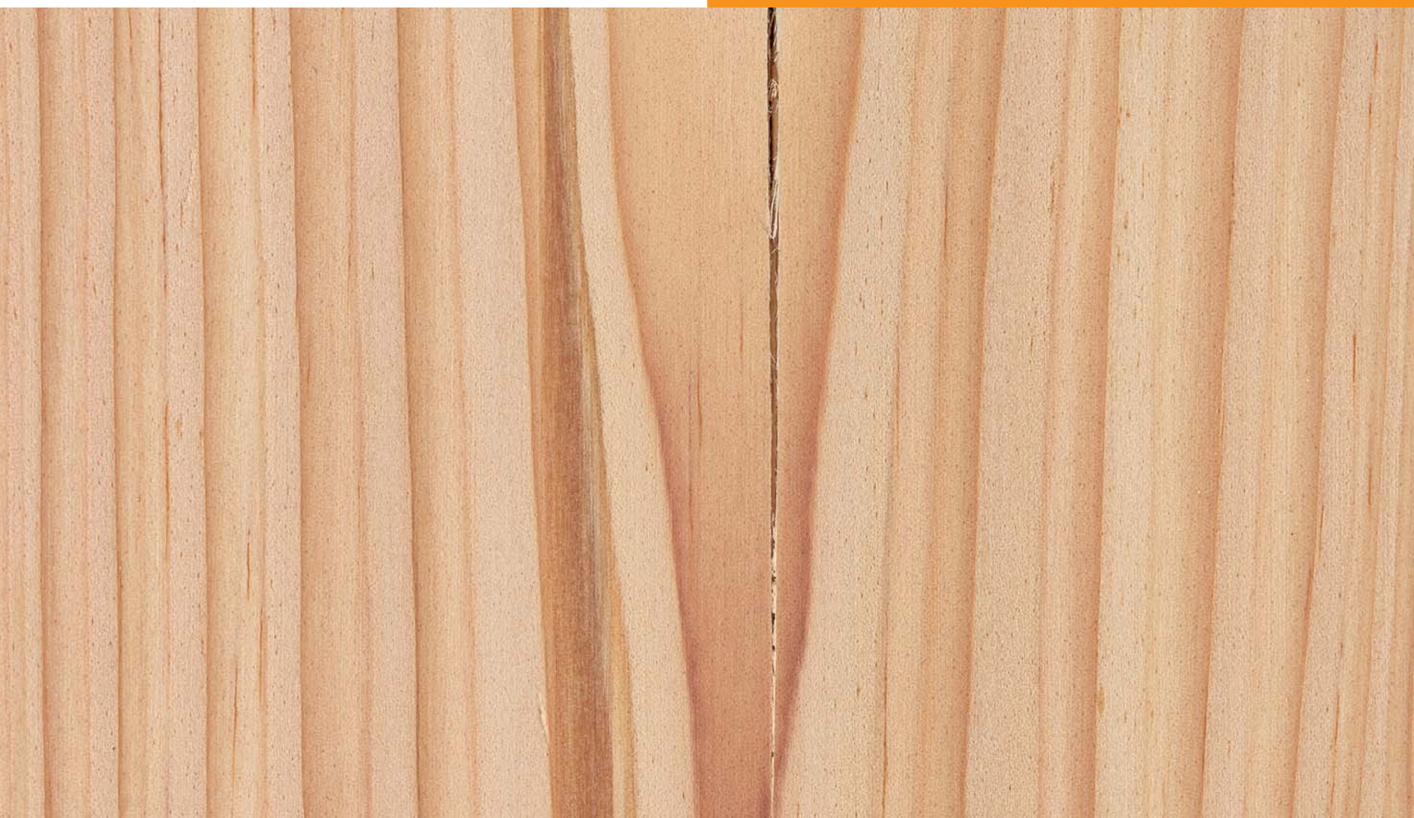
# DRVNA INDUSTRIJA

SCIENTIFIC JOURNAL
OF WOOD TECHNOLOGY



ZNANSTVENI ČASOPIS
ZA PITANJA DRVNE TEHNOLOGIJE

*Pseudotsuga menziesii* (Mirb.) Franco

UDK 674.031.677.7
ISO: Drv. Ind.
CODEN: DRINAT
JCR: DRVNA IND
ISSN 0012-6772

3/22
VOLUME 73

UDK 630*8+674 Coden: Drinat ISSN 0012-6772

# DRVNA INDUSTRIJA

## SCIENTIFIC JOURNAL OF WOOD TECHNOLOGY

Znanstveni časopis za pitanja drvne tehnologije


**PUBLISHER AND EDITORIAL OFFICE**
Izdavač i uredništvo
***Faculty of Forestry and Wood Technology***
***University of Zagreb, Croatia***
*Fakultet šumarstva i drvne tehnologije*
*Sveučilišta u Zagrebu*
*www.sumfak.unizg.hr*

**CO-PUBLISHER** / Suizdavač
*Hrvatska komora inženjera šumarstva i drvne tehnologije*

**FOUNDER** / Osnivač
*Institut za drvnoindustrijska istraživanja, Zagreb*




***The journal Drvna industrija is a public scientific journal for publishing research results on structure, properties and protection of wood and wood materials, application of wood and wood materials, mechanical woodworking, hydrothermal treatment and chemical processing of wood, all aspects of wood materials and wood products production and trade in wood and wood products.***
***The journal is published quarterly and financially supported by the Ministry of Science and Education of the Republic of Croatia***

*Časopis Drvna industrija javno je znanstveno glasilo za objavu rezultata istraživanja građe, svojstava i zaštite drva i drvnih materijala, primjene drva i drvnih materijala, mehaničke i hidrotermičke obrade te kemijske prerade drva, svih aspekata proizvodnje drvnih materijala i proizvoda te trgovine drvom i drvnim proizvodima.*
*Časopis izlazi četiri puta u godini uz financijsku potporu Ministarstva znanosti i obrazovanja Republike Hrvatske.*

# Contents
# Sadržaj

**CIRCULATION:** *400 pieces*

**INDEXED IN:** *Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ*

**MANUSCRIPTS ARE TO BE SUBMITTED** *by the link http://journal.sdewes.org/drvind*

**CONTACT WITH THE EDITORIAL** *e-mail: editordi@sumfak.hr*

**SUBSCRIPTION:** *Annual subscription for foreign subscribers is 55 EUR. Subscription in Croatia is 300 kn. For pupils, students and retired persons the subscription is 100 kn. Subscription shall be paid to the IBAN HR0923600001101340148 with the indication "Drvna industrija"*

**PRINTED BY:** *DENONA d.o.o., Getaldićeva 1, Zagreb, www.denona.hr*

**DESIGN:** *Bernardić Studio*

**THE JOURNAL IS AVAILABLE ONLINE:** *https://drvnaindustrija.com*

**COVER:** *Tangential section of Pseudotsuga menziesii (Mirb.) Franco, xylotheca of Institute for Wood Science, Faculty of Forestry and Wood Technology University of Zagreb*

**DRVNA INDUSTRIJA · VOL. 73, 3 · P. 257-360 · AUTUMN 2022. · ZAGREB EDITORIAL COMPLETED 1. 7. 2022.**

**NAKLADA:** *400 komada*

**ČASOPIS JE REFERIRAN U:** *Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ*

**ČLANKE TREBA SLATI** *putem poveznice http://journal.sdewes.org/drvind*

**KONTAKT S UREDNIŠTVOM:** *e-mail: editordi@sumfak.hr*

**PRETPLATA:** *Godišnja pretplata za pretplatnike iz inozemstva iznosi 55 EUR. Pretplata u Hrvatskoj iznosi 300 kn, a za đake, studente i umirovljenike 100 kn. Pretplata se plaća na IBAN HR0923600001101340148 s naznakom "Drvna industrija".*

**TISAK:** *DENONA d.o.o., Getaldićeva 1, Zagreb, www.denona.hr*

**DESIGN:** *Bernardić Studio*

**ČASOPIS JE DOSTUPAN NA INTERNETU:** *https://drvnaindustrija.com*

**NASLOVNICA:** *Tangentni presjek drva Pseudotsuga menziesii (Mirb.) Franco, ksiloteka Zavoda za znanost o drvu, Fakultet šumarstva i drvne tehnologije Sveučilišta u Zagrebu*

**DRVNA INDUSTRIJA · VOL. 73, 3 · STR. 257-360 · JESEN 2022. · ZAGREB REDAKCIJA DOVRŠENA 1. 7. 2022.**

## Dear readers,

We bring you the latest issue of *Drvna industrija*, a quarterly journal, which has been published for over 70 years. Throughout its history, the Journal has brought together the leading international researchers and practicing engineers to present and discuss recent advances in wood science and technology.

It is my honor to have the opportunity to act as a guest editor of the current issue. I am very pleased that a number of authors, with whom I have collaborated for many years, have promptly accepted my proposal to submit an article for this issue. My request was positively answered by authors from academic institutions, which I give in alphabetical order: Gdańsk University of Technology (Poland), Mendel University in Brno (Czech Republic), Poznań University of Life Sciences (Poland), Technical University in Zvolen (Slovakia), University of Zagreb (Croatia), and University of West Hungary in Sopron (Hungary).

The topics of interest include: primary and secondary machining processes, cutting process investigated in orthogonal tests and with the use of circular saw blades, kiln drying, detachable connection of wood products, honeycomb panels with facings made of thin particleboards, quality of large-size pine timber, an alternative raw material for the production of particleboard, thermal modification of wood, methods for enhancing the properties of wood surface, and research of wood fiber characteristics.

I hope that the contributions presented in this issue will be found interesting and that nobody will think: "*I have little patience with scientists who take a board of wood, look for its thinnest part, and drill a great number of holes where drilling is easy*." (Albert Einstein)

Eventually, I would like to thank the reviewers who made a great contribution to the quality of the published papers. Thanks to their efforts, the editors have been able to maintain a high standard of the journal *Drvna industrija*.

Professor Kazimierz A. Orlowski
Gdańsk University of Technology, Poland
(Guest Editor)

Josip Miklečić[1], Andrea Lončarić[2], Nikolina Veseličić[2], Vlatka Jirouš-Rajković[3]

# Influence of Wood Surface Preparation on Roughness, Wettability and Coating Adhesion of Unmodified and Thermally Modified Wood

# Utjecaj pripreme površine na hrapavost, kvašenje i adheziju premaza na nemodificiranome i toplinski modificiranom drvu

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 18. 2. 2022.
Accepted – prihvaćeno: 20. 4. 2022.
UDK: 684.4.057; 684.4.059
https://doi.org/10.5552/drvind.2022.0016



**ABSTRACT** • *In this research, the influence of face milling, sanding and UV irradiation of the hornbeam and ash wood sample on the wetting and adhesion strength of solvent-based and water-borne coating was studied. The adhesion of coatings to substrates is one of the most important parameters for finishing quality and service life of wood coatings, while wetting properties are usually used to assess the quality of surfacing process and could also provide important information on the adhesion ability of coatings. Surface roughness, contact angle of coatings and water as well as adhesion strength of coatings were tested on differently prepared (face milled, sanded and UV irradiated) samples of unmodified and thermally modified ash and hornbeam wood. Surface roughness was measured with stylus-type profilometer over the traverse of 12.5 mm and with a cut-off value of 2.5. Contact angle was measured using the sessile drop method 2 s, 10 s and 30 s after the application of the liquid drop on the sample surface, and adhesion strength was measured according to ASTM D4541. Results showed that sanding of hornbeam and ash wood resulted in the least rough surface compared to the face milled and UV irradiated surface. Contact angles of the water-borne coating were on average three times higher than the contact angles of the solvent-based coating. Sanding the surface of hornbeam and ash samples increased the adhesive strength in relation to the face milled surface, while UV irradiation of the sanded surface decreased the adhesive strength of most samples coated with solvent-based coating.*

**KEYWORDS:** *face milling; sanding; UV irradiation; wetting; adhesion*

[1] Author is assistant professor at University of Zagreb, Faculty of Forestry and Wood Technology, Institute of Furniture and Wood in Construction, Zagreb, Croatia. orcid.org/0000-0002-6425-0274
[2] Authors are former students at University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb, Croatia.
[3] Author is full professor at University of Zagreb, Faculty of Forestry and Wood Technology, Institute of Furniture and Wood in Construction, Zagreb, Croatia. orcid.org/0000-0002-5321-8826

**SAŽETAK •** *U radu je istraživan utjecaj čeonog blanjanja, brušenja i UV zračenja grabovine i jasenovine na kvašenje i adhezivnu čvrstoću premaza na bazi organskih otapala i vodenog premaza. Adhezija premaza jedan je od najvažnijih parametara za kvalitetu površinske obrade i trajnost premaza za drvo, dok svojstva kvašenja obično služe za ocjenu kvalitete nanošenja i adhezije premaza. Na različito pripremljenim uzorcima (obrađenim čeonim blanjanjem, brušenjem ili UV zračenjem) nemodificirane i toplinski modificirane grabovine i jasenovine ispitivana je hrapavost, kontaktni kut premaza i vode te adhezivna čvrstoća premaza. Hrapavost površine mjerena je profilometrom na duljini vrednovanja 12,5 mm, uz referentnu duljinu od 2,5 mm. Kontaktni kut mjeren je metodom s kapljicom, i to 2 s, 10 s i 30 s nakon nanošenja kapljice na površinu uzorka, a adhezivna čvrstoća određivana je prema normi ASTM D4541. Rezultati su pokazali da je brušenje grabovine i jasenovine rezultiralo najmanje hrapavom površinom u usporedbi s čeono blanjanom i UV zračenom površinom. Kontaktni kutovi vodenog premaza bili su u prosjeku tri puta veći od kontaktnih kutova premaza na bazi organskih otapala. Brušenjem površine uzoraka grabovine i jasenovine adhezivna je čvrstoća postala veća od čvrstoće čeono blanjanih površina, dok je UV zračenjem na brušenim površinama većine uzoraka smanjena adhezivna čvrstoća premaza na bazi organskih otapala.*

