture content and bulk density of the specimens
Tablica 2. Sadržaj vode i nasipna gustoća uzoraka

	Humidity, % / *Sadržaj vode*, %			**Average bulk density** / *Prosječna nasipna gustoća* kg/m³
	average total *prosjek, ukupno*	average internal *prosjek, unutarnji*	average external *prosjek, vanjski*	
pure cement / *čisti cement*	19			1913
WG 10 %	26	41	19	1223
WG 10 % / cement powdered *cement u prahu*	28	42	19	1210
cement powdered / *cement u prahu*	22	34	18	1166

imum wood/cement ratio of 15 %, with a very high water/cement ratio of 1.3. This surplus water will escape gradually over the time and burden the environment with moisture. A plastic consistency can be achieved with less use of water only when at the same time the wood components are considerably reduced. The most advantageous fact for the cured product combination, namely a high content of wood substance and a small amount of water, inevitably leads to a fresh concrete, which is no longer ductile but crumbling in consistency.

The moisture content of the pressure test specimens was determined immediately after the pressure test, using the kiln-dry method. Since the inner region of the specimen seemed to have a different moisture than the outer area, the moisture was determined on each sample from both the edge regions (up to 20 mm below the surface) and from the innermost area. In order to determine the average total moisture, each wood concrete sample was granulated and a portion (about 1/5 of the sample mass) of the well-mixed pellets dried to kiln. A significantly higher moisture content was recorded inside the cubes than in the outer areas.

The average moisture content of each wood concrete sample ranges from 22 to 29 %. The moisture content of the specimens with cement powdered wood particles were the lowest. The specimens with water glass pre-treated particles showed significantly higher moisture content than those with only cement powdered particles. A reason could be that water glass makes it difficult for the remaining moisture to escape. Another aspect is the tendency of wood particles to absorb water from the air.

The gross density was determined from the mass and dimensions of the specimen before the pressure test. They are within 1200 ± 50 kg/m³ (Table 2). Due to the use of fillers, the gross density could be reduced by an average of 36 % (WG 10 %) to 39 % (cement powdered) in comparison to those of the pure cement cubes.

As a result of the pressure tests, the mean value of the breaking stress of pure cement specimens was 45.15 N/mm². When comparing the reference test of pure cement with those of the wood cement specimens, it is clear that the introduction of 15 mass % of wood in relation to the mass of cement brings a very strong decrease of almost 90 % to 5 N/mm². Due to the high humidity in the samples, the strength is expected to rise during the drying process. It has been determined as not appropriate to compare the cement modulus of elasticity with wood cement modulus due to measuring errors caused by deformation of the testing machine steel crossbar. Therefore, only the properties of differ-

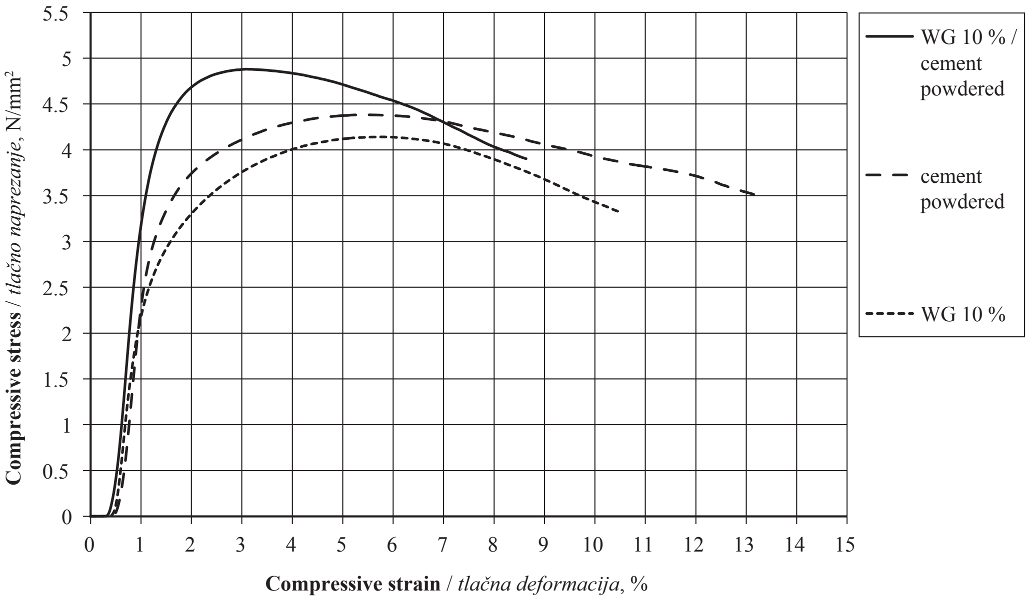

Figure 2 Compressive stress-strain curves of selected specimens
Slika 2. Tlačne krivulje naprezanje – deformacija za odabrane uzorke

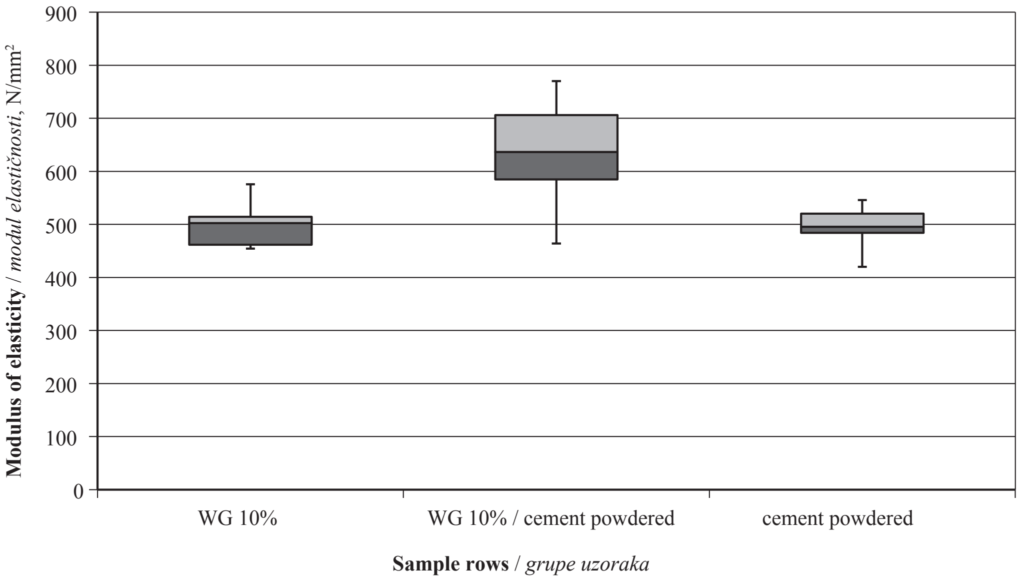

Figure 3 Moduli of elasticity - box plot of sample rows
Slika 3. Prikaz rezultata modula elastičnosti za različite uzorke

ent mineralized wood concrete test specimens are compared with each other when considering the material properties.

As shown in the stress-strain diagram (Figure 2), the maximum stresses of the water glass mineralized samples (WG 10 %, sample row B) are on average 4.17 N/mm² with a standard deviation of 0.08 N/mm². The strengths were significantly higher when using particles soaked with water glass and then powdered with cement (WG 10 % / cement powdered, sample row C). A mean of 4.93 N/mm² could be achieved. The statistical scatter was slightly higher, but still low (standard deviation is 2.4 % of the mean). The cement powdered test row had an average maximum stress of 4.48 N/mm². The highest scattering of the three series of measurements is with a standard deviation of 5.2 % on average.

Results of the modulus of elasticity MOE (Figure 3) for the WG 10 % series show that the linear-elastic range ends at 2 to 2.5 N/mm², an average modulus of 502.35 N/mm² is achieved. In comparison with the only water glass mineralized wood concrete, the WG 10 % / cement powdered samples showed a greater range of linear-elastic behaviour, amounting to 3 to 3.5 N/mm². The maximum stress is reached at a strain of 3 to 4 %. So a less severe deformation was observed. In addition, the modulus of elasticity with an average of 636.22 N/mm² is bigger.

The mean modulus of the cement powdered series of 495.38 N/mm² resembles the WG 10 % series and the linear-elastic range ends between 2.5 and 3 N/mm².

4 CONCLUSION
4. ZAKLJUČAK

It can be concluded that a wood concrete, whose binder is Portland cement, could be developed. The filling material consists of water-glass and / or Portland cement mineralized wood particles. Through the use of only 15 mass % wood particles as filler, the gross density of the concrete can be significantly reduced by 36 to 39 %. The fresh concrete mixed with water, at a water/cement ratio of 1.0 to 1.1, has a crumbling, easily malleable consistency - but it is not flowing. The achieved compressive strength of the wood concrete of 4 to 5 N/mm² is higher than the required compressive strength transverse to the fibre $f_{c,90,k}$ of softwood (3.2 N/mm² for C50 strength class).

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Effect of Refiner Plate Pattern Design on Refined Fibre Size Distribution – a Time Series Study

Utjecaj dizajna diskova za razvlaknjivanje na raspodjelu veličina proizvedenih vlakana – analiza vremenskog niza

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ABSTRACT • *In a multi-step batch or continuous operating process, quantitative & qualitative optimization of every single step is always aimed at. Even the smallest aberration in processing parameters affects the quality of the final product. Therefore, it is necessary to study time series quality of products delivered by every single step, so as to ensure product quality in a long run. Refining is one of the most crucial steps in fibreboard manufacturing, as it has a major impact on fibre quality and energy consumption. Refining plate pattern is key to good results, which have to be optimized based on experience or onsite testing. We tested three different refining plate patterns: straight bar design pattern (TYPE 1), spiral bars design pattern (TYPE 2) and bar with groove pattern (TYPE 3), and their impact on fibre size quality in a time series. Reported results include fibre size distribution of three different types of plate patterns observed for 1500 hrs and relative quantity of fine fibres observed in time series for three variants of disc type refiners. Our research showed that fibre quality within desired limits was best delivered by TYPE 2 plates; however, fibre quality also varied with time series for three of them, so different time periods of desired fibre quality were analysed.*

Key words*: *refining plate pattern, fibre size quality, disc type refiner

SAŽETAK • *U procesu sastavljenome od više kraćih faza ili u kontinuiranome operativnom procesu kvantitativna i kvalitativna optimizacija usmjerena je na svaku pojedinu fazu. Čak i vrlo malo odstupanje parametara obrade utječe na kvalitetu konačnog proizvoda. Stoga je kvalitetu proizvoda u realnom vremenu potrebno pratiti u svakoj fazi proizvodnje kako bi se dugoročno osigurala kvaliteta proizvoda. Razvlaknjivanje je jedna od najvažnijih faza u proizvodnji ploča vlaknatica jer ima velik utjecaj na kvalitetu vlakana i potrošnju energije. Dizajn diska mlina za razvlaknjivanje ključan je za dobar rezultat te njegov dizajn mora biti optimiziran na temelju iskustva ili na temelju rezultata istraživanja u pogonu. U radu se prikazuju rezultati ispitivanja triju različitih dizajna ploča za razvlaknjivanje: ploča s ravnim trakama (TYPE 1), ploča sa spiralnim trakama (TYPE 2) i ploča s trakama s utorom (TYPE 3) te njihov utjecaj na kvalitetu vlakana s obzirom na dimenzije u vremenskom nizu. Predstavljeni rezultati obuhvaćaju distribuciju veličine vlakana dobivenih primjenom triju različitih vrsta ploča za razvlaknjivanje tijekom 1500 sati i relativne količine finih vlakana promatranih u vremenskom nizu za tri varijante ploča za raz-*

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vlaknjivanje. Uočeno je da se najbolja kvaliteta vlakana u željenim veličinama postiže primjenom ploče TYPE 2, no kvaliteta vlakana mijenja se u vremenskom nizu, a analizirana su različita vremenska razdoblja u kojima se postiže željena kvaliteta vlakana.

Ključne riječi: *dizajn ploče za razvlaknjivanje, kvaliteta veličine vlakana, vrsta diskova za razvlaknjivanje*

1 INTRODUCTION
1. UVOD

Hydrothermal refining is the process of converting steamed chips into fibre bundles, widely utilized in fibre board and pulping industries (Lumiainen, 2010). Factors affecting the choice of a refiner can be divided into two categories, first refiner considerations and second system considerations. Refiner considerations include plate diameter, pattern design detail, surface and sub-surface dams, refining intensity (fibre type) and alloy. System considerations include refiner throughput, system stability, stock contamination, available horsepower, operating scheme, and control method. Refining plate pattern is the criteria affecting energy consumption as well as fibre size quality. That is why refiner plate pattern is continuously researched and improved. Plate pattern has changed from classical constant angle type and bar with groove type to more advanced and improved types, for example curved refining bars with jagged leading sidewalls (Gingras, 2011), plates with logarithmic spiral type bars (Antensteiner, 2008), damless refiner plate for wood fibres (Savujz'irvi and Liifgren,1999), rough edged refiner plate cutter bars (Wasikowski,1996), tooth refiner plates having V-shaped teeth (Gingras, 2012). Despite the efforts to find a computer model to design plates, in the end the selection is based on experience and onsite testing of the process (Rowell, 2012).

The refiner plate design is characterized by bar width (*b*), groove width (*g*), groove depth (*gd*), sector angle (*q*), and bar angle (*f*); plate designs are typically characterized by the length of intersecting edges between the opposing plates, termed as the "bar edge length" (*BEL*) (Figure 1).

BEL is a standardized measure in the industry estimated using TAPPI standard TIP 0508-05 (1994):Eq.(1)

$$BEL = \int_{R2}^{R1} \frac{n_r(r) \cdot n_s(r)}{\cos \phi} dr \quad (1)$$

Where $n_r(r)$ and $n_s(r)$ are the number of bars on the rotor and stator plate at a given radius, R_1 and R_2 are the inner and outer radii of the refiner plates, respectively.

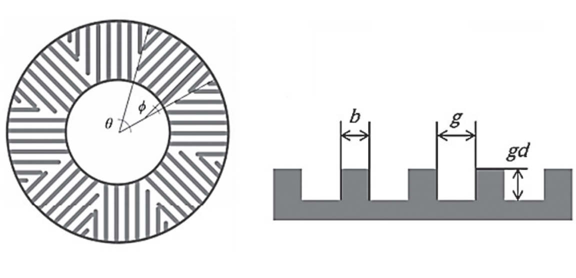

Figure 1 Characteristic features of a refiner plate
Slika 1. Karakteristična obilježja ploča za razvlaknjivanje

To approximate this integral, the number of bars on each plate can be roughly estimated by setting (2):

$$n(r) = \frac{2 \cdot \pi \cdot r}{b + g} \quad (2)$$

With this, Equation 1 can be integrated directly to yield Eq. 3

$$BEL = \frac{(2 \cdot \pi)^2}{\cos \phi} \cdot \left(\frac{R_2^3 - R_1^3}{3 \cdot (b+g)^2} \right) \quad (3)$$

At this point, attention must be directed to define an operating parameter used through the research, i.e. the no-load power. No-load power refers to the power used by the refiner for purposes other than changes in fibre morphology. The LC (low consistency) refiner no-load power has been estimated to 20-35 % of the total refiner motor power, (Dietermann and Roux, 2005). During the process of defibration, radial compression collapses the lumen, the cross section bound by fibre cell wall, which enhances paper smoothness and sheet uniformity in paper making (Page and Grace, 1967). In this work, effect was observed of plate pattern type on the size quality of fibres produced. The purpose of this research was:

(1) to compare on-site efficiency of three types of plate pattern,
(2) to understand differences in time series performance of these types of plate pattern in a disc type refiner.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

In this research refiner plates with different pattern design (TYPE 1, TYPE 2 and TYPE 3) were used and the fibre-size i.e. fibre-quality distribution was evaluated. Wooden raw material composed of 80 % softwood and 20 % hardwood was processed at 1500 rpm. The distance between refiner plates was automatically optimized according to tool wear. Samples of fibres were taken from belt conveyer at the interval of 2, 10, 30, 200, 350, 500, 650, 800, 950, 1100, 1250 and 1378 hrs. Samples were stored in laboratory plastic bags to provide constant relative humidity and marked by number, time and date. The weight of specimens were scaled for 30 g and homogenized at 20 °C and 60 % relative humidity for 24 hours. For size analysis, the cascade laboratory sieving machine was employed (Figure 1). The sieves with different sizes (2; 1; 0.5; 0.25; 0.16; 0.08 mm) were used to determine the volume of fibres on sieve of each type of sieve opening. The fibres were sieved for 50 minutes and the weight of fibres from each section was determined. This laboratory process was used for all samples separately. Data were mathematically evaluated and listed in

Figure 2 Laboratory cascade sieve
Slika 2. Laboratorijsko kaskadno sito

graphs. Although the size range was very wide, the solution of size distribution in time was included as well as the quantity of particles by means of descriptive statistics of the total produced amount of each fibre type by each tested plate. The trends were evaluated using software MS Excel and then software STATISTICA.10 to obtain the total amount of fibre type produced by each tested refiner plate. The ANOVA test with Duncan´s post-hoc test was employed to determine statistically significant differences between the effects of refiner plates.

Quantity of fibres with specified size (Q) was calculated using equation (4), where m_n is the weight of fibres on n^{th} sieve in a cascade starting from the top, and m_0 is the total weight of the fibres.

$$Q = \frac{m_n}{m_0} \cdot 100[\%] \quad (4)$$

3 RESULTS
3. REZULTATI

The research provided solid ground for size-evaluation in time series, and size distribution of fibres produced by each refiner plate type was reported. Results in figures represent trends of change in fibre size with time and also relative quantity of fine fibre produced by different refiner plates. For plate Type 1 (Figure 3), in the time range of 500-800 hrs, the relative amount of dust fibres (undesirable) was found to be minimum, whereas other desired fibre sizes of 0.16 to 1 were found to be at a maximum relative amount. So, the range between 500 and 900 hrs can be considered as optimum performance time for the refiner plate.

Fibres processed by TYPE 2 (Figure 4) were found to be in the desired size in time ranging between 300 and 900 hours, the relative amount of dust fibres (bottom) shows a steep fall in the first section of operation and rise after 900 hours. The amount of fibres with dimension of 0.08 to 1 mm showed a decrease during the whole duration of operation. Larger particles (above 1 mm) showed a steady tendency with the same percentage as at the beginning. Their share during the production is up to 8 %.

Type 3 plate pattern (Figure 5) is represented by decreasing quantity of dust fibres whose size is smaller than the last sieve i.e. 0.08 mm up to 600 hrs. The quantity of fibres with the size of 0.08 to 0.016 mm is increased or constant in the second half of the production, as well as the quantity of particles with dimensions greater than 0.5 mm. Although these facts are not convincing for mill efficiency, the positive results are achieved for fibres concerned. It can be concluded that the quantity of high quality size fibres are used in a steady range throughout the production time up to 750 hours.