**KLJUČNE RIJEČI:** *čeono blanjanje; brušenje; UV zračenje; kvašenje; adhezija*

## 1 INTRODUCTION
## 1. UVOD

Wood surface preparation is of great importance for the good appearance and functional properties of wood coatings. It has been reported that surfacing of wood causes changes in both morphology and chemistry of the wood surface (Liptáková and Kudela 1994). Different wood species will show different physical and chemical changes under the same processing and environmental conditions, which could affect wood-coating interaction and coating performance (Liptáková *et al.*, 1995). It is known that thermally modified wood has altered characteristics compared to unmodified wood. Thermally modified wood is shown to have lower hygroscopicity, liquid water uptake, changed acidity, and anatomical structure (Jirouš-Rajković and Miklečić, 2019). It has also been shown that thermal modification has influence on the surface roughness and wettability of wood and wood-based materials (Candan *et al.*, 2010; Unsal *et al.*, 2011; Candan *et al.*, 2012; Candan *et al.*, 2021a). Thermal modification was shown to reduce the wettability and surface roughness of rowan (*Sorbus aucuparia* L.) wood (Candan *et al.*, 2021b). Changed surface properties of thermally modified wood can be determinative for the quality of many processes, such as coating, machining, etc. (Candan *et al.*, 2021b). Surface roughness and wetting properties are usually used to assess the quality of surfacing process and could also provide important information on the adhesion ability of coatings on wood surfaces (de Moura and Hernández 2005; Hernández and Cool 2008b, Vitosytė *et al.*, 2012). The adhesion of coatings to substrates is one of the most important parameters for finishing quality and service life of wood coatings. Sanding is one of the most common methods of wood surfacing before finishing with the aim of achieving a surface without visible defects that will allow uniform absorption of the coating. Sanding is an abrasive cutting process characterized by a negative rake angle of the cutting edge and by the random position of grit embedded in the holding tissue (Csanády and Magoss, 2020). The abrasive grain induces superficial cell crushing and fibrillation in wood (Stewart and Crist 1982; de Meijer *et al.*, 1998; de Moura and Hernández 2005; de Moura and Hernández 2006a). Sanded surfaces are also characterized by lumens clogged by fine dust, scratches and packets of microfibrils torn out from cell walls (de Meijer *et al.*, 1998; Murmanis *et al.*, 1983; Murmanis *et al.*, 1986; de Moura and Hernández, 2006b). Crushing and clogging of cells could hinder penetration (Richter *et al.*, 1995; de Meijer *et al.*, 1998; de Moura and Hernández 2005) of coating material in wood, while slight fibrillation and scratches accelerate spreading of liquid coatings on sanded surfaces. However, it has been established that sanding homogenizes the wood surface and reduces the influence of the anatomical structure on the coating behaviour (Richter *et al.*, 1995**;** de Moura and Hernández 2005; Hernández and Cool 2008a). Face milling is a surfacing method in which the milling cutter is positioned perpendicular to the workpiece. It is reported to generate lower cutting forces and consequently lower sub-surface damage of the wood surface structure compared to conventional planing (de Moura *et al.*, 2010; Kläusler *et al.*, 2014). The surface milling also generates cell wall fibrillation on the surface (Hernández and Cool, 2008b; de Moura *et al.*, 2010; Cool and Hernández, 2011a; Cool and Hernández, 2011b), which could affect wood-coating interactions. To avoid the formation of mechanical weak boundary layers, the wood surface cells should be the least deformed during surface preparation (de Moura *et al.*, 2010). This weak boundary level can prevent penetration and anchoring of adhesives and coatings to intact wood material (Stehr and Johansson, 2000). It has been reported that a freshly cut wood surface soon undergoes a natural transformation process known as surface inactivation (Nussbaum, 1995). This inactivation of wood surface contributes to the change of wood surface free energy due to migration of low molecular extractives to the wood surface, and oxidation (Nussbaum, 1999; Gindl *et al*., 2004). The wettability of wood surfaces has been shown to decrease with surface ageing (Nussbaum, 1999; Wålinder and Ström, 2001; Jirouš-Rajković *et al*., 2007), and freshly prepared surface has been identified as one of the most critical factors for good adhesion of coating (Nussbaum, 1995). Gindl *et al*. (2006) reported that short term ultraviolet light irradiation used as a pre-treatment to activate spruce and teak wood surfaces caused a significant increase in wettability and free surface energy of wood surfaces indicating good coating and adhesion properties of the activated material. UV irradiation provided cleaning of the wood surface and changes in surface morphology and in surface chemical composition. Patachia *et al*. (2012) also established increase of the surface energy of wood and lower initial contact angle for water after 24 h of exposure to UV light (254 nm), probably due to the formation of more hydrophilic compounds resulting from lignin and/or wood extractives degradation. It has also been shown that the plywood surfaces pre-treated with UV irradiation showed improved adhesion strength of coating compared to untreated or gamma irradiation pre-treated plywood samples (Khan *et al*., 2006). The aim of this paper is to evaluate the effects of two machining processes (face milling and sanding) and UV irradiation of unmodified and commercially thermally modified hornbeam (*Carpinus betulus* L.) wood and ash (*Fraxinus excelsior* L.) wood on wood surface roughness, wettability and adhesion of solvent-based and water-borne wood coatings.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Wood and coating materials
### 2.1. Uzorci drva i premaza

Radial-textured samples of unmodified and thermally modified ash (*Fraxinus excelsior* L.) and hornbeam (*Carpinus betulus* L.) wood without any visible defects were used in this study. Wood samples were commercially thermally modified using ThermoWood® process with a peak temperature of 190 °C for ash wood and 212 °C for hornbeam wood. Before preparing the surface, wood samples were machined and planed to the dimensions of 300 mm × 100 mm × 18 mm (L×R×T) and conditioned at (23±2) °C and (50±5) % relative humidity (RH) to the constant mass. Conditioned samples were divided into three groups. The surface of the first group of samples was hand-sanded with paper grit size P80, P120 and P150 along the grain. After sanding, the surface of samples was cleaned with compressed air. The surface of the second group of samples was face milled on a CNC machine with an 80 mm diameter three-blade cutter, 20,000 rpm rotation speed and 5 m/min feed speed. The surface of the third group of samples was hand-sanded like in the first group and additionally exposed to UV light in a QUV weathering tester equipped with UVA-340 fluorescent lamps for 2 hours at a distance of 50 mm with (60±3) °C black panel temperature (BPT) and 0.77 W/m$^2$nm irradiation.

The prepared wood samples were finished with two commercial clear coatings. Two-component solvent-based polyurethane coating Chromos CHROMODEN (density 1.02 g/cm$^2$, solid content 50 %) and one-component water-borne coating based on polyurethane and acrylate dispersion JORDAN 1K ECO-FINISH (density 1.02 g/cm$^2$, solid content 34 %). In this experiment, coatings were applied in two coats on previously prepared wood samples with a film applicator with adjustable gap heights in a wet film thickness of 100 mm. The first coat of each coating was sanded with paper grit size 240 after 24 h drying time at (23±2) °C and (50±5) % RH and then the second coat was applied. The finished wood samples were conditioned for seven days at (23±2) °C and (50±5) % RH before testing the coated wood surface.

### 2.2 Surface roughness
### 2.2. Hrapavost površine

For each wood species and type of surface preparation, surface roughness was measured at five locations with Surtronic S-126 stylus-type profilometer manufactured by Taylor-Hobson equipped with a 5 mm stylus tip radius and 90° tip angle at a speed of 0.5 mm/s. The profiles were spaced by a minimum of 30 mm. Roughness measurement was performed in the direction perpendicular to the wood grain over the traverse of 12.5 mm, and roughness profiles were filtered with a cut-off value of 2.5 using a Gaussian filter. For the evaluation of surface roughness, parameters *Ra* and *Rz* were used. *Ra* represents arithmetic mean deviation of the assessed profile and *Rz* is the average maximum peak to valley of five consecutive sampling lengths within the measuring length.

### 2.3 Contact angle
### 2.3. Kontaktni kut

The contact angle of distilled water and tested coatings was measured using the sessile drop method and video measuring system with Dino-Lite Microscope. Immediately after preparation of the surface, in total five liquid drops of 0.01 ml volume were applied on each type of wood sample with dimensions of 100 mm × 100 mm × 18 mm (L×R×T) for each liquid. The contact angles were measured 2 s, 10 s and 30 s after the application of the liquid drop, and the average contact angle was calculated from five measurements for each type of sample and measuring time.

### 2.4 Adhesion strength
### 2.4. Adhezivna čvrstoća

For adhesion strength, pull-off test was performed according to ASTM D4541 at eight locations per wood species and prepared wood surface. On the coated surface, 10 mm diameter aluminum dollies were glued with two-component UHU plus 300 adhesive and allowed to cure for 24 hours. The dollies were pulled-off perpendicular to the substrate using a PATTI instrument where adhesion strength was measured, and adhesion and cohesion fracture were estimated.

### 2.5 Statistical analysis
### 2.5. Statistička analiza

Statistical analysis was performed with the Kruskal-Wallis test using TIBCO® Data Science/Statistica™ 14 software.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The results of surface roughness presented in Table 1 show that surface roughness after machining of thermally modified hornbeam wood is lower than that of unmodified wood. Sandak *et al*. (2017) also found lower roughness of thermally modified specimens than unmodified specimens of deodar cedar wood, black pine wood and black poplar wood after machining. For ash wood, only face milled thermally modified samples exhibited lower roughness values compared to unmodified samples. Zdravković *et al*. (2020) also reported that thermal modification of ash wood at 160 °C improved surface quality after CNC face milling. It has been shown that exposing the surface of hornbeam and ash wood to UV irradiation increased the surface roughness compared to the sanded surface. However, this increase is statistically significant only for thermally modified hornbeam samples for both roughness parameters. Jankowska *et al*. (2020) also established increased surface roughness values after 24 hours of UV irradiation for garapa (*Apuleia leiocarpa* (Vogel) J.F. Macbr.), tatajuba (*Bagassa guianensis* Aubl.), courbaril (*Hymenea courbaril* L.) and massaranduba (*Manilkara bidendata* (A. DC.) A. Chev.) wood species. Also, it can be seen that parameters Ra and Rz are higher for the UV irradiated surface compared to the face milled surface for all samples except for unmodified hornbeam samples, and statistically significant only for thermally modified ash samples for both roughness parameters. For hornbeam wood, as a representative of the diffusely porous wood species, sanding with paper grit size P80, P120 and P150 resulted in the least rough surface compared to the face milled and UV irradiated surface. Furthermore, thermal modification of the hornbeam wood reduced the difference in roughness between the face milled and sanded surface, which was not the case on ash wood. Also, for ash wood as a representative of the ring-porous wood species, sanding resulted in a finer surface for the parameter *Rz* and in most cases for the parameter *Ra*. Differences in roughness between hornbeam and ash wood are due to differences in wood surface structure.