Total performance of the refiner plates were also evaluated as mean values of the total produced fibres along the refiner life span (see Table 1). Considering

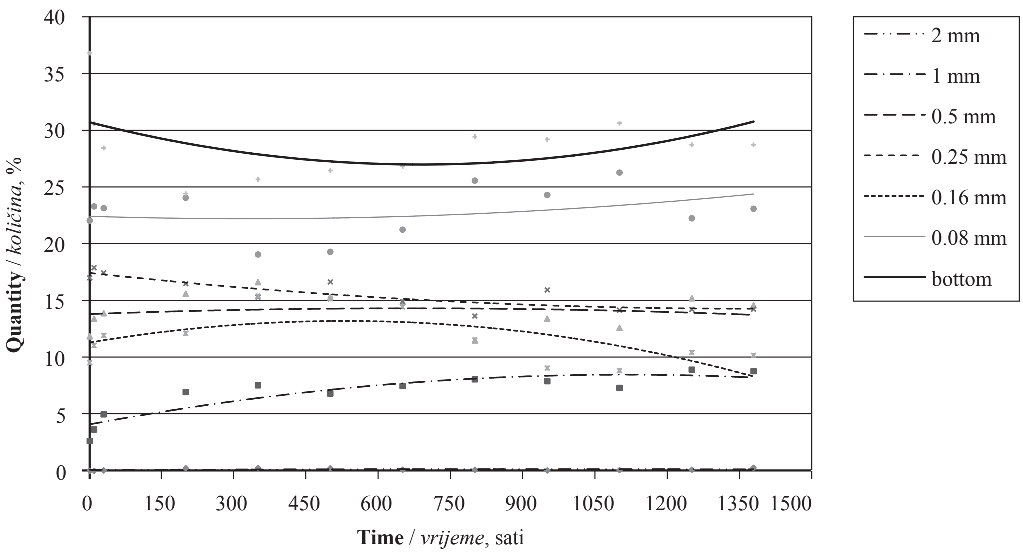

Figure 3 Fibre-sizes in time, processed by TYPE 1 in tool life cycle (trends of results are included)
Slika 3. Veličina vlakanaca u ovisnosti o vremenu uzimanja uzorka; za proizvodnju vlakanaca primijenjena je ploča TYPE 1 tijekom životnog ciklusa alata (uključena je trend linija rezultata)

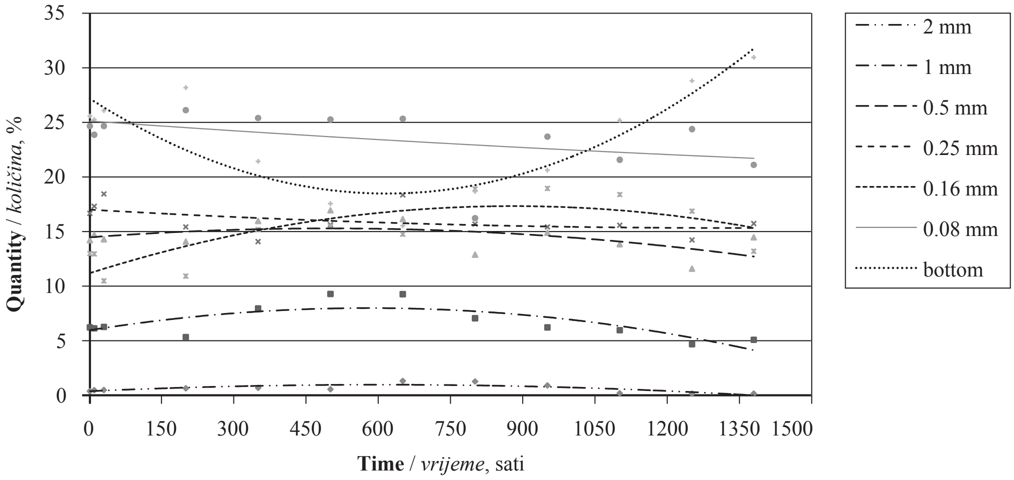

Figure 4 Fibre-sizes in time, processed by TYPE 2 in tool life cycle (trends of results are included)
Slika 4. Veličina vlakanaca u ovisnosti o vremenu uzimanja uzorka; za proizvodnju vlakanaca primijenjena je ploča TYPE 2 tijekom životnog ciklusa alata (uključena je trend linija rezultata)

fibres on 1 mm sieve, TYPE 1 and TYPE 2 produced the same amount of fibres (ANOVA; $p > 0.05$). At the same time, TYPE 3 produced a higher amount of 1 mm fibres compared to TYPE 1 (ANOVA; $p < 0.05$). The plates delivered the same amount of fibres considering 0.5 mm sieve. On the other hand, the dimension of 0.25 showed insignificant differences between the total amount of produced fibres considering all types of refiner plates. All tested Types performed with fibres amount to around 15 % (ANOVA, $p > 0.05$). With the use of 0.16 mm sieve, different amounts were produced by TYPE 3 and TYPE 1 (ANOVA; $p < 0.05$). Fibre production of TYPE 3 was lower by 1.5 %. Fibre production on 0.08 sieve was higher by 3.5 % with TYPE 1 compared to TYPE 3 (ANOVA; $p < 0.05$). Interestingly, the dust fibres on the last sieve (*Bottom)* were produced in the same amount of 29 % by TYPE 3 and TYPE 1, while TYPE 2 showed a significantly lower production of fibres (ANOVA; $p < 0.05$).

According to results, the plate pattern has significant influence on fibre-quality during its lifetime. With TYPE 1 and TYPE 2, longer life span and higher volume of high quality fibres were obtained, however low quality dust fibres were also produced in considerable amount. TYPE 2 and TYPE 1 have the highest amount of high quality fibres (sieve range 0.08 to 0.25 mm) with no significant change until the end of the tool life span. Nevertheless, the percentage share of the high quality fibres is not constant during the whole processing time. Results with TYPE 1 showed a decreasing tendency of high quality fibres during the whole operation. On the other hand, the lifetime of refiner plates was longer than in case of the last Type. Although TYPE 3 has the shortest production time, the quality of fibres is high. The share of the fibres with high quality is constant and high from the beginning to the end of lifetime. On the other hand, the lifetime limits its recommendation for future use. With respect to the presented facts, TYPE 2 and TYPE 1 are considered as the best option for the use in the process, the lifetime is long and the volume of high quality fibres is high throughout the production. Despite the short lifetime,

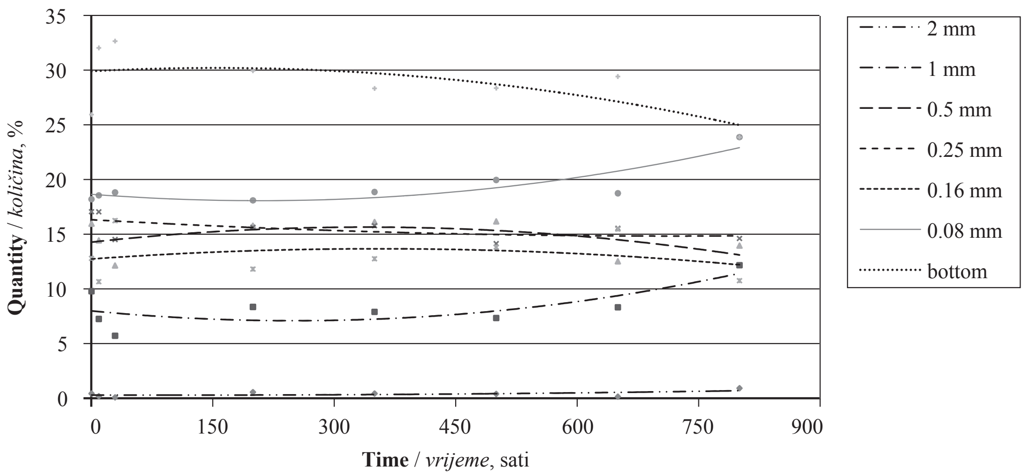

Figure 5 Fibre-sizes in time, processed by TYPE 3 in tool life cycle (trends of results are included)
Slika 5. Veličina vlakanaca u ovisnosti o vremenu uzimanja uzorka; za proizvodnju vlakanaca primijenjena je ploča TYPE 3 tijekom životnog ciklusa alata (uključena je trend linija rezultata)

Table 1 Descriptive statistics of the total amount of fibres considering the total amount of fibres obtained in refiner plate life span
Tablica 1. Deskriptivna statistika ukupne količine vlakanaca određenih dimenzija u ukupnoj količini proizvedenih vlakanaca tijekom životnog ciklusa diska za razvlaknjivanje

TYPE 1, %						
	1 mm[p]	0.5 mm[r]	0.25 mm[t]	0.16 mm[u]	0.08 mm[w]	Bottom[x]
mean	6.79	14.08	15.67	11.67	22.80	28.81
min	2.68	11.51	13.66	8.87	19.07	24.41
max	8.95	16.63	17.90	15.42	26.26	36.76
st.dev	1.98	1.56	1.44	2.28	2.20	3.15
TYPE 2, %						
	1 mm[p,q]	0.5 mm[r,s]	0.25 mm[t]	0.16 mm[u,v]	0.08 mm[w]	Bottom[y]
mean	6.53	14.40	15.94	14.82	23.41	23.54
min	4.59	11.50	13.98	10.39	16.12	15.43
max	9.19	16.84	18.33	18.84	26.00	30.83
st.dev	1.50	1.44	1.40	2.93	2.74	4.83
TYPE 3, %						
	1 mm[q]	0.5 mm[s]	0.25 mm[t]	0.16 mm[v]	0.08 mm[y]	Bottom[x]
mean	8.32	14.62	15.52	13.01	19.37	28.81
min	5.68	12.12	14.11	10.63	18.07	23.86
max	12.14	16.15	17.04	16.22	23.86	32.65
st.dev	1.93	1.64	1.10	2.05	1.90	2.93

[p,q,r,s,t,u,v,w,x,y,z] values having the same letter are not significantly different (Duncan test) / *Vrijednosti označene istim slovom značajno se ne razlikuju*

TYPE 3 is then recommended due to constant fibre quality, which was also high at the start of production, compared to TYPE 1 and TYPE 2, and did not significantly fall during the production. Considering TYPE 1 compared to TYPE 2, high quality fibres were produced at the beginning, however with decreasing tendency during the production. The quantity of high-quality fibres reached the peak in time ranging between 200 and 500 hours and after that its quantity declined. Since plate pattern design includes numerous mathematical and technical niceties, more research is required to understand the behaviour of each plate.

4 CONCLUSIONS
4. ZAKLJUČAK

1. In this study, three Types of refiner plates were successfully compared in terms of mean values of fibre sizes produced along the life span. Various trends and different plate life spans were presented.
2. The results show that TYPE 1 and TYPE 2 plates provide very similar total amount of fibres since ANOVA shows difference only in the amount of fibres on the bottom of cascade sieve i.e. dust particles.
3. TYPE 3 is found to provide constant fibre quality, which does not significantly fall during the life span of the plate. On the other hand, the total life span of the plate is lower than that of TYPE 1 and TYPE 2.

Acknowledgments – Zahvala

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Koncept *Membrain* – dosad najveći studentski projekt u Republici Hrvatskoj – projekt samoodržive montažne drvene kuće

Uvod

Tim studenata Sveučilišta u Zagrebu prvi je put sudjelovao na prestižnom međunarodnom natjecanju *Solar Decathlon Europe* s projektom *Koncept Membrain*. Mjeseci truda i rada rezultirali su gradnjom samoodržive montažne kuće u parku dvorca Versailles u Francuskoj. Hrvatski tim studenata dobio je mnoge pohvale i osvojio simpatije organizatora i posjetitelja, ali i ostalih natjecatelja.

Solar Decathlon

Tijekom 1990-ih u SAD-u je nastala ideja o natjecanju kojim bi se studente, buduće inženjere, potaknulo na korištenje obnovljivim izvorima energije. Stoga je pod pokroviteljstvom Ministarstva energetike SAD-a 2002. organizirano prvo natjecanje *Solar Decathlon*. Održano je Washingtonu, u parku National Mall (ispred Bijele kuće). Sudjelovali su isključivo timovi s američkih sveučilišta, a posjetilo ga je više od 100 000 posjetitelja. Sljedeći *Solar Decathlon* održan je 2005. na istome mjestu, a već su tada uz timove američkih sveučilišta na njemu sudjelovali i timovi iz Kanade i Španjolske. Od te se godine natjecanje održava svake druge godine na istome mjestu, a popis zemalja sudionika sa svakim je natjecanjem sve veći, kao i broj posjetitelja. Zbog velikog interesa natjecanje se s vremenom proširilo na Europu i Kinu.

Pravo sudjelovanja na natjecanju ostvaruju sva registrirana sveučilišta i stručni studiji koji u svom sastavu imaju fakultete arhitektonske, elektrotehničke, strojarske i građevinske struke te drugih struka koje pronalaze interese u temama o energetskoj učinkovitosti i održivosti. Natječu se ponajprije studenti, ali je dopušteno, a katkad i nužno, sudjelovanje profesora i profesionalaca. Dopušteno je i sudjelovanje timova sastavljenih od više sveučilišta iz pojedine zemlje, kao i više sveučilišta iz različitih zemalja.

Natjecanje *Solar Decathlon* temelji se na izgradnji samoodržive montažne kuće čije se potrebe za energijom zadovoljavaju iz obnovljivih izvora, prije svega od Sunca. Natjecanje se sastoji od dvije faze. U prvoj fazi, koja traje dva mjeseca, potrebno je napraviti idejno rješenje te dokazati da natjecateljski tim ima znanja, mogućnosti i ambicije dovesti projekt do završetka, tj. do izgradnje kuće na natjecanju *Solar Decathlon*. Najvažniji kriteriji koji se pri tome razmatraju jesu financijska i organizacijska mogućnost završetka projekta. Usto, za odabir finalista bitni su kriteriji inovativnost i integracija projekta u nastavni program sveučilišta. Ako tim prođe u drugu fazu natjecanja, tj. ako uđe među 20 finalista, ima 18 mjeseci za dovršetak izvedbenog projekta i izgradnju objekta. Organizator periodično provjerava izvedbu projekta na temelju projektne dokumentacije koju su timovi dužni dostaviti prema unaprijed određenim rokovima. Vrhunac natjecanja je izgradnja svih objekata i njihovo izlaganje na lokaciji održavanja natjecanja.

Objekti se ocjenjuju u deset kategorija, a to su:

1. arhitektonska izvedba
2. konstrukcije
3. energetska učinkovitost
4. ravnoteža proizvodnje i potrošnje električne energije
5. ugodnost stanovanja
6. funkcionalnost
7. industrijalizacija
8. inovativnost
9. održivost
10. društvena prihvatljivost.

Svaku kategoriju ocjenjuje tročlana komisija, a ocjenjivanje se provodi tijekom cijelog trajanja natjecanja. Sve dok traju mjerenja, npr. energetske učinkovitosti, kuće su zatvorene za javnost kako bi se uklonila mogućnost utjecanja na rezultate.

Solar Decathlon Europe

Zahvaljujući velikom uspjehu *Solar Decathlona* u SAD-u, 2010. prvi je put održano natjecanje *Solar Decathlon Europe* u Madridu, na temelju sporazuma između španjolske vlade i Ministarstva energetike SAD-a. Prvi *Solar Decathlon Europe* posjetilo je oko 190 000 osoba, a za sudjelovanje na natjecanju prijavilo se 46 timova od kojih je izabrano 17 finalista. Idući *Solar Decathlon Europe* održan je 2012., također u Madridu, a razgledalo ga je oko 250 000 posjetitelja. Sudjelovalo je 20 timova finalista iz 11 zemalja svijeta, a samo dva tima zbog tehničkih i/ili financijskih razloga nisu mogli izložiti svoju kuću.

Dogovorom između vlada SAD-a i Francuske, *Solar Decathlon Europe 2014.* održan je u Versaillesu, u parku dvorca, od 16. lipnja do 19. srpnja. Poziv za prijavu objavljen je 10. listopada 2012. pod pokroviteljstvom francuske vlade. Na natjecanje su se prijavila 44 tima iz 23 zemlje svijeta. Prijave su stizale iz Europe, Azije te Sjeverne i Južne Amerike. Neki su timovi bili sastavljeni od sudionika sa sveučilišta iz različitih zemalja, čime je započeta nova era natjecanja, ali i znanstvene suradnje u istraživanju i razvoju solarne energije.

Za *Solar Decathlon Europe* 2014. iznimno su formirane dvije skupine finalista: 20 glavnih i pet zamjenskih timova. Zamjenski su timovi osmišljeni za slučaj da neki glavni tim odustane u procesu razrade projekta. Prvotni je plan bio da svi timovi do 1. studenog 2013., tj. do treće isporuke dokumentacije, ravnopravno sudjeluju u natjecanju. Tada se, prema stanju projekata, trebalo odlučiti o nastavku rada na projektu za glavne timove, ili o prekidu rada za zamjenske timove. No ponukani ozbiljnošću zamjenskih timova i njihovim angažmanom, organizatori su pokušali, i uspjeli, naći način da se i zamjenskim timovima omogući sudjelovanje na natjecanju te izlaganje njihovih objekata. Do početka natjecanja ostala su dva zamjenska tima koja su u zadanom roku uspjela izvesti svoje projekte do kraja.

Tim UniZG

Tim UniZG (sl 1.) tim je studenata Sveučilišta u Zagrebu, sastavljen radi sudjelovanja na natjecanju *Solar Decathlon Europe 2014*. To je prvi tim iz Republike Hrvatske koji je sudjelovao na natjecanju tog tipa. Osim sudjelovanja na natjecanju, njihovim se radom željelo postići povećanje svijesti javnosti i studenata o potrebi iskorištavanja obnovljivih izvora energije i o održivom razvoju. S vremenom se tim razvijao te je od malog broja studenata narastao do više od 70 studenata i 30 profesora mentora s 13 zagrebačkih fakulteta. To su Fakultet elektrotehnike i računarstva, Fakultet strojarstva i brodogradnje, Građevinski fakultet, Arhitektonski fakultet, Šumarski fakultet, Ekonomski fakultet, Prirodoslovno-matematički fakultet, Fakultet kemijskog inženjerstva i tehnologije, Prehrambeno-biotehnološki fakultet, Filozofski fakultet, Fakultet političkih znanosti, Tekstilno-tehnološki fakultet i Grafički fakultet.

Da bi projekt bio uspješno proveden, studenti su bili podijeljeni u nekoliko timova: Arhitektura, Konstrukcije i materijali, Strojarstvo, Elektroenergetika, Automatika, Organizacija građenja, Drvna tehnologija, Ekoinženjerstvo i Marketing.

Potrebno je napomenuti kako su u trenutku gradnje kuće granice među tim timovima praktički izbrisane, te su svi zajedno radili u skladu sa svojim mogućnostima i kompetencijama prema potrebama projekta.

Slika 1. Tim UniZG na dan otvorenja natjecanja u Versaillesu (Foto: tim UniZG, 2014.)

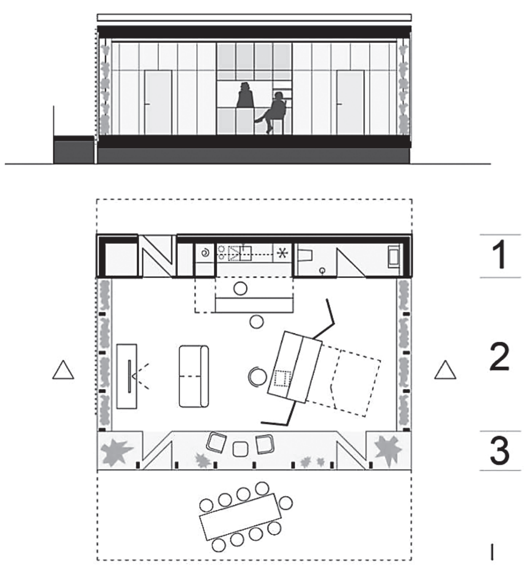
Glavni je mentor tima prof. Mladen Jošić s Arhitektonskog fakulteta u Zagrebu, voditelj cijelog tima Hrvoje Nikola Vučemilo, student Fakulteta elektrotehnike i računarstva, a menadžer za sponzorstva je Stipo Dubravac, student Šumarskog fakulteta.

Većina članova tima UniZG kao motivaciju za rad na projektu ponajprije ističe interdisciplinarnost koja se zbog isprepletenosti različitih struka danas nameće kao nužnost. Također treba spomenuti da su iz rada na projektu proizašli mnogi završni i diplomski radovi koji svjedoče o važnosti projekta. Projekt je pokazao da studenti Sveučilišta u Zagrebu svojim znanjem i idejama, te uz pomoć mentora sa Sveučilišta, itekako mogu biti konkurentni na međunarodnoj razini. To je dobar pokazatelj u kojem smjeru treba ići kako bi se ostvario puni potencijal studenta Sveučilišta u Zagrebu.

Jedna od glavnih ideja kojom su se studenti vodili pri izradi projekta bila je da kuća u konačnici bude izrađena iskorištenjem domaćih resursa ako je ikako moguće. Zahvaljujući tome, ostvarena je suradnja s brojnim domaćim tvrtkama koje su prepoznale značenje projekta. Pri tome treba istaknuti tvrtke iz Hrvatske drvne industrije koje su financijski i materijalno potpomogle uspješnu izradu projekta. To su Spin Valis, Hrvatske šume, Drvene kuće – Macola, Drvene konstrukcije – Voćin, Bernarda, Lokve, Schachermayer, Hafele, Elgrad, Egger i obrt Kolar.