The results of contact angles of water-borne coating, of solvent-based coating and of distilled water measured after 2, 10 and 30 s are presented in Figures 1. It can be seen that the lowest values of contact angles were measured on the solvent-based coating (Fig-

**Table 1** Results of roughness parameters *Ra* and *Rz* (values in parentheses are standard deviations)
**Tablica 1.** Rezultati parametara hrapavosti *Ra* i *Rz* (u zagradama su standardne devijacije)

| **Type of wood** *Vrsta drva* | **Modification** *Modifikacija* | **Type of surface** *Vrsta površine* | ***Ra*, mm*** | ***Rz*, mm*** |
|---|---|---|---|---|
| Hornbeam *grabovina* | Unmodified *nemodificirano* | Face milled / *čeono glodana* | 4.28 (0.858)a | 30.8 (3.915)a |
| | | Sanded / *brušena* | 2.68 (0.396)a | 23.3 (3.650)b |
| | | UV irradiated / *UV zračena* | 3.16 (0.789)a | 26.3 (4.804)ab |
| | Thermally modified *toplinski modificirano* | Face milled / *čeono glodana* | 2.48 (0.471)ab | 20.6 (3.190)ab |
| | | Sanded / *brušena* | 2.48 (0.277)a | 18.4 (2.770)a |
| | | UV irradiated / *UV zračena* | 3.62 (0.614)b | 29.0 (3.335)b |
| Ash *jasenovina* | Unmodified *nemodificirano* | Face milled / *čeono glodana* | 3.60 (0.938)a | 27.9 (5.493)a |
| | | Sanded / *brušena* | 3.28 (1.372)a | 30.4 (11.437)a |
| | | UV irradiated / *UV zračena* | 4.12 (0.876)a | 33.7 (9.916)a |
| | Thermally modified *toplinski modificirano* | Face milled / *čeono glodana* | 3.22 (1.152)a | 23.3 (11.128)a |
| | | Sanded / *brušena* | 5.40 (1.910)ab | 47.2 (13.604)ab |
| | | UV irradiated / *UV zračena* | 6.24 (1.616)b | 54.8 (8.258)b |

*Means within the unmodified and thermally modified wood samples followed by the same letter are not significantly different at 5 % level of significance using the Kruskal-Wallis test.
**Srednje vrijednosti za pojedine nemodificirane i modificirane uzorke drva s istim slovima ne razlikuju se značajno pri stupnju značajnosti od 5 % (utvrđeno Kruskal-Wallisovim testom).*

ure 1a), and a significant difference in contact angles of solvent-based coating was found between the face milled and sanded surface only for contact angles measured after 2 s. Furthermore, contact angles of the solvent-based coating were reduced by 40 % between 2 and 30 s on all samples. Surface preparation did not affect the contact angles of the solvent-based coating measured after 10 and 30 seconds. Figure 1b shows the difference in contact angles of the water-borne coating with respect to surface preparation and wood species. A statistically significant difference was found between sanded and UV irradiated surface. Sanding of the surface of hornbeam samples increased contact angles of the water-borne coating compared to the face milling

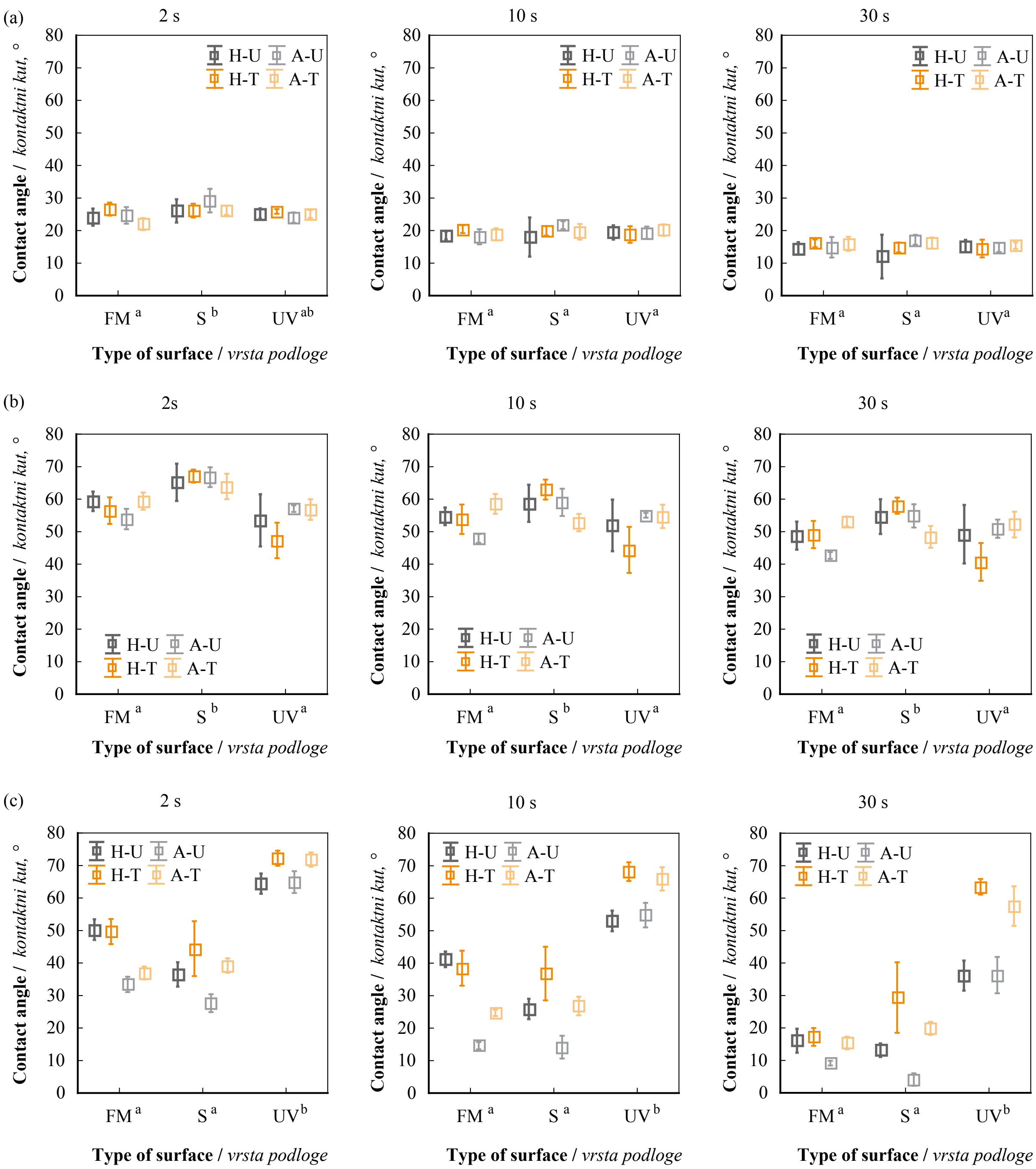



**Figure 1** Mean value and standard deviation of contact angles of solvent-based coating (a), water-borne coating (b) and water (c) 2 s, 10 s and 30 s after liquid drop application on wood samples; H-U - unmodified hornbeam, H-T - thermally modified hornbeam, A-U - unmodified ash, A-T - thermally modified ash, FM - face milled, S - sanded, UV - UV irradiated (Means within the measuring interval followed by the same letter are not significantly different at 5% level of significance using the Kruskal-Wallis test)

**Slika 1.** Srednja vrijednost i standardna devijacija kontaktnih kutova premaza na bazi organskih otapala (a), vodenog premaza (b) i vode (c) 2 s, 10 s i 30 s nakon nanošenja kapljice tekućine na uzorke drva; H-U – nemodificirana grabovina, H-T – toplinski modificirana grabovina, A-U – nemodificirana jasenovina, A-T – toplinski modificirana jasenovina, FM – čeono glodana površina, S – brušena površina, UV – UV ozračena površina (srednje vrijednosti unutar mjernog intervala s istim slovom ne razlikuju se značajno pri stupnju značajnosti od 5%; utvrđeno Kruskal-Wallisovim testom) of the surface, while UV irradiation reduced contact angles of the water-borne coating compared to the sanded surface. This result is obtained after 2, 10, and 30 s, but these differences diminish with prolonged standing of the water-borne coating drop on the sample surface. For the ash wood samples, this relationship between differently prepared samples is visible only for a measurement interval of 2 s. In addition, contact angles of the water-borne coating are on average three times higher than contact angles of the solvent-based coating. The higher contact angle of water-borne coating compared to the solvent-based coting was also obtained by Gibbons *et al*. (2020) in researching 23 commercial coatings on southern yellow pine wood. Accordingly, it can be assumed that solvent-based coating will form more effective contact with hornbeam and ash wood surface than water-borne coating due to better wettability. Unlike the water-borne coating, UV irradiation of the sanded wood surface significantly increased contact angles of water (Figure 1c) and they are higher than those of the water-borne coating (Figure 1b). Furthermore, contact angles of the water on the face milled and sanded surface are lower than contact angles of the water-borne coating (Figure 1c). These results support the statement from the study by Gindl *et al*. (2004) that the wettability of wood with water does not sufficiently explain the interaction between wood and coating. In general, contact angles of water are higher on face milled than on sanded surfaces. These results correspond to the results of de Moura and Hernandez (2005) on sugar maple wood and Hernandez and Cool (2008a) on paper birch wood. Based on the results of contact angles with water, it can be concluded that ash wood surfaces machined with face milling and sanding are more wettable than hornbeam wood surfaces. Moreover, contact angles of the water for ash wood samples are affected by the modification for all three measurement intervals and this is in line with the findings of other authors that wettability of wood by water is lower for thermally modified wood than for unmodified wood (Pétrissans *et al*., 2003; Petrič *et al*., 2007; Kocaefe *et al*., 2008). Pétrissans *et al*. (2003) state that the higher level of cellulose crystallinity in thermally modified wood compared to unmodified wood is the reason for lower wettability of thermally modified wood with water compared to unmodified wood. Moreover, Hakkou *at al*. (2005) attributed the wettability increase of thermally modified wood to the reorganization of the lignocellulosic polymeric components of wood due to lignin plasticization.

Figure 2 presents the results of the adhesive strength of solvent-based and water-borne coatings. It can be seen that on most samples the adhesive strength is lower on thermally modified samples compared to unmodified samples. Altgen and Militz (2017) also reported reduction in adhesion strength of some water-borne coatings on thermally modified wood, which was related to the mechanical interaction of the specific substrate/coating system. De Moura *et al*. (2013) also established reduced pull-off adhesion strength of polyurethane coating applied to thermally modified *Eucalyptus grandis* and *Pinus caribaea* wood samples compared to unmodified samples. They assumed that the reduction in adhesive strength is related to the decrease in the mechanical properties of wood during thermal modification. The same results were also obtained by

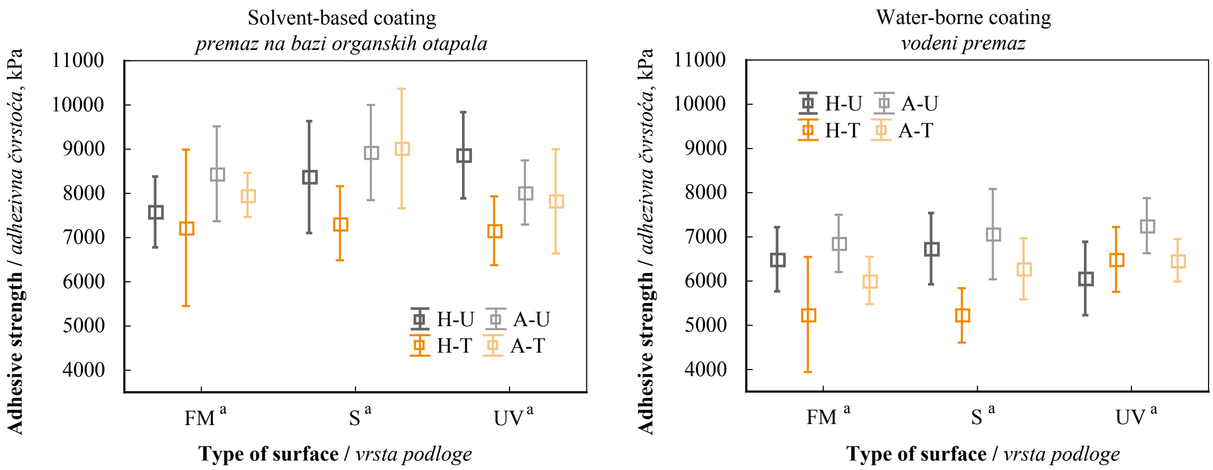



**Figure 2** Mean value and standard deviation of adhesion strength of water-borne and solvent-based coating: ; H-U - unmodified hornbeam, H-T - thermally modified hornbeam, A-U - unmodified ash, A-T - thermally modified ash, FM - face milled, S - sanded, UV - UV irradiated (Means within the measuring interval followed by the same letter are not significantly different at 5 % level of significance using the Kruskal-Wallis test)

**Slika 2.** Srednja vrijednost i standardna devijacija adhezivne čvrstoće vodenog premaza i premaza na bazi organskih otapala; H-U – nemodificirana grabovina, H-T – toplinski modificirana grabovina, A-U – nemodificirana jasenovina, A-T – toplinski modificirana jasenovina, FM – čeono glodan uzorak, S – brušeni uzorak, UV – UV ozračeni uzorak (srednje vrijednosti unutar mjernog intervala s istim slovom ne razlikuju se značajno pri stupnju značajnosti od 5%; utvrđeno Kruskal-Wallisovim testom)

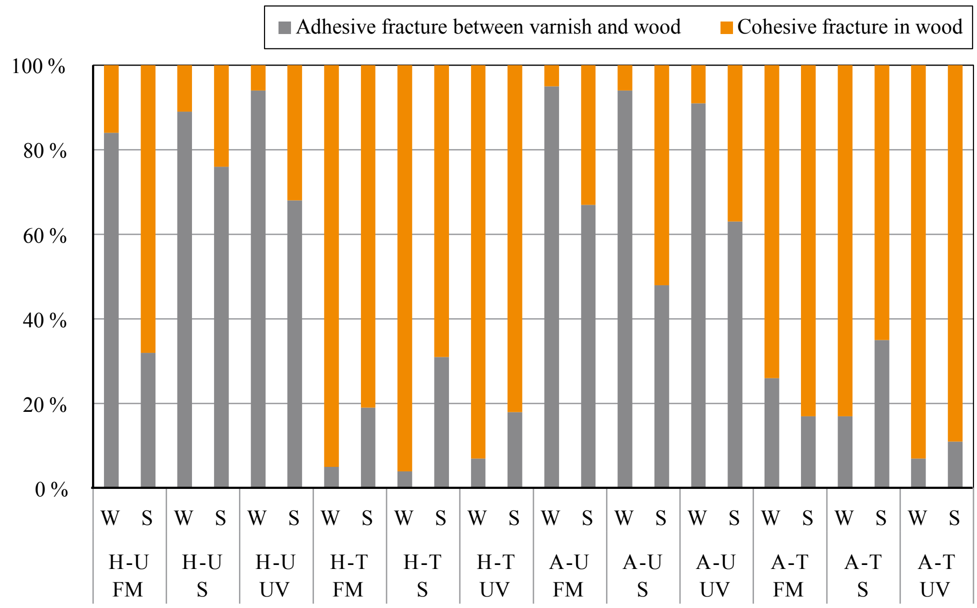



**Figure 3** Mean proportion of adhesive fracture between coating and wood and cohesive fracture in wood (W - water-borne coating, S - solvent-based coating, H-U - unmodified hornbeam, H-T - thermally modified hornbeam, A-U - unmodified ash, A-T - thermally modified ash, FM - face milled, S - sanded, UV - UV irradiated)
**Slika 3.** Srednji udio kohezijskog loma između premaza i drva te kohezijskog loma po drvu (W – vodeni premaz, S – premaz na bazi organskih otapala, H-U – nemodificirana grabovina, H-T – toplinski modificirana grabovina, A-U – nemodificirana jasenovina, A-T – toplinski modificirana jasenovina, FM – čeono glodano drvo, S – brušeno drvo, UV – UV zračeno drvo)