Koncept Membrain

Počevši već od stanice, membrane su vitalni dijelovi svih živih organizama – one moraju biti u izravnom kontaktu s okolišem, dok tvari selektivno cirkuliraju unutar staničnog prostora. Slično tome, i *Koncept Membrain* projekt je pametne samoodržive kuće koncipirane s visokotehnološkom membranom koja štiti jezgru kuće te omogućuje život u njoj. Membrana apsorbira sekundarne prostore i oslobađa jezgru koju korisnik potom prilagođuje svojim potrebama.



Slika 2. Prikaz slojeva *Kocept Membrain* kuće (1 – sjeverni zid unutar kojega su smješteni strojarnica, ulazni prostor, kuhinja, garderobni ormar i kupaonica, 2 – centralni dio – jezgra okružena staklenicima, 3 – zimski vrt) (Foto: Tim UniZG, 2013.)

Ovojnica komunicira s vanjskim svijetom, upija energiju i prenosi je u unutrašnjost, gdje stvara ugodnu mikroklimu. Također, membrana obuhvaća kuhinju, kupaonicu, spremište, strojarnicu, ulaz i staklenik, a time oslobađa unutarnji prostor i stvara fleksibilni prazni prostor. Ona je „mozak" cijele kuće, prilagodljiva je i slojevita, a obavija kuću sa svih njezinih strana. Dakle, dvije ključne komponente kuće jesu membrana i jezgra (sl. 2.).

Projekt *Koncept Membrain* također je usko vezan za izgradnju kampusa Borongaj. Kampus je osmišljen kao ekološki rezervat, pa se i gradi u skladu s ekološkim i energetskim standardima. Energetski koncept u potpunosti slijedi najsuvremenija načela i tehnologije iskorištavanja te primjene obnovljivih izvora energije, uštede energije, zaštite okoliša i održive gradnje te potiče na eksperimentiranje sa svim poznatim novim energentima i tehnologijama njihove primjene.

Sustavi kuće

Kako bi se osigurala brza gradnja kuće te njezino normalno funkcioniranje nakon sastavljanja, studenti su implementirali mnoge sustave koje su uglavnom sami osmislili i izradili.

Nosiva konstrukcija kuće napravljena je od drvenih lameliranih stupova, horizontalnih podnih i stropnih ploča te ukrutnih zidova. Drvo je odabrano kao materijal s dugom tradicijom u hrvatskoj kulturi gradnje, a ima sjajna svojstva – malu specifičnu gustoću, nisku toplinsku provodljivost i negativan utisak CO_2.

Kao toplinska izolacija upotrijebljena je ovčja vuna. Ona je korištena za ispunu posebno projektiranih kutija od OSB ploča na ukrutnim zidovima te na podnim i stropnim pločama. Vuna je izabrana kao prirodni materijal i nusproizvod uzgoja ovaca koji se zbog preniske kvalitete ne rabi za izradu odjevnih predmeta, a ima jednako dobra svojstva kao i klasična mineralna vuna.

Na južnome, istočnome i zapadnom zidu toplinska se izolacija postiže sustavom staklenika koji svojim dvostrukim izostaklom smanjuju gubitke topline, stvaraju prostor za uzgoj biljaka, a zbog solarne energije zimi smanjuju potrebu aktivnoga grijanja.

Krov kuće je dinamična površina fotonaponskih solarnih panela, poznatija pod nazivom „harmonika". Ovisno o insolaciji, ona mijenja svoju geometriju i kut nagiba panela te se prilagođuje za optimalno skupljanje električne energije i štiti kuću od prekomjernog osunčavanja ljeti. Zimi, kada je Sunce nisko, krov se nabere povećavajući tako nagib fotonaponskih panela te proizvodi više energije i istodobno propuštajući više Sunčeve energije u unutrašnjost kuće.

Unutar konstrukcije spuštenog stropa ugrađen je pasivni sustav phase-change materijala (PCM) koji promjenom svoga agregatnog stanja povećava toplinski kapacitet kuće zadržavajući konstantnu temperaturu prostora.

Sve potrebe za grijanjem i hlađenjem koje pasivni sustavi ne mogu ostvariti, kao i potrebe za sanitarnom toplom vodom, nadoknađuje sustav dizalice topline koji, koristeći se energijom dobivenom od solarnih panela, hladi/grije vodu koja se sustavom niskotemperaturnog podnoga grijanja distribuira kroz kuću. Za aktivan sustav grijanja/hlađenja primijenjen je sustav ventilacije s rekuperacijom zraka.

Svim sustavima unutar *Membrain kuće* upravlja glavni računalni sustav koji istodobno omogućuje nadzor i upravljanje. Interakcija s korisnikom ostvaruje se putem tableta ili pametnog telefona. Na kampusu će služiti kao glavni obrazovni alat koji će posjetiteljima davati informacije o potrošnji energije te uštedama ostvarenim korištenjem obnovljivih izvora i održive gradnje.

Za zvučnu izolaciju strojarnice upotrijebljene su drvno-cementne ploče koje nude mnoge pogodnosti za okoliš i održivi razvoj, a vrlo se jeftino proizvode – dva najskuplja elementa su cement i radna snaga. Kako se ne proizvode u velikoj tvornici ili postrojenju, tijekom proizvodnje znatno su umanjeni ugljični otisak i potrošnja energije. Cilj nije bio proizvesti materijal velike čvrstoće, već lagan i porozan, pogodan za korištenje na fasadi, koji omogućuje bolju toplinsku i zvučnu izolaciju. Vrlo je otporan na vlagu, nametnike, insekte i vatru.

Drvna tehnologija

Studenti Šumarskog fakulteta okupljeni u timu Drvna tehnologija bili su zaduženi za mnoge poslove u sklopu rada na projektu *Koncept Membrain*. Među ostalim bili su to poslovi osmišljavanja i izrade namještaja, proračuni trajnosti drvene fasade kojom se oblagao sjeverni zid kuće, izrada drvene ograde terase, izrada unutarnjih vrata te savjetovanje s ostatkom tima u vezi s uporabom drva i drvnih materijala.

Unutarnja vrata na strojarnicama, ulaznom prostoru i kupaonici izrađena su od jelove konstrukcije i brezovih furnirskih ploča, a studenti su ih izradili sami. Za toplinsku i zvučnu izolaciju upotrijebljena je ovčja vuna, što je koncept primijenjen i na ostatku kuće.

Namještaj, koji su projektirali i velikim dijelom izradili studenti Šumarskog fakulteta, u potpunosti je prilagođen konceptu pametne prilagodljive kuće. Kuhinja se, sa svim svojim uređajima, nalazi unutar membrane, a namještaj u jezgri kuće jednostavan je, lako pomičan i sklopiv. Ta je ideja jasno naglašena i korištenim materijalom – namještaj u jezgri kuće izrađen je od hrastovine kao tradicionalnoga hrvatskog materijala za izradu namještaja i opremu interijera. Drvo hrasta lužnjaka visokokvalitetni je materijal iznimnih estetskih, fizikalnih i mehaničkih svojstava. Kuhinja i garderobni ormar izrađeni su od suvremenih materijala kakvi se rabe u izradi namještaja da bi se približili suvremenom visokotehnološkom konceptu membrane u kojoj se nalaze. To je prije svega ploča iverica, oplemenjena folijom, ploče sa saćastom ispunom, furnirska ploča od brezovine, inoks i aluminij. Ploče iverice dobar su primjer održivih materijala zato što se za njihovu proizvodnju uglavnom upotrebljava drvo koje se zbog nešto niže kvalitete ne može iskoristiti za izradu drugih predmeta, kao i reciklirano drvo, što smanjuje potrebu za sječom šuma. Namještaj izrađen od ploča iverica na kraju svojega životnog vijeka može se iskoristiti za proizvodnju biogoriva.

Koncept namještaja

Osnovni koncept namještaja kojim su se vodili studenti Šumarskog fakulteta prilikom projektiranja

a) b) c) d)

Slika 3. Kuhinja u različitim fazama otvorenosti (a – zatvorena, b – poluotvorena, c – otvorena, sa spremljenim kuhinjskim otokom, d – otvorena, s izvučenim kuhinjskim otokom) (Foto: Novak, M., 2014.)

namještaja bila je prilagodljivost. Ona se ponajprije ogleda u tome što je sav namještaj lako pomičan i nenametljiv u prostoru. Stoga se kuhinja sastoji od dva dijela. Nepomični dio s ugrađenim uređajima nalazi se u membrani kuće, dok se pomični kuhinjski otok može izvući iz membrane u središnji prostor kuće prema potrebi. Ako korisnici kuće imaju potrebu za više prostora u jezgri kuće, kuhinjski se otok vrlo jednostavno može spremiti u membranu i zatvoriti. Slika 3. prikazuje kuhinju u različitim fazama otvorenosti. Kuhinjski je otok projektiran u tri dijela kako bi se uštedio prostor i povećala funkcionalnost namještaja. On se sastoji od šanka, sklopivoga blagovaoničkog stola za šest osoba i kuhinjskog elementa. Funkcionalnost kuhinjskog elementa dodatno je povećana time što se dva barska stolca mogu spremiti unutar njega da ne smetaju u prostoru dok nisu potrebni.

U membrani je uz kuhinju smješten i garderobni ormar koji se izvlači iz zida. Dok je garderobni ormar zatvoren, pročelje ormara postaje dio zida. Na taj je način jezgra kuće rasterećena od monumentalnih formi koje bi mogle biti nametljive u prostoru, a korisnici kuće i dalje imaju dovoljno prostora za spremanje.

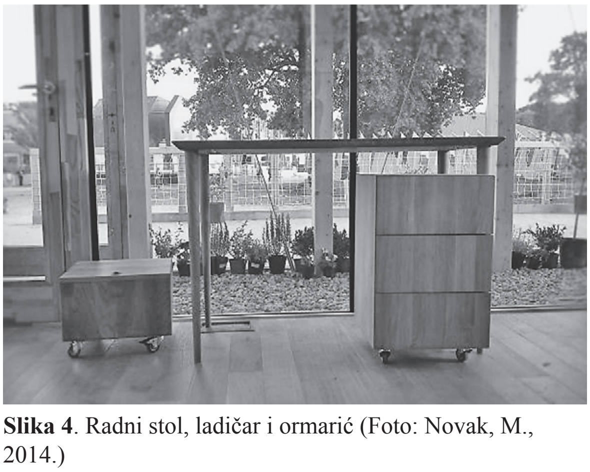
Namještaj u jezgri kuće čine radni stol i ladičar (sl. 4.), preklopni bračni krevet (sl. 5.), četiri ormarića koja mogu poslužiti i za sjedenje te šest blagovaoničkih stolaca.

Pri projektiranju namještaja vodila se briga i o povećanoj funkcionalnosti. To se vidi na primjeru ormarića koji mogu poslužiti za spremanje predmeta, kao i za sjedenje i odlaganje predmeta. Naravno, uz sve navedeno bilo je potrebno voditi brigu o kvaliteti, trajnosti i održivosti izrađenog namještaja.

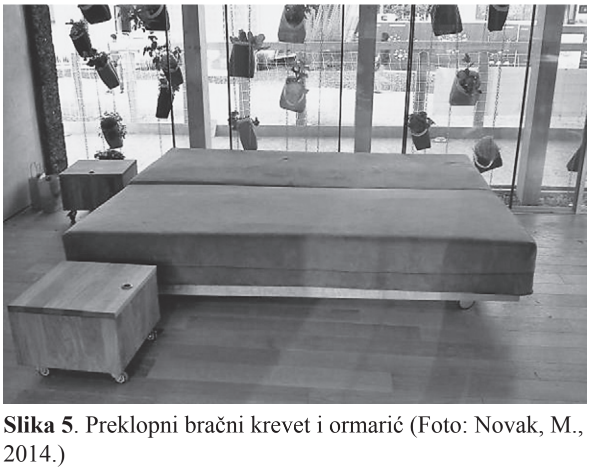
Gradnja *Koncept Membrain kuće*

Nakon mjeseci rada na dokumentaciji, planiranja te prikupljanja financijskih i materijalnih sredstava, u proljeće 2014. počela je i gradnja kuće u Kineskom paviljonu Zagrebačkog velesajma (sl. 6.). Kako bi se ispunili ograničeni rokovi za sastavljanje kuće, mnogi su sustavi zamišljeni kao prefabrikati, tj. predmontirani su kako bi se smanjilo vrijeme potrebno za sastavljanje u Versaillesu. Kuća je odmah nakon sastavljanja rastavljena te uz pomoć pet šlepera otpremljena na put prema Versaillesu.

Sastavljanje kuće u Versaillesu (sl. 7.) počelo je 16. lipnja, a trajalo je do 28. lipnja. U tom roku kuća je uspješno sastavljena, s tim da je potrebno napomenuti kako su neki sustavi prvi put postavljeni tek u Francuskoj, što je važno istaknuti s obzirom na to da je nekolicina ostalih timova kasnila s izgradnjom i produžila je za vrijeme natjecanja. Pri izgradnji kuća organizatori su timove smatrali pravim građevnim tvrtkama, stoga su svi sudionici tijekom cijelog vremena gradnje na gradilištu nosili zaštitnu opremu, svako je gradilište bilo ograđeno zaštitnom ogradom te je osim organizatorskih nadzornika za zaštitu na radu svaki tim imao i svoje nadzornike. Radilo se u dvije smjene, jutarnjoj i večernjoj, kako bi kuće bile izgrađene navrijeme, tj. do početka službenog dijela natjecanja.



Slika 4. Radni stol, ladičar i ormarić (Foto: Novak, M., 2014.)



Slika 5. Preklopni bračni krevet i ormarić (Foto: Novak, M., 2014.)

Slika 6. Postavljanje stropne ploče u Kineskom paviljonu (Foto: tim UniZG, 2014.)

Slika 7. Sastavljanje kuće u Versaillesu

Kuća je bila otvorena za javnost od 28. lipnja do 14. Srpnja, kada je završeno natjecanje. Timovi su imali rok za rastavljanje objekata do 19. srpnja, a tim UniZG kuću je uspješno rastavio i poslao na put prema Zagrebu u zadanom roku.

Rezultati *Solar Decathlona Europe 2014.*

Na natjecanju *Solar Decathlon Europe 2014.*, održanome u parku dvorca Versailles, svoje su projekte predstavila 22 sveučilišna tima iz 17 zemalja s područja Europe, Azije te Sjeverne i Južne Amerike (sl. 8.), tj. 20 natjecateljskih timova i dva izložbena. Tim UniZG sa svojim je projektom *Koncept Membrain* sudjelovao kao jedan od izložbenih timova. Za vrijeme cjelokupnog trajanja natjecanja, tj. do izložbe, kuću *Koncept Membrain* razgledalo je otprilike 80 000 posjetitelja.

Natjecanje su posjetile osobe različitih interesnih skupina, a mnogi od njih bili su puni pohvala za *Koncept Membrain kuću* (sl 9.). Posjetitelji su bili zadivljeni time

Slika 8. Pogled na Solarno selo u Versaillesu (Foto: *Solar Decathlon Europe 2014.*)

Slika 9. Eksterijer *Koncept Membrain kuće* u Versaillesu (Foto: *Solar Decathlon Europe 2014.*)

Slika 10. Interijer *Koncept Membrain kuće* u Versaillesu (Foto: *Solar Decathlon Europe 2014.*)

što je hrvatski tim projektirao i izgradio svoju kuću bez pomoći profesionalaca i uz znatno skromnija sredstva od ostalih timova. Posjetitelja se najviše dojmila jednostavnost izvedbe ukomponirana u funkcionalnost, a doživjeli su je kao ugodan i otvoren prostor ispunjen svjetlošću i toplinom (sl. 10.). Potrebno je naglasiti kako se koncept same *Membrain kuće* toliko razlikovao od ostalih kuća na natjecanju da je označen kao jedan od inovativnijih. To je bitna činjenica zato što je to prvo sudjelovanje nekog tima iz Hrvatske na takvom natjecanju, a tim UniZG pokazao je što studenti zagrebačkog Sveučilišta znaju i mogu napraviti kad dobiju priliku.

Nakon zbrajanja bodova za svih deset ocjenjivanih kategorija, ukupnim je pobjednikom proglašen talijanski tim RhOME s projektom *RhOME for denCity*, a tim UniZG dobio je posebno priznanje za sudjelovanje na *Solar Decathlonu Europe 2014*. Edwin Rodríguez Ubiñas, jedan od glavnih organizatora natjecanja, tijekom cijele gradnje i natjecanja pomno je pratio UniZG tim te je izrazio veliko zadovoljstvo radom i trudom hrvatskog tima.

Više o natjecanju *Solar Decathlon Europe 2014*. možete saznati na web adresi: http://www.solardecathlon2014.fr/en/, a o timu UniZG i *Konceptu Membrain* možete saznati na web adresi: http://www.membrain.com.hr/.

Marko Šostar, mag. ing. tech. lign.
Stipo Dubravac, univ. bacc. ing. techn. lign.

25. MEĐUNARODNO ZNANSTVENO SAVJETOVANJE *AMBIENTA 2014*

25th INTERNATIONAL SCIENTIFIC CONFERENCE
New Materials and Technologies in the Function of Wooden Products

Godine 2014. Šumarski fakultet Sveučilišta u Zagrebu proslavio je svoju 25. godišnjicu organiziranja međunarodnoga znanstvenog savjetovanja s područja šumarstva i drvne tehnologije, među sudionicima popularno nazvanu **AMBIENTA**, koja je, kao i dugi niz godina dosad, održana tijekom 41. međunarodnog sajma namještaja, unutarnjeg uređenja i prateće industrije *Ambienta '14* (15. – 19. listopada 2014.) u organizaciji Zagrebačkog velesajma. *Ambienta* se još od 1990. održava redovito jedanput u godini, te je s godinama postala glavni događaj za susrete i umrežavanje profesionalaca iz znanstvenoistraživačkih institucija i drvne industrije Hrvatske i šireg područja.

Tijekom svih ovih dvadeset pet godina osnovni je cilj savjetovanja bio dovesti na jedno mjesto vodeće znanstvenike, nastavnike, istraživače, postdiplomante i doktorante kako bi razmijenili i podijelili svoja iskustva i rezultate istraživanja o svim aspektima znanosti o drvu i tehnologiji. *Ambienta* je ujedno interdisciplinarni forum za istraživače, stručnjake i nastavnike na kojemu mogu predstaviti najnovije inovacije, trendove, zabrinutosti, praktične izazove s kojima se susreću i raspraviti o njima, kao i o usvojenim rješenjima na području materijala od drva i tehnologije.

Godine 2014. jubilarno je, 25. međunarodno znanstveno savjetovanje održano pod nazivom *Novi materijali i tehnologije u funkciji proizvoda od drva*, čime su organizatori željeli potaknuti raspravu o novim, konkurentnijim drvnim materijalima i tehnologijama. Nadalje, jedan od ciljeva savjetovanja bio je davanje informacija o tome kako se uključiti u nove programe financiranja iz fondova Europske unije, čime će se omogućiti mnogo veća ulaganja u znanost, istraživanje i inovacije, kao i u financiranje konkurentnih znanstvenoistraživačkih projekata te uspostaviti bolja povezanost znanstvenih institucija s gospodarstvom.

Organizatori savjetovanja bili su Šumarski fakultet Sveučilišta u Zagrebu, InnovaWood, Hrvatska komora inženjera šumarstva i drvne tehnologije, Akademija šumarskih znanosti, Akademija tehničkih znanosti Hrvatske, Hrvatsko šumarsko društvo, Znanstveno vijeće za poljoprivredu i šumarstvo HAZU, Oddelek za lesarstvo Biotehniške fakultete Univerze v Ljubljani, Zveza lesarjev Slovenije i Zagrebački velesajam.