Miklečić *et al*. (2017) for thermally modified beech (*Fagus sylvatica* L.) wood samples. Only sanded ash wood samples coated with solvent-based coating and UV irradiated hornbeam samples coated with water-borne coating exhibited higher adhesive strength on thermally modified samples. In addition, higher values of adhesive strength were measured on the solvent-based coating compared to the water-borne coating, which is partly related to the lower contact angles of the solvent-based coating compared to the water-borne coating (Figures 1a and 1b). Jaić *et al*. (2014) reported higher values of adhesion for solvent-based than for water-borne coatings on sanded beech wood surface. Sönmez *et al*. (2011) also reported higher values of adhesion for two-component polyurethane coating than for water-borne coating on Scots pine (*Pinus sylvestris* L.), Eastern beech (*Fagus oriantails* L.) and oak (*Quercus petraea* L.) wood surfaces. Adhesion between a water-borne coating and the substrate is primarily based on a mechanical bonding, while the adhesion of a two-component polyurethane coating could be based on both chemical and mechanical bonding mechanisms (Jaić *et al*., 2014). Furthermore, lower adhesive strength of solvent-based coating was measured on all hornbeam samples than on ash samples except for UV irradiated hornbeam samples. Higher adhesive strength of coating applied to ash wood is probably caused by the difference in texture and structure between ash wood and hornbeam wood. Sanding the surface of hornbeam and ash samples increased the adhesive strength in relation to the face milled surface, while UV irradiation of the sanded surface decreased the adhesive strength of most samples coated with solvent-based coating. However, statistical analysis did not determine a significant impact of surface preparation on the adhesive strength of solvent-based and water-borne coating. De Moura and Hernández (2005) reported that adhesion of the polyurethane coating was better on sanded than on planed sugar maple (*Acer saccharum* Marsh) wood surfaces.

From the results of the fracture mode under the pulled-off dolly, it can be seen that for unmodified samples the adhesive fracture between wood and coating predominates, while for thermally modified samples cohesive fracture in wood predominates (Figure 3). Furthermore, when testing the adhesion of coating on unmodified samples, a higher proportion of adhesive fracture was recorded for water-borne coating than for solvent-based coating, while on thermally modified samples a higher proportion of adhesive fracture was recorded for solvent-based coating than for water-borne coating. It can be concluded from the obtained results that the surface preparation does not affect the type and proportion of the fracture mode after adhesion test.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

In this research, it was found out that UV irradiation increased the surface roughness of hornbeam and ash wood sanded surface. Moreover, sanding of hornbeam and ash wood resulted in the least rough surface compared to the face milled and UV irradiated surface, while machining of thermally modified hornbeam wood decreased surface roughness compared to unmodified wood. It can be concluded that sanding is more favourable for surface preparation than face milling before applying the coating (regardless of the type of coating material). In addition, the contact angles of the water-borne coating were on average three times higher than contact angles of the solvent-based coating. Furthermore, the ash wood surfaces machined with face milling and sanding were more wettable than hornbeam wood surfaces. UV radiation of the sanded wood surface significantly increased the contact angles of water on hornbeam and ash wood, and they were higher than those of the water-borne coating. The influence of pre-treatment with UV radiation on the wetting of the wood surface with coatings needs to be further investigated. Moreover, wetting of the wood surface with water should not be taken as an indicator of the quality of wetting the wood surface with water-borne coatings. The higher adhesive strength was measured on the solvent-based coating compared to the water-borne coating. Moreover, adhesive strength was lower on thermally modified samples compared to unmodified samples. It was also found out that the investigated surface preparation does not significantly affect the adhesion strength and the type and proportion of the fracture mode after adhesion test.

## 5 REFERENCES
## 5. LITERATURA


1. Altgen, M.; Militz, H., 2017: Thermally modified Scots pine and Norway spruce wood as substrate for coating systems. Journal of Coatings Technology and Research, 14: 531-541. https://doi.org/10.1007/s11998-016-9871-8
2. Candan, Z.; Hiziroglu, S.; McDonald, A. G., 2010: Surface quality of thermally compressed Douglas fir veneer. Materials & Design, 31 (7): 3574-3577. ttps://doi.org/10.1016/j.matdes.2010.02.003
3. Candan, Z.; Buyuksari, U.; Korkut, S.; Unsal, O.; Cakicier, N., 2012: Wettability and surface roughness of thermally modified plywood panels. Industrial Crops and Products 36 (1): 434-436. https://doi.org/10.1016/j.indcrop.2011.10.010
4. Candan, Z.; Gonultas, O.; Gorgun, H. V.; Unsal, O., 2021a: Examining parameters of surface quality performance of paulownia wood materials modified by thermal compression technique. Drvna industrija, 72 (3): 231-236. https://doi.org/10.5552/drvind.2021.1973
5. Candan, Z.; Gorgun, H. V.; Korkut, S.; Unsal, O., 2021b: Surface roughness and wettability performance of thermally modified rowan wood as a fast-growing species. Drewno, 63 (208): 1-10.
6. Cool, J.; Hernández, R. E., 2011a: Evaluation of four surfacing methods on black spruce wood in relation to poly(vinyl acetate) gluing performance. Wood and Fiber Science, 43 (2): 194-205.
7. Cool, J.; Hernández, R. E., 2011b: Performance of three alternative surfacing processes on black spruce wood and their effects on water-based coating adhesion. Wood and Fiber Science, 43 (4): 365-378.
8. Csanády, E.; Magoss, E., 2020: Mechanics of wood machining (eBook). Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-51481-5
9. de Meijer, M.; Thurich, K.; Militz, H., 1998: Comparative study on penetration characteristics of modern wood coatings. Wood Science and Technology, 32: 347-365
10. de Moura, L. F.; Cool, J.; Hernández, R. E., 2010: Anatomical evaluation of wood surfaces produced by oblique cutting and face milling. IAWA Journal, 31 (1): 77-88.
11. de Moura, L. F.; Hernández, R. E., 2005: Evaluation of varnish coating performance for two surfacing methods on sugar maple wood. Wood and Fiber Science, 37 (2): 355-366.
12. de Moura, L. F.; Hernández, R. E., 2006a: Effects of abrasive mineral, grit size and feed speed on the quality of sanded surfaces of sugar maple wood. Wood Science and Technology, 40 (6): 517-530. https://doi.org/10.1007/s00226-006-0070-0
13. de Moura, L. F.; Hernández, R. E., 2006b. Evaluation of varnish coating performance for three surfacing methods on sugar maple wood. Forest Products Journal, 56 (11-12): 130-136.
14. de Moura, L. F.; Brito, J. O.; Nolasco, A. M.; Uliana, L. R., 2013: Evaluation of coating performance and color stability on thermally rectified *Eucalyptus grandis* and *Pinus caribaea* var. hondurensis woods. Wood Research, 58 (2): 231-242.
15. Gibbons, M. J.; Nikafshar, S.; Saravi, T.; Ohno, K.; Chandra, S.; Nejad, M., 2020: Analysis of a wide range of commercial exterior wood coatings. Coatings, 10: 1013. https://doi.org/10.3390/coatings10111013
16. Gindl, M.; Reiterer, A.; Sinn, G.; Stanzl-Tschegg, S. E., 2004: Effects of surface ageing on wettability, surface chemistry and adhesion of wood. Holz als Roh- und Werkstoff, 2004, 62 (4): 273-280. https://doi.org/10.1007/s00107-004-0471-4
17. Gindl, M.; Sinn, H.; Stanzl-Tschegg, S. E., 2006: The effects of ultraviolet light exposure on the wetting properties of wood. Journal of Adhesion Science and Technology, 20 (8): 817-828. https://doi.org/10.1163/156856106777638653
18. Hakkou, M.; Pétrissans, M.; Zoulalian, A.; Gérardin, P., 2005: Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. Polymer Degradation and Stability, 89 (1): 1-5. https://doi.org/10.1016/j.polymdegradstab.2004.10.017
19. Hernández, R. E.; Cool, J., 2008a: Evaluation of three surfacing methods on paper birch wood in relation to water and solvent-borne coating performance. Wood and Fiber Science, 40 (3): 459-469.
20. Hernández, R. E.; Cool, J., 2008b: Effects of cutting parameters on surface quality of paper birch wood machined across the grain with two planing techniques. Holz als Roh- und Werkstoff, 66 (2): 147-154. https://doi.org/10.1007/s00107-007-0222-4
21. Jankowska, A.; Rybak, K.; Nowacka, M.; Boruszewski, P., 2020: Insight of weathering processes based on monitoring surface characteristic of tropical wood species. Coatings, 10 (9): 877. https://doi.org/10.3390/coatings10090877
22. Jaić, M.; Palija, T.; Đorđević, M., 2014: The impact of surface preparation of wood on the adhesion of certain types of coatings. Zaštita materijala 55 (2): 163-169.
23. Jirouš-Rajković, V.; Bogner, A.; Mihulja, G.; Vrsaljko, D., 2007: Coating adhesion and wettability of aged and

preweathered fir wood and pine wood surfaces. Wood Research, 52 (2): 39-48.
24. Jirouš-Rajković, V.; Miklečić, J., 2019: Heat-treated wood as a substrate for coatings, weathering of heat-treated wood, and coating performance on heat-treated wood. Advances in Materials Science and Engineering, 2019: 8621486. https://doi.org/10.1155/2019/8621486
25. Khan, M. A.; Khan, R. A.; Aliya, B. S.; Nasreen, Z., 2006: Effect of the pretreatment with UV and gamma radiations on the modification of plywood surface by photocuring with epoxy acrylate. Journal of Polymers and the Environment, 14 (1): 111-118. https://doi.org/10.1007/s10924-005-8713-z
26. Kläusler, O.; Rehm, K.; Elstermann, F.; Niemz, P., 2014: Influence of wood machining on tensile shear strength and wood failure percentage of one-component polyurethane bonded wooden joints after wetting. International Wood Products Journal, 5 (1): 18-26. https://doi.org/10.1179/2042645313Y.0000000039
27. Kocaefe, D.; Poncsak, S.; Doré, G.; Younsi, R., 2008: Effect of heat treatment on the wettability of white ash and soft maple by water. Holz als Roh- und Werkstoff, 66: 355-361. https://doi.org/10.1007/s00107-008-0233-9
28. Liptáková, E.; Kúdela, J., 1994: Analysis of the wood-wetting process. Holzforchung, 48 (2): 139-144. https://doi.org/10.1515/hfsg.1994.48.2.139
29. Liptáková, E.; Kúdela, J.; Bastl, Z.; Spirovová, I., 1995: Influence of mechanical surface treatment of wood on the wetting process. Holzforschung, 49 (4): 369-375. https://doi.org/10.1515/hfsg.1995.49.4.369
30. Miklečić, J.; Turkulin, H.; Jirouš-Rajković, V., 2017: Weathering performance of surface of thermally modified wood finished with nanoparticles-modified waterborne polyacrylate coatings. Applied Surface Science, 408: 103-109. https://doi.org/10.1016/j.apsusc.2017.03.011
31. Murmanis, L.; River, B. H.; Stewart, H. A., 1983: Microscopy of abrasive-planed and knife-planed surfaces in wood-adhesive bonds. Wood and Fiber Science, 15 (2): 102-115.
32. Murmanis, L.; River, B. H.; Stewart, H. A., 1986: Surface and subsurface characteristics related to abrasive-planing conditions. Wood and Fiber Science, 18 (1): 107-117.
33. Nussbaum, R. M., 1995: The critical time limit to avoid natural inactivation of spruce surfaces (*Picea abies*) intended for painting or gluing. Holz als Roh- und Werkstoff, 53 (6): 384. https://doi.org/10.1007/s001070050112
34. Nussbaum, R. M., 1999: Natural surface inactivation of Scots pine and Norway spruce evaluated by contact angle measurements. Holz als Roh- und Werkstoff, 54 (1):419-424. https://doi.org/10.1007/s001070050067
35. Patachia, S.; Croitorua, C.; Friedrich, C., 2012: Effect of UV exposure on the surface chemistry of wood veneers treated with ionic liquids. Applied Surface Science, 258 (18): 6723-6729. https://doi.org/10.1016/j.apsusc.2011.12.050
36. Petrič, M.; Knehtl, B.; Krause, A.; Militz, H.; Pavlič, M.; Pétrissans, M.; Rapp, A.; Tomažić, M.; Welzbacher, C.; Gérardin, P., 2007: Wettability of waterborne coatings on chemically and thermally modified pine wood. Journal of Coatings Technology and Research, 4: 2003-2006. https://doi.org/10.1007/s11998-007-9023-2
37. Pétrissans, M.; Gérardin, P.; El Bakali, I.; Serraj, M., 2003: Wettability of heat-treated wood. Holzforschung, 57 (3): 301-307. https://doi.org/10.1515/HF.2003.045
38. Richter, K.; Feist, W. C.; Knaebe, M. T., 1995: The effect of surface roughness on the performance of finishes. Part 1. Roughness characterization and stain performance. Forest Products Journal, 45 (7-8): 91-97.
39. Sandak, J.; Goli, G.; Cetera, P.; Sandak, A.; Cavalli, A.; Todaro, L., 2017: Machinability of minor wooden species before and after modification with thermo-vacuum technology. Materials, 10 (2): 121. https://doi.org/10.3390/ma10020121
40. Sönmez, A.; Budakçı, M.; Demirci, Z.; Akkuş, M., 2011: Effects of thermal aging on the film hardness of some wood varnishes. BioResources, 6 (4): 4594-4605.
41. Stehr, M.; Johansson, I., 2000: Weak boundary layers on wood surfaces. Journal of Adhesion Science and Technology, 14 (10): 1211-1224. https://doi.org/10.1163/156856100742168
42. Stewart, H. A., Crist, J. B., 1982: SEM examination of subsurface damage of wood after abrasive and knife planing. Wood Science, 14 (3): 106-109.
43. Unsal, O.; Candan, Z.; Korkut, S., 2011: Wettability and roughness characteristics of modified wood boards using a hot-press. Industrial Crops and Products, 34 (3): 1455-1457. https://doi.org/10.1016/j.indcrop.2011.04.024
44. Vitosytė, J.; Ukvalbergienė, K.; Keturakis, G., 2012: The effects of surface roughness on adhesion strength of coated ash (*Fraxinus excelsior* L.) and birch (*Betula* L.) wood. Materials Science (Medžiagotyra), 18 (4): 2012. https://doi.org/10.5755/j01.ms.18.4.3094
45. Wålinder, M. E. P.; Ström, G., 2001: Measurement of wood wettability by Wilhelmy method. Part 2. Determination of apparent contact angles. Holzforschung, 55 (1): 33-41. https://doi.org/10.1515/HF.2001.006
46. Zdravković, V.; Palija, T.; Karadolamovic, Z., 2020: Influence of thermal modification of ash wood (*Fraxinus excelsior* L.) and machining parameters in cnc face milling on surface roughness using response surface methodology (RSM). Sigma Journal of Engineering and Natural Sciences, 11 (2): 231-241.
47. ***ASTM D4541-02. Standard test method for pull-off strength of coatings usin portable adhesion tester.