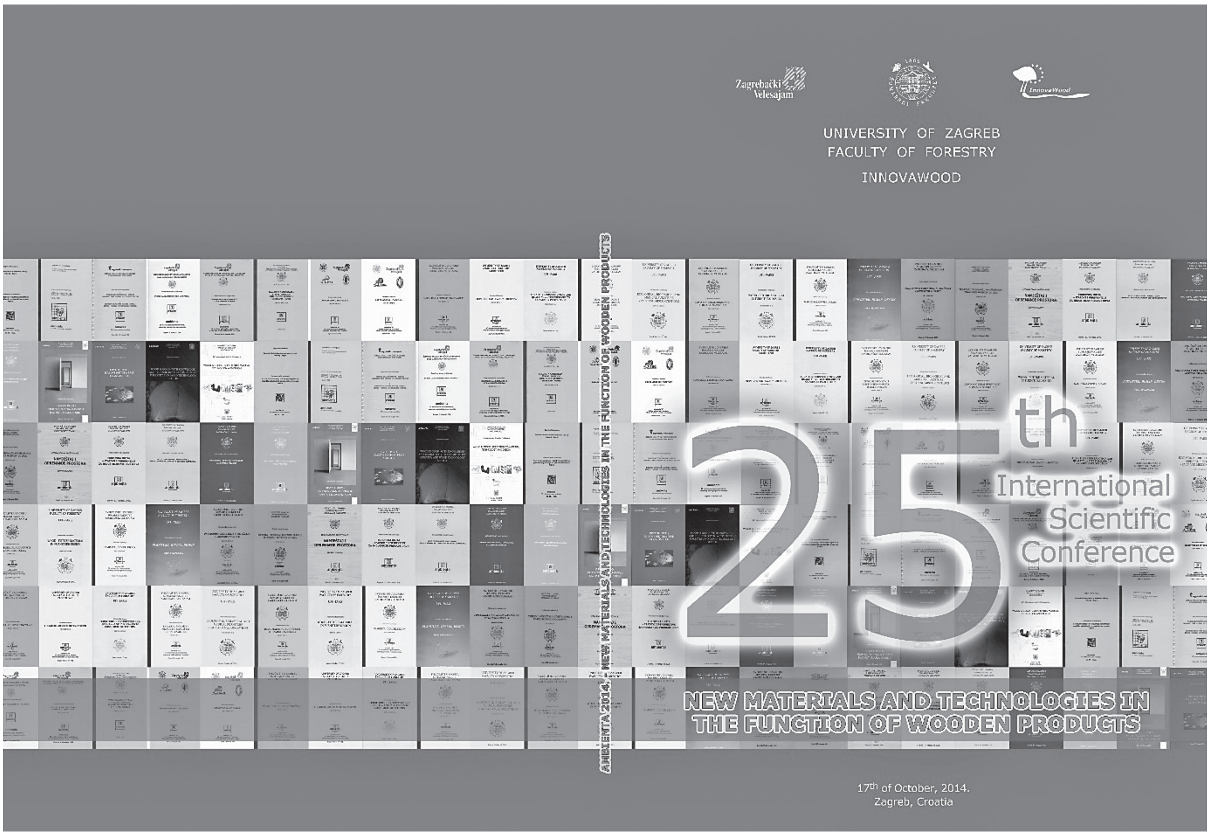
Glavni pokrovitelj savjetovanja bilo je Ministarstvo poljoprivrede, a supokrovitelji su bili Ministarstvo poduzetništva i obrta, Ministarstvo gospodarstva, Hrvatski šumarski institut, Hrvatske šume d.o.o., Hrvatska komora inženjera šumarstva i drvne tehnologije, Hrvatska gospodarska komora, Hrvatska gospodarska komora Zagreb, Virovitičko-podravska županija, Zagrebačka županija, Hrvatski drvni klaster i Hrvatski klaster konkuretnosti drvnoprerađivačkog sektora.

Savjetovanju su prisustvovali predstavnici drvnoindustrijskih tvrtki, predstavnici tvrtki koje se bave prodajom namještaja i ostalih proizvoda od drva, Šumarskog fakulteta u Zagrebu, Zagrebačkog velesajma, Ministarstva poljoprivrede, Hrvatskih šuma d.o.o., kolege znanstvenici iz Austrije, Bugarske, Češke, Grčke, Mađarske, Makedonije, Poljske, Slovačke, Slovenije, Srbije i Turske, brojni studenti drvne tehnologije te više zainteresiranih stručnjaka različitih područja koji nisu izravno povezani s drvnom industrijom.

Nadalje, savjetovanje je 2014. godine ponovno održano, i to deveti put, u suradnji s najvećom europskom organizacijom iz sektora šumarstva, industrijske prerade drva i industrije namještaja InnovaWoodom. Tijekom dugogodišnje suradnje u organiziranju savjetovanja InnovaWood je, zajedno s više od 70 svojih članica iz 24 zemlje, uspješno pomogao ostvariti ciljeve savjetovanja, ponajprije uspostavljanjem efektivnijih mehanizama kao podrškom inovacijama u navedenim sektorima, preko aktivnosti u područjima istraživanja, edukacije i transfera tehnologije.

I posljednje je savjetovanje još jedan doprinos kampanji *Drvo je prvo*, čiji je cilj promicanje drva kao prirodnoga, ekološki prihvatljivog materijala. Iz programa je vidljivo da je okupljenim stručnjacima iz različitih zemalja i različitih disciplina zajednička ljubav prema drvu i drvnoj struci te želja za što uspješnijom promocijom drva. Zbornik radova s tog savjetovanja daje mnogo korisnih informacija za struku u cjelini u obliku novih spoznaja na području biotehničkih znanosti vezanih za valorizaciju i ocjenu stanja konkurentnosti na tržištu te za oblikovanje namještaja, nove tehnologije i tehnološke procese obrade drva, kao i primjene drva, drvnih i drugih materijala u izradi namještaja i u graditeljstvu kojima struka može povećati konkurentnost svoje tržišne ponude.

Ovogodišnje, 25. međunarodno znanstveno savjetovanje međunarodno je već po broju prijavljenih radova (25) i interesu eminentnih domaćih i stranih stručnjaka, a pokazalo je da suradnja Šumarskog



Slika 1. Naslovnica zbornika

fakulteta i Zagrebačkog velesajma i u krizna vremena može rezultirati organizacijom savjetovanja na visokoj međunarodnoj razini. To je rezultat ne samo kvalitete dosadašnjih znanstvenih savjetovanja već i višegodišnje međunarodne suradnje priznatih stručnjaka Šumarskog fakulteta kao punopravnog člana organizacije InnovaWood. Evidentno je da suradnja s organizacijom InnovaWood i dalje pridonosi još većoj afirmaciji Šumarskog fakulteta te učvršćivanju njegova položaja na razini vodećih međunarodnih znanstvenih institucija. Zbog velikog broja prijavljenih radova i 2014. godine dio je radova (13) prezentiran putem postera.

Na savjetovanju su izloženi sljedeći radovi.

1. Birbilis, Dimitrios – Karastergiou, Sotirios – Adamopoulos, Stergios – Kakavas, Konstantinos – Tsioukas, Thomas
   Properties of Pine (*Pinus Nigra*) and Beech (*Fagus Sylvatica*) Wood Impregnated with Hot Rape Oil and Surface Treated with Turpentine
2. Klarić, Kristina – Greger, Krešimir – Francetić, Marko
   ISO 9001 Quality Management Certification in Croatian Wood Industry
3. Hrovatin, Jasna – Klos, Robert – Fabisiak, Beata
   Impact of new Materials and Technologies in the Design of Wooden Products
4. Kováč, Ján – Krilek, Jozef
   Influence of selected factors on the vibrations of a chainsaw
5. Moro, Maja
   Employment Trends in the Croatian Furniture Manufacturing
6. Bego, Margarita
   Conservation and Restoration of the Alt Deutsch cabinet
7. Šimek, Milan – Tauber, Jiří – Voith, Petr – Dlauhý, Zdeněk
   CNC Manufacturing Technology Case Study of an Armchair Design
8. Svoboda, Jaroslav – Tauber, Jiří – Tesařová, Daniela
   Decreasing the concentration of cigarette smoke in the interior using controlled air-ionization
9. Župčić, Ivica – Žulj, Ivan – Grbac, Ivica – Premuš, Igor
   Welding of chemical modified oak
10. Aydin, Ismail – Demirkir, Cenk – Colak, Semra – Colakoglu, Gursel – Ozturk, Hasan
    Effect of Wood Species and Adhesive Types on Thermal Conductivity of Plywood
11. Demir, Aydin – Aydin, Ismail – Ozturk, Hasan
    Effect of Fire Retardant Chemicals on Formaldehyde Emission of Plywood
12. Pirc Barčić, Andreja – Motik, Darko – Liker, Branko – Kavran, Marijan
    Market Possibilities of Wooden Biomass in Croatia
13. Simeonova, Ralitsa – Jivkov, Vassil – Marinova, Assia
    Bending Strength under Compression Test of Glued Joints of Frame Structural Elements Made of Plywood
14. Bahcevandziev, Konstantin – Mihajlovski, Nikola
    Swelling and transverse anisotropy of impregnated and coated spruce wood *(Picea abies Karst)*

15. Kyuchukov, Georgi – Kyuchukov, Borislav – Jivkov, Vassil – Marinova, Assia – Gruevski, Georgi – Kanarchev, Krassimir
Comparative research on the destructive bending moments of some corner joints of frame structural elements made of solid spruce wood with a cross section of 50 X 30 mm
PART II: End corner open mortise and tenon joints
16. Smardzewski, Jerzy – Majewski, Adam
Mechanical Properties of Auxetic Honeycomb Core with Triangular Cells
17. Stasiak-Betlejewska, Renata – Borkowski, Stanisław
The Machines Operation Effectiveness In The Furniture Production In The Context Of Toyota Production System Applying
18. Domljan, Danijela – Vlaović, Zoran – Grbac, Ivica
Design concepts of multifunctional furniture for sitting and lying related to the industry
19. Španić, Nikola – Jambreković, Vladimir – Antonović, Alan
Chemical and Thermal Properties of WPC Surface After Exposure to Concentrated Acids
20. Antonović, Alan – Jambreković, Vladimir – Španić, Nikola – Medved, Sergej – Ištvanić, Josip – Devčić, Matej
Influence of pH value of liquefied wood as a hardener of urea-formaldehyde resin with 4 % melamine addition in particleboard production
21. Jakimovska Popovska, Violeta – Aziri, Basri – Iliev, Borche
Water Impact on the Change of the Physical Characteristics of Combined Water-Resistant Wood Based Panels
22. Jevtić, Petronije
Accelerated Weathering of Wood Coatings by QUV-A With Direct Water Spray
23. Rogoziński, Tomasz
Wood Dust Separation in a Pulse-jet Fabric Filter
24. Rademacher, Peter – Meier, Dietrich – Hofmann, Tomás – Pařil, Petr – Baar, Jan – Sablík, Pavel – Čermák, Petr – Paschova, Zuzanna – Rousek, Radim – Koch, Gerald – Schmitt, Uwe – Melcher, Eckhard – Nemeth, Robert
Property Improvement of Wood from fast growing Plantations due to Wood Modification with renewable Modification Agents
25. Šprdlík, Vaclav – Mihailović, Stefan – Brabec, Martin – Rademacher, Peter – Klímová, Hana
Ammonia treatment of beech veneer and application in furniture design

U veljači 2014. godine u Republici Hrvatskoj započela je provedba novoga okvirnog programa Europske unije za istraživanje i inovacije *Obzor 2020.* (*Horizon 2020.)* za razdoblje 2014. – 2020., čime je započeo novi ciklus ulaganja u znanost, istraživanje i inovacije. Europski institut za inovacije i tehnologiju, kao inicijator tog programa, pridonijet će svim prioritetima *Obzora 2020.* promoviranjem istraživanja orijentiranoga na komercijalnu upotrebu, potičući stvaranje malih i srednjih poduzeća te transdisciplinarne, međusektorske i prekogranične mobilnosti na konceptu „trokuta znanja“ što ga čine istraživanje, obrazovanje i inovativno poduzetništvo. Misao vodilja novoga okvirnog programa jest ponuda rješenja i odgovora na gospodarsku krizu, investiranje u buduće poslove i razvoj, rješavanje pitanja građana EU o njihovoj materijalnoj sigurnosti, općoj sigurnosti i okolišu, kao i jačanje globalne uloge EU u istraživanjima, inovacijama i tehnologijama.

Zaključno, glavni cilj ovog savjetovanja bio je okupiti sve sudionike „trokuta znanja” na jednome mjestu kako bi u idućem razdoblju potaknuli razvoj novih ili pridonijeli poboljšanju postojećih drvnih materijala i tehnologija, sve s ciljem konkurentnosti drvnotehnološkog sektora na globalnome svjetskom tržištu.

Savjetovanje je također bila prilika za stjecanje novih spoznaja utemeljenih na znanstvenoistraživačkom timskom radu znanstvenika s više domaćih i inozemnih fakulteta i instituta.

Zbornik radova u elektroničkoj verziji moguće je nabaviti s poveznice http://www.ambienta2014.com

prof. dr. sc. Ivica Grbac
doc. dr. sc. Alan Antonović

GVAJAK

UDK: 674.031.751.722

NAZIVI

Gvajak je naziv drva botaničke vrste *Guaiacum officinale* L. iz porodice *Zygophyllaceae.*

Trgovački je naziv te vrste pockholz (Njemačka); lignum vitae (SAD, Velika Britanija); gaiac (Francuska); guaiacum wood (Velika Britanija); pockhout (Nizozemska); gwayak (Poljska); guaiac (Rumunjska) te guayacan (Venezuela).

NALAZIŠTE

Stabla gvajaka mogu se pronaći u tropskim kišnim šumama Srednje Amerike, u sjevernom dijelu Južne Amerike, u zapadnoj Indiji, Hondurasu, Panami, Kolumbiji i Venezueli.

STABLO

U svojoj domovini gvajak naraste od 10 do 13 metara, uz dužinu debla do 5 metara te prsni promjer do 0,5 metara. Trupci gvajaka razlikuju se po kori: u vrste *Guaiacum officinale* kora je tanka, glatka i ljuskava, a u *Guaiacum sanctum* kora je gruba. Žica je redovito dvostruko usukana i nepravilna.

DRVO

Makroskopska obilježja

Drvo gvajaka je jedričavo. Srž drva je različite boje, od maslinasto zelene do smeđe ili čak crne, često s malobrojnim prugama. Drvo je fine teksture i rastresito je porozno. Granica goda i pore jasno su vidljivi povećalom. U tamnoj srži pore su jedva vidljive. Zbog ispunjenosti pora zelenim sadržajem one mogu biti vidljive u rano formiranoj bjeljici. Oko 30 % mase suhog drva čine gumaste tvari zbog kojih drvo izgleda voštano. Drvni traci i aksijalni parehnim vidljivi su pod povećalom.

Mikroskopska obilježja

Traheje su pojedinačno raspoređene, rjeđe se pojavljuju u parovima i u malim skupinama. Promjer traheja iznosi 30...75...175 mikrometara, a gustoća im je 6...12...20 na 1 mm^2 poprečnog presjeka. Volumni je udio traheja od 7,0 do 13,0 %. Traheje u bjeljici često su ispunjene zelenkastim tvarima.

Aksijalni je parenhim apotrahealan, paratrahealno aliforman, unilateralan, katnog rasporeda. Volumni udio aksijalnog parenhima iznosi oko 3 %.

Drvni su traci gvajakovine homogeni, visine 60...120 mikrometara, odnosno od 4 do 6 stanica, širine 8...10 mikrometara, odnosno jednu stanicu. Gustoća drvnih trakova je 12...17...19 na 1 mm. Volumni udio drvnih trakova iznosi od 11 do 13 %. U drvnim tracima i u aksijalnom parenhimu ima kristala kalcija. Drvna su vlakanca libriformska, odnosno vlaknaste traheide. Dugačka su 440...590...830 mikrometara. Debljina staničnih stijenki vlakanaca iznosi 2,65...4,3...6,6 mikrometara, a promjer lumena 0,7...4,2...7,7 mikrometara. Volumni udio vlakanaca kreće se od 70 do 80 %.

Fizička svojstva

Gustoća standardno suhog drva, ρ_o	950...1200...1300 kg/m^3
Gustoća prosušenog drva, ρ_{12-15}	970...1230...1310 kg/m^3
Gustoća sirovog drva, ρ_s	1400...1500 kg/m^3
Poroznost	12,6...18,0...36,7 %
Radijalno utezanje, β_r	oko 5,6 %
Tangentno utezanje, β_t	oko 9,3 %
Volumno utezanje, β_v	oko 15,0 %

Mehanička svojstva

Čvrstoća na tlak	90...126 MPa
Čvrstoća na savijanje	120...144 MPa
Tvrdoća (prema Janki), paralelno s vlakancima	oko 16,1 MPa
Tvrdoća (prema Janki), okomito na vlakanca	oko 8,8 (14,8) MPa
Modul elastičnosti	11,0...12,3...13,5 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se vrlo teško strojno i ručno obrađuje, a njegova obrada zahtijeva veći utrošak energije. Dobro se blanja i tokari. Izblanjane površine vrlo su glatke. Politiranje je često jedini izbor površinske obrade kojim se može postići visoki sjaj, i to zbog velikog udjela gumastih tvari u drvu. Teško se lijepi. Čavlanje se ne preporučuje.

Sušenje

Zbog velike gustoće drvo se teško suši, a zbog nepažljivog sušenja može raspucati. Jednom prosušeno drvo srednje je stabilnih dimenzija.

Trajnost i zaštita

U normi HRN 350-2, 2005 ne postoje podaci o otpornosti i trajnosti gvajakovine.

To je drvo vrlo otporno na gljive truležnice i na napade insekata te prirodno otporno na kiseline. Zbog velike gustoće i velikog sadržaja gumastih tvari gvajakovina jedva upija zaštitna sredstva, no ona je tako prirodno trajna da se može upotrebljavati nezaštićena.

Uporaba

Gvajakovina je jedna od najgušćih i najtvrđih vrsta drva na tržištu. Vrlo je velike čvrstoće pa je drvo gvajaka superioran materijal za izradu propelera, ležajeva, osovina brodskih vijaka, zupčanika, kugla i tokarene robe. Podaci govore da gvajakovina upotrijebljena za navedene namjene traje tri puta dulje od čelika ili bronce upravo zbog svojstva samopodmazivanja.

Sirovina

Drvo gvajaka na tržište dolazi u obliku trupaca od duljine 0,6 do 3,0 metara, a promjera od 7,0 do 50,0 centimetara.

Napomena

Smola gvajakovine još se od 1508. godine upotrebljava u medicini, pa se stoga to drvo naziva i *drvom života* (*lignum vitae*).

Upravo zbog pretjeranog iskorištavanja gvajak se još od 1998. nalazi na IURDN listi ugroženih vrsta. Prema trenutačnim CITES regulativama, vrste *Guaiacum* svrstane su u grupu II. (apendix II.), koja obuhvaća vrste drva kojima trenutačno ne prijeti iskorjenjivanje, no njihova se trgovina mora strogo kontrolirati.

Verawood ili marcaibo drvo života (*Bulnesia arborea* Engl.) s područja Venezuele povezuje se s pravim drvom života i katkad služi kao zamjena za gvajak.

Slične su vrste
Guaiacum coulteri A. Gray
Guaiacum guatamalense Pl.
Guaiacum sanctum L.
Bulnesia spp.

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630*946 Associations, societies, conferences, exursions, institutions

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Ispravak / errata corrige

U radu „Energy Consumption of Beech Timber Drying in Oscillation Climates“ autora Gorana Milića i suradnika, objavljenome u broju 4 /2014 časopisa Drvna industrija, pogreškom su objavljeni neodgovarajući grafički prilozi.
Grafički prilozi na slikama 2. i 3. međusobno su zamijenjeni, a naslov ordinate slike 2. treba glasiti: Energy consumption, kWh / utrošak energije, kWh.

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Correction / errata corrige

In the paper „Energy Consumption of Beech Timber Drying in Oscillation Climates“ by Goran Milić et al. published in Drvna industrija No. 4 /2014, wrong graphs have been published by mistake. Graphs in Figure 2 and 3 have been mixed up, and y axis title in Figure 2 should be Energy consumption, kWh / utrošak energije, kWh. The Editorial Board would like to apologize to the authors for unintended errors occurred during the preparation of the paper for publishing.

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Web stranice

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