**Corresponding address:**

**Assist. Prof. JOSIP MIKLEČIĆ, PhD**
University of Zagreb, Faculty of Forestry and Wood Technology, Institute of Furniture and Wood in Construction, Svetosimunska 23 Zagreb, CROATIA, e-mail: jmiklecic@sumfak.unizg.hr

# Lin Testing laboratory for furniture and playground equipment

**accredited testing laboratory for furniture and playground equipment according to HRN EN ISO/IEC 17025**

**more than 40 methods in the scope of the testing of furniture, coatings and parts for furniture, children's playgrounds and playground equipment**

outside the scope of accreditation:

research of constructions and ergonomics of furniture

testing of finishing materials and proceses

testing of flammability and ecology of upholstered furniture

furniture expertise

***Laboratory*** **is a member of the Laboratoria Croatica CROLAB – an association whose goal is the development of Croatian laboratories as an infrastructure for the development of production and the economy within a demanding open market, using common potentials and synergy effects of the association, while the**

***Faculty of Forestry and Wood technology*** **is a full member of the INNOVAWOOD – association whose aim it to contribute to business successes in forestry, wood industry and furniture industry, stressing the increase of competitiveness of the European industry.**

**Research of beds and sleeping, research of children's beds, optimal design of tables, chairs and corpus furniture, healthy and comfort sitting at school, office and in home are some of numerous researches performed by the** ***Institute for furniture and wood in construction*****, which enriched the treasury of knowledge on furniture quality.**

17025-HAA 1338 TEST

**Good cooperation with furniture manufacturers, importers and distributors makes us recognizable**

**Knowledge is our capital**



**University of Zagreb • Faculty of forestry and wood technology**
Testing laboratory for furniture and playground equipment
Institute for furniture and wood in construction
Svetošimunska cesta 23
HR-10000 Zagreb, Croatia

Ewa Skorupińska[1,3], Krzysztof Wiaderek[2], Maciej Sydor[3]

# Withdrawal Resistance of T-Nuts in Various Furniture Materials

# Otpor izvlačenju unit-matica iz različitih materijala za namještaj

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 20. 2. 2022.
Accepted – prihvaćeno: 18. 3. 2022.
UDK: 630*83; 684.4.058
https://doi.org/10.5552/drvind.2022.0017



**ABSTRACT** • *T-nuts are factory installed in the holes of the ready-to-assemble furniture components. There is a risk that the t-nut spontaneously falls out during transport or storage and get lost; the t-nut can also be pushed into inaccessible spaces during assembly. These complications can make furniture assembly impossible. For this reason, sufficient force to hold the t-nut in the hole is essential. The article presents the test results of the forces holding the t-nuts in five furniture materials (softwood, Oriented Strand Board, plywood, and particleboard in two variants). The M6 t-nuts with four prongs were installed in predrilled 8 mm holes. The resistance to withdrawal of the t-nuts was measured with a universal testing machine. The tested materials could be divided into three groups in terms of the risk of the t-nut falling out: softwood and plywood – low risk, F = 1113.2-1158.0 N; OSB and particleboard – moderate risk, F = 592.3-645.5 N, particleboard with a pad – high risk, F = 645.5 N. The results show that the withdrawal resistance is not correlated with the density of the wood material, and that it decreased with the degree of wood material processing – the less processed the material, the greater the resistance to withdrawal of the t-nuts.*

**KEYWORDS:** *T-nut; pinewood; oriented strand board; plywood; particleboard; furniture materials*

**SAŽETAK** • *Unit-matice tvornički se ugrađuju u provrte dijelova namještaja spremnih za montažu. Postoji opasnost da unit-matice tijekom transporta ispadnu ili da se pri montaži umetnu u pogrešne rupe. Takve situacije mogu zakomplicirati ili onemogućiti sastavljanje namještaja. Stoga je potrebna dovoljna sila da se unit-matica zadrži u provrtu. U članku su prikazani rezultati ispitivanja sila koje drže unit-matice u pet materijala za namještaj (u drvu četinjača, OSB pločama, furnirskim pločama i u dvije varijante iverica). Unit-matice M6 s četiri trna ugrađene su u prethodno izbušene provrte od 8 mm. Otpor njihovu izvlačenju mjeren je univerzalnim uređajem za mehanička ispitivanja. Rezultati su pokazali da se prema riziku od ispadanja unit-matica ispitivani materijali mogu podijeliti u tri skupine: drvo četinjača i furnirska ploča – mali rizik, F = 1113,2 – 1158,0 N; OSB ploče i iverice – umjereni rizik, F = 592,3 – 645,5 N; iverice s podlogom – visoki rizik, F = 645,5 N. Ispitivanja su potvrdila da otpor izvlačenju nije u korelaciji s gustoćom drvnog materijala te da se on sa stupnjem prerade drvnog materijala smanjuje: što je materijal manje prerađen, to je otpor izvlačenju unit-matica veći.*

**KLJUČNE RIJEČI:** *Unit-matica; borovina; OSB ploča; furnirska ploča; ploča iverica; materijali za namještaj*

[1] Author is employee at Euroline sp. z o.o., Leszno, Poland.
[2] Author is researcher at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Furniture, Poznań, Poland
[3] Authors are researchers at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Woodworking and Fundamentals of Machine Design, ul. Poznań, Poland

## 1 INTRODUCTION
## 1. UVOD

T-nuts with bolts are used to create non-permanent screwed joints between furniture components. Furniture fasteners of this type are commonly used in industrially produced ready-to-assemble furniture. Furniture with t-nuts is simple to assemble with standard fastening tools, offers strong joints, and can be dismantled without furniture damage. During furniture production, the t-nuts are pressed into the drilled holes in the furniture components. The components of furniture with fasteners, as self-assembly kits, are delivered to end customers. The t-nuts are usually made of steel and have a sleeve with internal screw thread and a flange with prongs. The prongs are disposed radially of the flange and prevent the nut from turning while screwing in the bolt (Figure 1).

However, when the furniture is assembled by the end customer, the t-nut can be pushed out of the hole. The t-nuts can also be lost during transport and storage of the ready-to-assemble furniture kits. If it falls into inaccessible spaces or if it cannot be put back into the hole, then the furniture cannot be assembled, which can be a reason for complaint. Therefore, it is benefical to ensure a sufficiently high resistance to prevent these t-nuts from falling out of their holes. The force holding the t-nuts in furniture components depends on:

1. T-nut (material, size, design);
2. Technological factors (an engineering fit between the hole and the t-nut sleeve, a force with which the t-nut was pressed into the hole, coaxially of pressing, shape, and quality of the hole in the piece of furniture resulting from the drilling technology);
3. Properties of the furniture component material.

Assuming that the design of the nuts and the technology of their preassembly are appropriate, it was decided to check the effect of the furniture material on the t-nuts withdrawal resistance.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

Five furniture materials were selected for laboratory testing of t-nuts withdrawal resistance. Twelve samples of each tested material were made (Table 1).

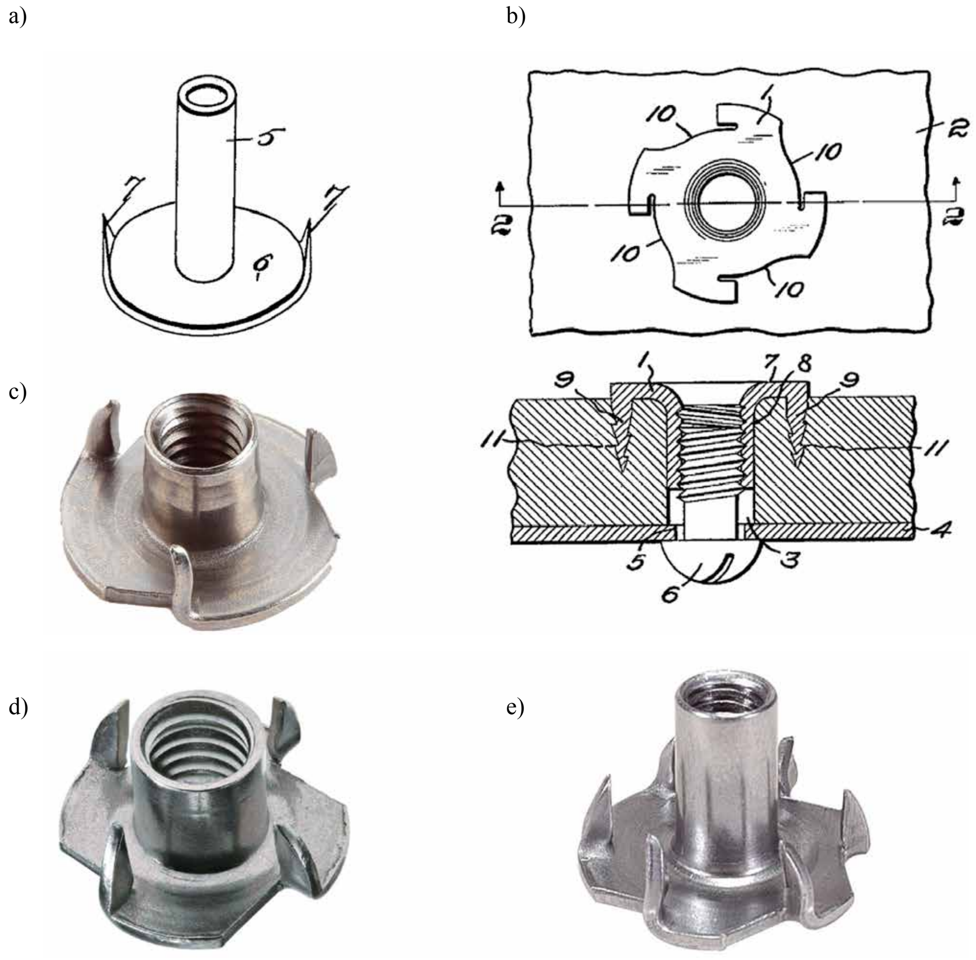



**Figure 1** T-nuts: a – according to patent US945737A (Anderson, 1910), b – according to patent US2102558A (Gustav, 1937), c – with three prongs, d – with four prongs, e – with six prongs
**Slika 1.** Unit-matica: a – prema patentu US945737A (Anderson, 1910.), b – prema patentu US2102558A (Gustav, 1937.), c – s tri trna, d – s četiri trna, e – sa šest trnova

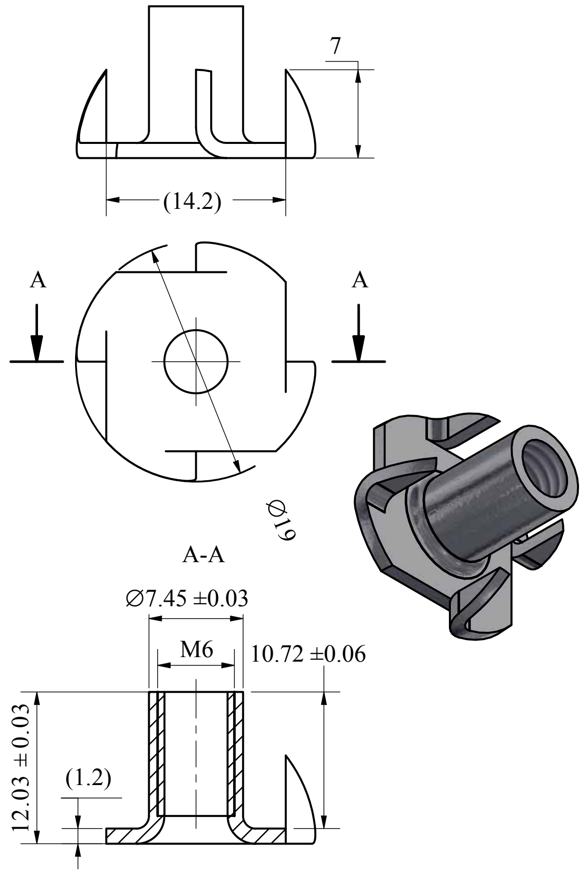



**Figure 2** Tested t-nuts with four prongs
**Slika 2.** Ispitivana unit-matica s četiri trna


**Figure 3** Hopper fed t-nut drive machine (Photo: Sigma Tool & Machine)
**Slika 3.** Stroj za ugradnju unit-matica sa spremnikom

A numerical control processing centre (Skipper 100L, Biesse Group, Pesaro, Italia) and 8 mm fully sharp twist drills for wood with carbide blades were used to drill holes in the tested furniture materials. Woodworking parameters used were as follows: rotation speed 3000 rpm (cutting speed $v_c$ = 75 m/min), feed 3.0 m/min (chip load $f_z$ = 0.5 mm/tooth). The steel M6 four prongs t-nuts (Figure 2) were placed in the holes using an industrial hopper-fed t-nut drive machine (model 2598, Sigma Tool & Machine, Toronto, Canada) with a pressure of 0.45 MPa (Figure 3).

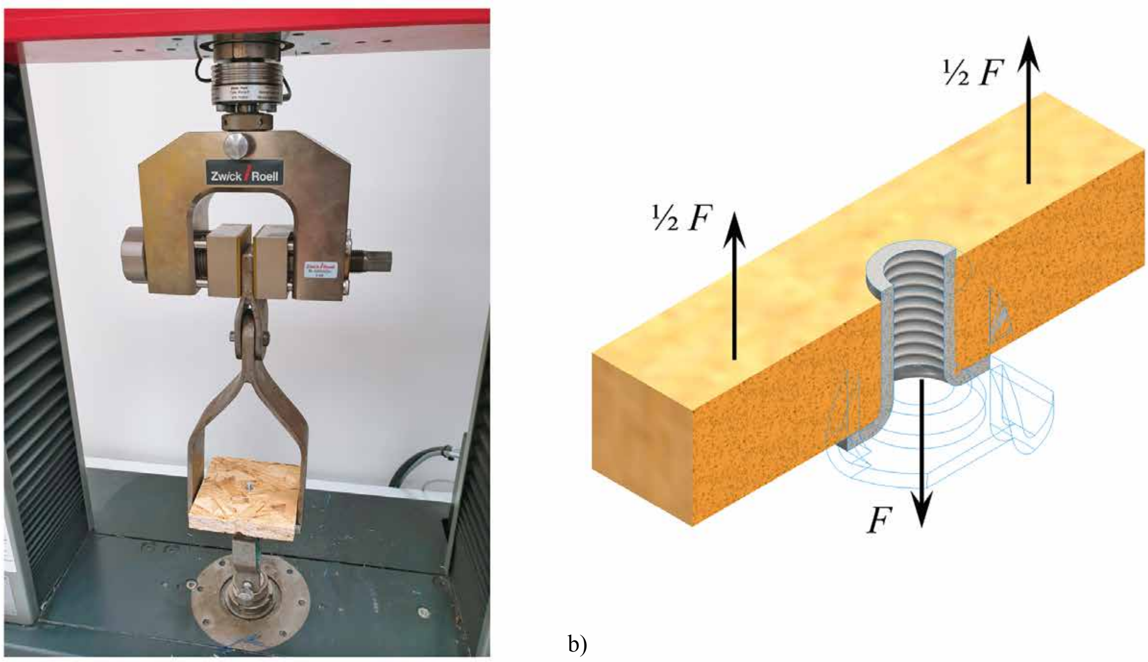
The test samples for withdrawal resistance tests are shown in Figure 4. All samples were subjected to a monthly conditioning process ($t$ = 23 ±2 °C, RH = 50 ±5 %) that ensured that they have obtained an equilibrium moisture content.

**Table 1** Tested furniture materials
**Tablica 1.** Ispitivani materijali za namještaj

| **Sample series designation** *Oznaka serije uzorka* | **Material** *Materijal* | **Dimensions** / *Dimenzije*, mm | | | | **Density** *Gustoća* kg/m³ | **Number of samples** *Broj uzoraka* *n* |
|---|---|---|---|---|---|---|---|
| | | **Width** *Širina* | **Height** *Visina* | **Thickness** *Debljina* | **Hole diameter** *Promjer provrta* *n* = 12, *k* = 11, α = 095 | | |
| CW_I | Pinewood / *borovina* (*P. sylvestris* L.) | 20 | 45 | 10 | 7.96 ± 0.04 | 585.1 | 12 |
| PW | Plywood (birch-alder, 9-layers) *furnirska ploča (breza – joha, 9-slojna)* | 95 | 100 | 15 | 7.94 ±0.03 | 695.3 | 12 |
| OSB | OSB/1 | 95 | 100 | 15 | 7.94 ±0.03 | 650.1 | 12 |
| PB_I | Particleboard / *ploča iverica* | 95 | 100 | 15 | 7.97 ± 0.03 | 717.3 | 12 |
| PB_II | Particleboard + ruber pad *ploča iverica s gumenim podloškom* | 95 | 100 | 15 + 2 (pad) | 7.97 ± 0.03 | 717.3 + 1520.0 | 12 |


a) b)

**Figure 4** Examples of test samples: a) OSB, b) particleboard with a rubber pad
**Slika 4.** Primjeri ispitnih uzoraka: a) OSB, b) iverica s gumenim podloškom




a) b)

**Figure 5** Withdrawal resistance tests of t-nuts: a) test stand; b) mode of loading the sample with forces
**Slika 5.** Ispitivanje otpora izvlačenju unit-matica: a) ispitno mjesto, b) način opterećenja uzorka silama

screw screwed into the t-nut. The design of the jig allowed to simulate pulling the t-nut out of the hole in the Group, Ulm, Germany) with the use of a specially made jig consisting of a clamp that holds a wooden element and a screw screwed into a t-nut. The design of the jig allowed to simulate pulling the t-nut out of the hole predrilled in furniture element. The testing device and the method of loading the sample with forces are shown in Figure 5.

The withdrawal resistance tests used the following parameters: initial force 2 N, traverse speed 100 mm/min. The force was measured until the t-nut prongs were fully removed from the wood material.

## 3 RESULTS
## 3. REZULTATI

The results of the withdrawal resistance test are the forces that pull the nuts out of the holes. The box plot in Figure 6 shows the locality, variability outside the upper and lower quartiles, means, and median values of these forces for five tested series of furniture materials.

The highest mean pulling out force for t-nuts was observed for softwood, with a similar value but slightly lower for plywood. Lower values of the tearing forces were observed for the OSB board and the particleboard

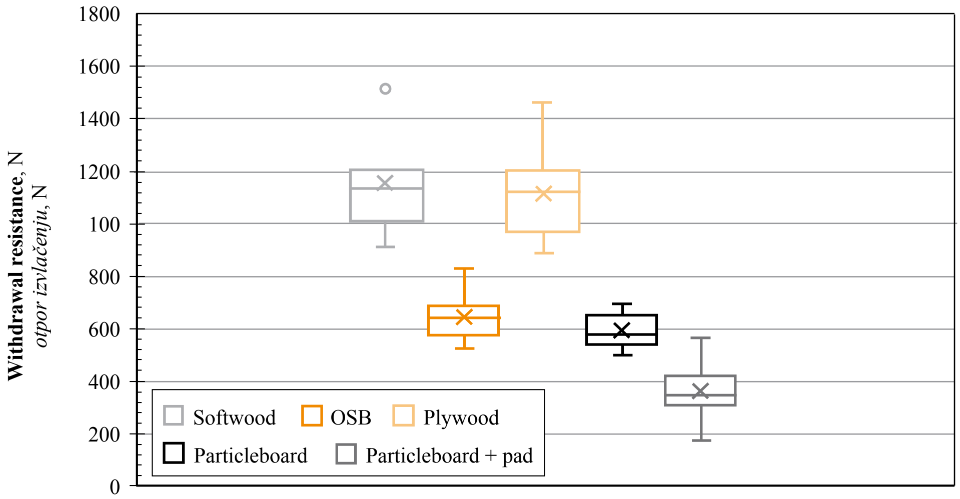



**Figure 6** Withdrawal resistance of tested materials (*n* = 12)
**Slika 6.** Otpor ispitivanih materijala izvlačenju (*n* = 12)

**Table 2** Main statistical parameters for tested furniture materials (*n* = 12)
**Tablica 2.** Glavni statistički parametri ispitivanih materijala za namještaj (*n* = 12)

| | **Softwood** *Drvo četinjača* | **OSB** | **Plywood** *Furnirska ploča* | **Particleboard** *Ploča iverica* | **Particleboard + rubber pad** *Ploča iverica s gumenim podloškom* |
|---|---|---|---|---|---|
| Mean, N | 1158.0 | 645.5 | 1113.2 | 592.3 | 366.1 |
| SD | 198.2 | 95.1 | 154.9 | 63.0 | 100.3 |
| Minimum, N | 913.0 | 526.1 | 887.8 | 500.1 | 174.9 |
| Median, N | 1136.5 | 640.1 | 1120.0 | 577.2 | 344.4 |
| Maximum, N | 1541.0 | 827.7 | 1461.0 | 693.3 | 561.3 |
| Slant | 1.02 | 0.73 | 0.68 | 0.33 | 0.20 |
| Curtosis | 0.41 | -0.04 | 1.19 | -0.98 | 0.83 |
| Shapiro-Wilk (*p*-value) | 0.085 | 0.360 | 0.543 | 0.471 | 0.898 |

without a pad. The weakest element was the particle board with a plastic pad. Table 2 summarizes the most important statistical parameters calculated for the five furniture materials tested.

The Shapiro-Wilk normality test of the force value distributions in series was performed. The computed p-values were greater than the significance level **α** = 0.05, so there was no reason to reject the null hypothesis $H_0$ (the values in the series follow a normal distribution). Therefore, it was assumed that it was possible to perform a one-way ANOVA. A one-way ANOVA was performed between subjects to compare the influence of five material variants on the pull force value of t-nuts. There was a significant effect of material type on the pulling force at the $p<0.05$ level for the five variants [$F(4, 55) = 83.14$, $p$ = 1,18045E-22]. Post hoc comparisons using the Tukey HSD test indicated that the softwood samples pulling force values were significantly different from force values of the OSB, particleboard, and particleboard with plastic pad samples. However, the softwood samples did not significantly differ from the plywood samples, and the OSB samples were statistically similar to the particleboard samples. Small differences justify the classification of the five tested materials into three groups, as shown in Table 3.

**Table 3** Summary of all pairwise comparisons for five materials tested (Tukey HSD test)
**Tablica 3.** Sažetak svih usporedbi u paru za pet ispitivanih materijala (Tukeyjev HSD test)

| **Samples series** *Uzorci* | **Mean pulling force, N** *Srednja sila izvlačenja*, N | **Group** *Skupina* | | |
|---|---|---|---|---|
| Softwood / *drvo četinjača* | 1158.0 | A | | |
| Plywood / *furnirska ploča* | 1113.2 | A | | |
| OSB / *ploča s orijentiranim iverjem* | 645.5 | | B | |
| Particleboard / *ploča iverica* | 592.3 | | B | |
| Particleboard + pad / *ploča iverica s podloškom* | 366.1 | | | C |

Taken together, these results suggest the following:

Softwood. Advantageously, a high value of the average t-nut withdrawal resistance ($F_{Mean}$ = 1158.0 N), but a very high value of the standard deviation in the sample series (*SD* = 198.2), could indicate a high risk of the nuts falling out of the holes. However, the advantageous feature of this material is a very high value of the minimum withdrawal resistance in the series

($F_{Min}$ = 913.0 N), which sugests that the risk of accidentally pushing the nut out of the hole during assembly is the lowest. The softwood standard deviation is the largest among all variants of tested material and is over three times greater than the standard deviation calculated for the particleboard. The explanation for this phenomenon is the large heterogeneity of the structure and thus large diversification of the properties of natural wood compared to other more homogeneous wood-based materials. The high variability of the tensile forces translates into unfavorably variable design properties of the "hole-nut" assembly pair.

OSB. Unfavorably low average t-nut withdrawal resistance ($F_{Mean}$ = 645.5 N). However, a moderate value of the standard deviation in the sample series (*SD* = 95.1), although the material appears to have a heterogeneous structure. A small value of the minimum t-nut withdrawal resistance ($F_{Min}$ = 526.1 N) indicates a high risk that the t-nuts will spontaneously fall off, which requires counteracting this risk in industrial production (a change in the structure of a furniture element or a technology change).

Plywood. The average t-nut withdrawal resistance is high ($F_{Mean}$ = 1113.2 N), similar to the softwood samples. Plywood offers slightly better force values replicability, indicated by a smaller standard deviation than softwood samples (*SD* = 154.9). In terms of the tests performed, plywood is a more homogeneous material than softwood. It also preferably has a high minimum t-nut pulling out force ($F_{Min}$ = 887.8 N).

Particleboard (without a pad). The average t-nut withdrawal resistance is small ($F_{Mean}$ = 592.3 N), slightly lower than the OSB, while the repeatability of the force values is the highest (*SD* = 63.0). The test results indicate the risk that the t-nuts will fall out spontaneously during customer assembly ($F_{Min}$ = 500.1 N), which (as in the OSB) requires counteracting.

Particleboard with a rubber pad. The lowest average t-nut withdrawal resistance ($F_{Mean}$ = 366.1 N). Unfavorably large standard deviation in the series (*SD* = 100.3). Very low minimum pulling out force ($F_{Min}$ = 174.9 N). The t-nuts withdrawal resistance is the smallest of all tested materials.

## 4 DISCUSSION
## 4. RASPRAVA

The assembly of ready-to-assemble furniture is usually performed by a nonspecialist, which imply the need to design furniture that is proof to assembly errors with uncomplicated fasteners (Branowski *et al.*, 2020). Few studies describe the load capacity of t-nuts in wood materials. In Eckelmann's studies, the loading force direction was the opposite of the direction used in our studies. The t-nuts were pulled through holes made in various types of wood materials, and the load capacity of the t-nuts joints was measured. The goal was to measure the value of the forces that break the screwed joint. The t-nuts in high-density wood are damaged due to the separation of the sleeve from the flange. The t-nut can be fully pulled through the hole in a less dense wood, locally damaging the surrounding wood. The ability of t-nuts to transfer forces is mainly related to the outer diameter and thickness of the t-nut flange. The properties of the wood material are another essential factor. The harder the wood material, the larger the t-nut flange diameter, and the greater the flange thickness – the stronger the joint (Eckelman, 1998).

Our research aimed to check the resistance of t-nuts to pull out of the five furniture materials (the t-nut withdrawal resistance). The t-nut anchoring mechanism in a fastened element is similar to that of nails. The t-nut prongs, nailed into the element, resist withdrawing through frictional forces like smooth shank nails. The nail-type anchoring mechanism of the prongs justifies comparing our test results with literature reports on the holding force of axially withdrawn nails. Similar to the work of (Chow *et al.*, 1988), our study shows that the t-nut withdrawal strength in plywood is greater than in OSB. Reports in the literature that describe the withdrawal resistance to nail removal in various wood species and wood-based materials indicate that the higher the density of the wood material – the greater the resistance (Rammer and Zelinka, 2015; Ringhofer *et al.*, 2018). The results of our research do not show such a relationship. This suggests that the friction coefficient between the prongs and the material of the furniture may be decisive in this case. Additional data collection would help to confirm this statement.

The t-nut withdrawal resistance in our research seems to depend on the degree of processing of the furniture material. The more processed the material, the less the t-nut withdrawal resistance. Chaharmahali *et al.*, 2008 stated that the greater the differentiation of properties of the phases in the wood composite, the lower the force holding the nails. Our results show the dependence between t-nut withdrawal resistance and degree of wood material processing. The t-nut withdrawal resistance decreases with an increasing degree of material processing. It is the smallest for particleboard, increasing in value for OSB and plywood, and it is the largest for softwood.

## 5 CONCLUSIONS
## 5. ZAKLJUČAK

The results of this study suggest the following:

1. In the case of mounting t-nuts in holes made in various wood-based materials, obtaining the highest

minimum force in the "nut-hole" assembly pair is crucial – it is even more important than obtaining a small dispersion of holding force values (low standard deviation in series). The minimum force holding the nuts in the holes determines the risk of inability to assemble the furniture.

2. The tested furniture materials can be divided into three groups: A (softwood, plywood) – high t-nuts withdrawal resistance, unfavorably large dispersion of this force value, but a low risk of the nut falling out due to the high value of the minimum force required to pull the nut out B (OSB, particleboard) – moderate minimum force, moderate dispersion of results, required and potentially possible improvement actions; C (particleboard with pad) – low minimum force and therefore a high risk of the nut falling out. The moderate value of the standard deviation (quite good repeatability of the results in the series) is a reasonable justification for undertaking an attempt to increase the average force holding the nuts in OSB and particleboard.
3. The test results show that the forces holding the nuts in the holes decrease with the increased degree of processing of wood materials.

## 6 REFERENCES
## 6. LITERATURA


1. Anderson, C. J., 1910: Screw-seat. US945737A.
2. Branowski, B.; Starczewski, K.; Zabłocki, M.; Sydor, M., 2020: Design issues of innovative furniture fasteners for wood-based boards. BioResources, 15: 8472-8495. https://doi.org/10.15376/biores.15.4.8472-8495
3. Chaharmahali, M.; Tajvidi, M.; Najafi, S. K., 2008: Mechanical properties of wood plastic composite panels made from waste fiberboard and particleboard. Polymer Composites, 29: 606-610. https://doi.org/10.1002/pc.20434
4. Chow, P.; McNatt, J. D.; Lambrechts, S. J.; Gertner, G. Z., 1988: Direct withdrawal and head pull-through performance of nails and staples in structural wood-based panel materials. Forest Products Journal, 38: 19-25.
5. Eckelman, C. A., 1998: Holding strength of T-nuts in solid wood and wood composites. Holz als Roh- und Werkstoff, 56: 253-258. https://doi.org/10.1007/s001070050314
6. Gustav, J., 1937: Nut and installation thereof. US2102558A.
7. Rammer, D. R.; Zelinka, S. L., 2015: Withdrawal strength and bending yield strength of stainless steel nails. Journal of Structural Engineering, 141: 04014134. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001088
8. Ringhofer, A.; Brandner, R.; Blaß, H. J., 2018: Cross laminated timber (CLT): Design approaches for dowel-type fasteners and connections. Engineering Structures, 171: 849-861. https://doi.org/10.1016/j.engstruct.2018.05.032



**Corresponding address:**

**EWA SKORUPIŃSKA**
Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Woodworking and Fundamentals of Machine Design,Wojska Polskiego 28, Poznań, POLAND, e-mail: ewa.skorupinska@up.poznan.pl

Ľubomír Javorek[1], Richard Kminiak[2], Mária Vargovská[1], Etele Csanády[3], Szabolcs Németh[3]

# Feed Cutting Force Component in Up and Down Sawing of Pine

# Komponenta posmične sile rezanja pri istosmjernom i protusmjernom piljenju borovine

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 23. 2. 2022.
Accepted – prihvaćeno: 25. 4. 2022.
UDK: 630*82; 674.05
https://doi.org/10.5552/drvind.2022.0018



**ABSTRACT** • *The monitoring of cutting force components is one of the possibilities to control machining processes from the point of view of its stability, machine tool spindle or cutting tool loading. This paper presents and compares the results of experimental longitudinal sawing of pine wood with 4 saw discs with different teeth number (16 and 24) and rake angle (10° and 20°) during up (conventional) and down (climb) cutting with different revolutions (4000 min$^{-1}$, 5000 min$^{-1}$, 6000 min$^{-1}$) and feed speed (15 m/min, 20 m/min, 25 m/min). The signal was obtained from Quart 3-components piezoelectric dynamometer.*

**KEYWORDS:** *pine wood; sawing; feed speed; rake angle; teeth number; feed force*

**SAŽETAK** • *Praćenje komponenata sile rezanja jedna je od mogućnosti kontrole procesa obrade drva sa stajališta stabilnosti alata te opterećenja osovine ili oštrice alata. U radu su prikazani rezultati istraživanja eksperimentalnoga uzdužnog piljenja borovine pilom s četiri lista i različitim brojem zuba (16 i 24) te pod različitim prsnim kutom (10° i 20°) tijekom protusmjernoga (konvencionalnog) i istosmjernog rezanja, uz različit broj okretaja osovine alata (4000 min$^{-1}$, 5000 min$^{-1}$, 6000 min$^{-1}$) i tri posmične brzine (15 m/min, 20 m/min, 25 m/min). Signal je dobiven uz pomoć Quart 3-komponentnoga piezoelektričnog dinamometra.*

**KLJUČNE RIJEČI:** *borovina; piljenje; posmična brzina; prsni kut; broj zuba; posmična sila*

## 1 INTRODUCTION
## 1. UVOD

Circular sawing is one of the most advanced technologies in woodworking industry. Saw discs (blades) are designed as universal rip saw blades for longitudinal or transversal cutting or trimming of all types of wood, soft or hard, dry or wet. Saw discs are used in single or multi-rip saw tools with single or double shaft or in splitting machines. Circular sawing has been in the focus of many researchers due to its widespread application.

[1] Authors are researchers at Department of Manufacturing and Automation Technology, Faculty of Technology, Technical University in Zvolen, Zvolen, Slovak Republic.
[2] Author is researcher at Department of Woodworking, Faculty of Wood Technology, Technical University in Zvolen, Zvolen, Slovak Republic.
[3] Authors are researchers at Institute of Wood Industry and Technology, Faculty of Wood Engineering and Creative Industrie, University of Sopron, Sopron, Hungary.

**Table 1** Mechanical properties of Swiss stone pine (*Pinus cembra* L) (Klement *et al*., 2011)
**Tablica 1.** Mehanička svojstva drva švicarskog bora (*Pinus cembra* L) (Klement *et al*., 2011.)

| **Properties** *Svojstvo* | **Parallel with grain** *Paralelno s vlakancima* | | **Perpendicular to grain** *Okomito na vlakanca* | |
|---|---|---|---|---|
| | *w* = 12 % | *w* > 30 % | *w* = 12 % | *w* > 30 % |
| Tensile strength, MPa / *Vlačna čvrstoća,* MPa | 104 | | 3 | 2.4 |
| Compression strength. MPa / *Tlačna čvrstoća,* MPa | 45 | 21 | 4.0 | |
| Shearing strength, MPa / *Čvrstoća na smicanje,* MPa | 11.3 | 5.9 | | |
| Bending strength, MPa / *Čvrstoća na savijanje,* MPa | 83 | 44 | | |
| Modulus of elasticity, MPa / *Modul elastičnosti,* MPa | 11 700 | | 430 | |
| Toughness J/cm$^2$ / *Žilavost,* J/cm$^2$ | | | 4.12 | 3.63 |
| Brinell hardness, MPa / *Tvrdoća prema Brinellu, MPa* | 40 | | | |
| Janko hardness*, MPa / *Tvrdoća prema Janki,* MPa | 30 | | 25.8 | 19.6 |

Cutting forces are very important variables in machining performance; they affect surface roughness, tool life, energy consumption.

The process of material removing was studied from the beginning of machining; the studies are related to detachment of chips, shear angle, friction angle, grain orientation (Piispanen, 1948; Kivimaa, 1950; Fischer, 1979; Teng *et al*., 2014:). The research is also oriented on the influence of mechanical and physical properties or moisture content of the machined material on power consumption (Beer, 2002; Lučić *et al.,* 2004; Dange *et al.,* 2011; Nasir and Cool, 2018). Consumption of energy depends on the type of machined material. The medium density fibreboard was researched by Aquilera (2011), oak and Douglas fir by Goli and Porankiewicz (2014), beech and spruce were researched in the experiments of Aguilera and Martin (2001). The value of cutting moment or force components received from machining can be used for comparing different models of machining (Kivimaa, 1950; Orlowski *et al.*, 2013; Orlowski *et al.,* 2017; Hlaskova *et al.*, 2019). The influence of technological factors on the main cutting force or its components or power parameters is analysed very often in the scientific papers (Ioras *et al.,* 2002; Naylor *et al.,* 2012; Palubicki, 2021).

For measuring cutting power, consumption energy or cutting forces were determined by different experimental stands and methods. The pendulum dynamic tester was used (Dange *et al.,* 2011) for studying energy consumption and cutting forces during orthogonal cutting with two blades, sharpened at 30° and 45°. Cutting velocity in the range between cca 2.3 m/s to 7.3 m/s was used. The experimental device with long arm (535 mm) rotated in vertical plane was used for monitoring and evaluation semi-orthogonal cutting and for designating multi-factors and dependency between tangential and normal force (Porankiewicz *et al.*, 2011; Porankiewicz and Goli, 2014). On the other hand, measurement of cutting power and then calculation of the main cutting (tangential) force from electrical cutting power is used very often (Kopecky and Rousek, 2005). Another way how to reduce energy consumption is to reduce the friction between saw disc body and workpiece (Fekiač *et al.*, 2022).

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Material of workpieces
### 2.1. Materijal uzoraka

The workpieces of nominal dimensions of 170 mm × 100 mm and 23 mm thickness were prepared and before sawing all samples were air-conditioned to the moisture content of 14 %. The properties of Swiss stone pine are presented in Table 1.

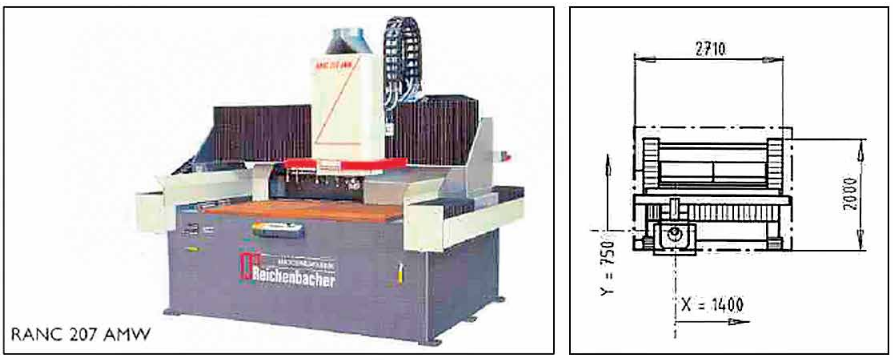



**Figure 1** CNC machine tool Reichenbecher RANC 207 AMW (27)
**Slika 1.** CNC alatni stroj Reichenbecher RANC 207 AMW (27)


**Figure 2** Saw discs 1, 2, 3, 4
**Slika 2.** Listovi pila 1, 2, 3 i 4

**Table 2** Saw disc parameters
**Tablica 2.** Parametri listova pile

| **Saw disc** *List pile* | **Dimensions, mm** *Dimenzije*, mm $D_1 \times d_3 \times a \times s_T$ | **Teeth number** *Broj zuba* | **Body thickness *a*, mm** *Debljina lista a,* mm | **Kerf width $s_T$, mm** *Širina propiljka $s_T$,* mm | **Tool cutting edge angle $k_r$, °** *Kut glavne oštrice* $k_r$, ° | **Rake angle** γ, ° *Prsni kut* γ, ° | **Clearance** angle α, ° *Leđni kut* α, ° |
|---|---|---|---|---|---|---|---|
| SD 1 | 190 × 30 × 1.8 × 2.6 | 16 | 1.8 | 2.6 | 90 | 10 | 12 |
| SD 2 | 190 × 30 × 1.8 × 2.6 | 16 | 1.8 | 2.6 | 90 | 20 | 12 |
| SD 3 | 190 × 30 × 1.8 × 2.6 | 24 | 1.8 | 2.6 | 90 | 20 | 12 |
| SD 4 | 190 × 30 × 1.8 × 2.6 | 24 | 1.8 | 2.6 | 90 | 10 | 12 |

## 2.2 Machine tool
## 2.2. Alatni stroj

The vertical CNC router Reichenbecher RANC 207 AMW (Figure 1) was used for experiments. Machine tool is defined as training centre and assigned for the machining of small and plane parts. All experiments were carried out in the laboratory of the University of Sopron, in Hungary.

Technical specifications:
- one working spindle: 7.5 kW at 18 000 $min^{-1}$;
- working feed rate: 20 m/min in *X*, *Y* axis;
- positioning speed up to 28 m/min;
- tool magazine: for 8 tools;
- fastening: SK30;
- working motion: *X*=1400 mm; *Y*=750 mm; *Z* = 250 mm;
- machine table: 1550 mm × 900 mm.

## 2.3 Woodworking tools
## 2.3. Alati za obradu drva

The Polish company GASS Suwalki (at present ASPI sp.o.o./s.k.) prepared 4 saw discs (Figure 2) for the experiment; parameters are given in Table 2. The tips of teeth of all discs were from tungsten carbide.

## 2.4 Technological conditions
## 2.4. Tehnološki uvjeti

The experiment was designed as full factorial experiment based on a model of a classical experiment plan, with three independent factors.

As input factors with influence on output characteristics, the following factors and their levels were determined:

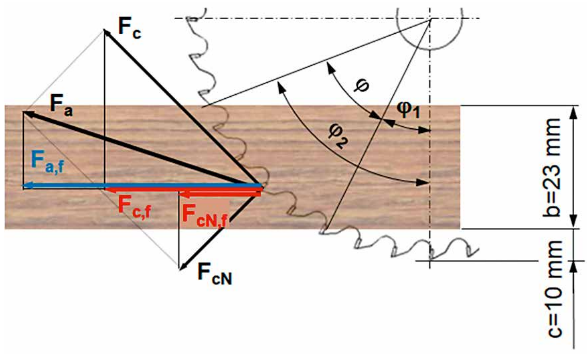



**Figure 3** Execution of sawing experiment: *c* – saw projection up the workpiece; *b* – workpiece thickness; $j_1$ – saw enter angle; $j_2$ – saw exit angle; φ – saw cutting angle; $F_a$ – active force and its projection $F_{a,f}$ to feed direction; $F_c$ – cutting force and its projection $F_{c,f}$ to feed direction; $F_{cN}$ – passive (thrust, deflecting) force and its projection $F_{cN,f}$ to feed direction
**Slika 3.** Parametri eksperimentalnog piljenja: *c* – istak pile iznad obratka; *b* – visina uzorka; $j_1$ – kut ulaska pile u zahvat; $j_2$ – kut izlaska pile iz zahvata; φ – kut zahvata; $F_a$ – aktivna sila i njezina projekcija $F_{a,f}$ na pravac posmične brzine; $F_c$ – sila rezanja i njezina projekcija $F_{c,f}$ na pravac posmične brzine; $F_{cN}$ – odrivna sila i njezina projekcija $F_{cN,f}$ na pravac posmične brzine

- rotational speed ($min^{-1}$): 4000; 5000; 6000;
- feed speed (m/min): 15; 20; 25;
- up and down cutting.

The projection of saw disc up of workpiece: 10 mm.

Dependent (measured) factors were:
- feed force $F_f$ (as sum of force $F_{c,f}$ and $F_{cN,f}$) measured in Y axis of measure platform;
- force $F_{fN}$, perpendicular to feed force measured in *X* axis of experimental platform (Figure 3).

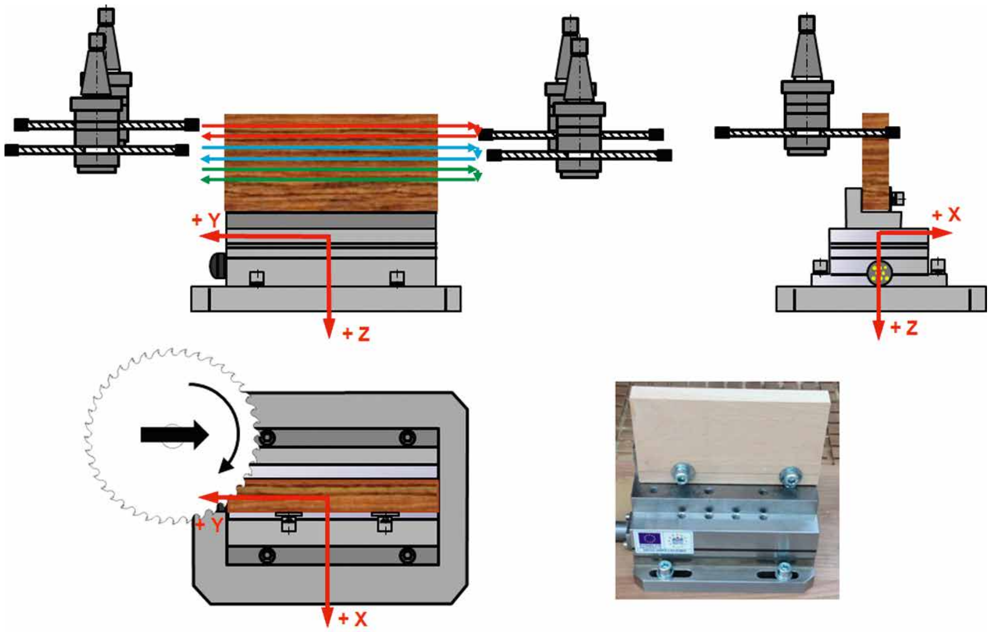



**Figure 4** Saw disc position vs. workpiece
**Slika 4.** Položaj lista pile u odnosu prema obratku

## 2.5 Experimental device
## 2.5. Mjerna oprema

Piezoelectric measuring system (Figure 5) made by Kistler (Kistler Instrumente AG, Switzerland) was used for measuring the cutting force components. The basic parts of the system were:

1. Quart 3-components dynamometer 9275B (parameters see Table 3).
2. Multichannel Charge Amplifier 5070A.
3. A/D Converter – DAQ System 5657A1.
4. NTB + software DynoWare.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The components $F_f$ and $F_{fN}$ are the basis for determining the active force $F_a$. Figure 5 illustrates the orientation of force components $F_f$, $F_{fN}$, and final (active) force $F_a$ based on the coordinate system of measure platform. This figure clearly shows that the feed force was positive for both types of cutting (down and up), but $F_{fN}$ was in harmony with the positive coordinate axis of the platform for down cutting, while this component was negative for up cutting.

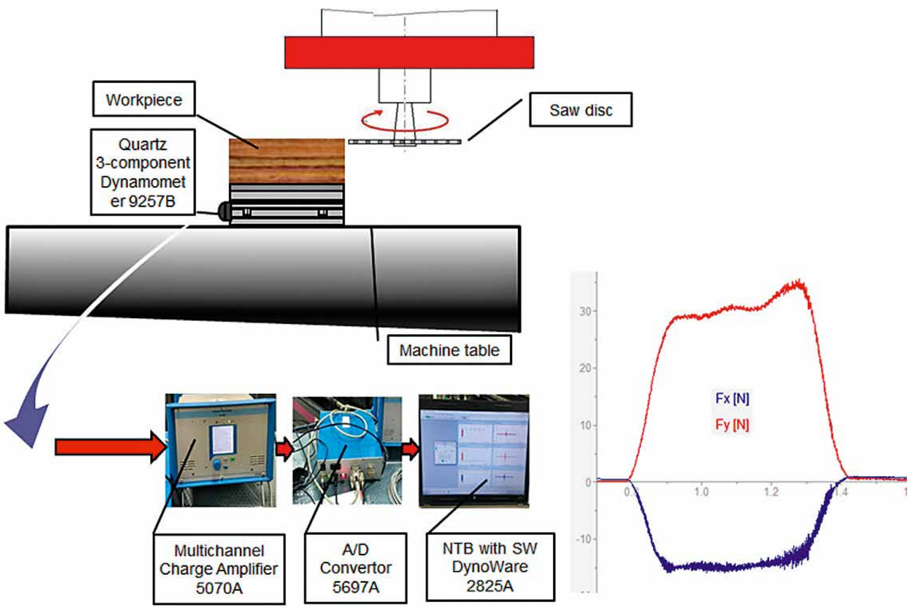



**Figure 5** Measuring chain
**Slika 5.** Mjerni lanac

**Table 3** Dynamometer type 9257A – chosen technical parameters
**Tablica 3.** Dinamometar tipa 9257A – odabrani tehnički parametri

| | | | |
|---|---|---|---|
| Range force application / *Raspon sila* | $F_x$, $F_y$, $F_z$ | kN | – 5 ... 5 |
| Overload / *Preopterećenje* / $F_x$ and $F_y$ ≤0,5 $F_z$ | $F_x$, $F_y$, $F_z$ | kN | –7,5 / 7,5 |
| | $F_z$ | kN | –7,5 / 15 |
| Response threshold / *Granica odziva* | | N | < 0,01 |
| Sensitivity / *Osjetljivost* | $F_x$, $F_y$ | pC/N | ≈ –7,5 |
| | $F_z$ | pC/N | ≈ –3,7 |
| Linearity (all ranges) / *Linearnost (svi rasponi)* | | % FSO | ±1 |
| Rigidity / *Krutost* | $c_x$, $c_y$ | kN/μm | >1 |
| | $c_z$ | kN/μm | >2 |
| Natural frequency / *Prirodne frekvencije* | $f_n$ $(x, y, z)$ | kHz | ≈ 3,5 |
| Operating temperature range / *Raspon radne temperature* | | °C | 0 …70 |
| Temperature coefficient of sensitivity / *Temperaturni koeficijent osjetljivosti* | | % / °C | – 0,02 |
| Capacitance (of channel) / *Kapacitet (kanala)* | | pF | 220 |
| Ground insulation / *Izolacija tla* | | W | >$10^8$ |

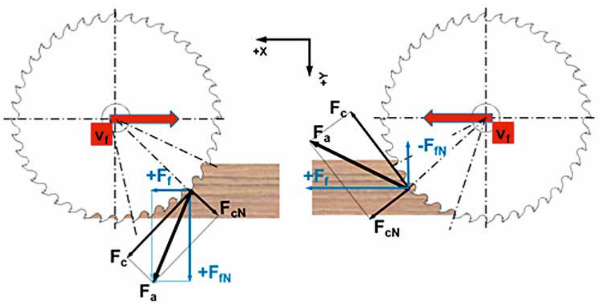



**Figure 6** Force components orientation based on coordinate system of dynamometer: down (in feed direction) – up (against feed direction)
**Slika 6.** Orijentacija komponenata sile zbog koordinatnog sustava dinamometra: istosmjerno (u smjeru posmične brzine) – protusmjerno (suprotno smjeru posmične brzine)

The data processing for every saw disc and technological parameters (i.e. type of sawing, revolutions, number of teeth, rake angle and feed speed) was the basis for evaluating feed force. The graphs (Figure 7) clearly show that feed force was smaller during down sawing for all revolutions, feed speeds and both rake angles.

### 3.1 Influence of sawing type
### 3.1. Utjecaj vrste piljenja

*Influence of sawing type (valid for SD1, z=16, γ=10°), Figure 7*

A more detailed analysis of the values shows that the ratio between feed force during up sawing and feed force during down sawing oscillates within the range from 1.25 to 2.42 (Table 4 or Figure 7).

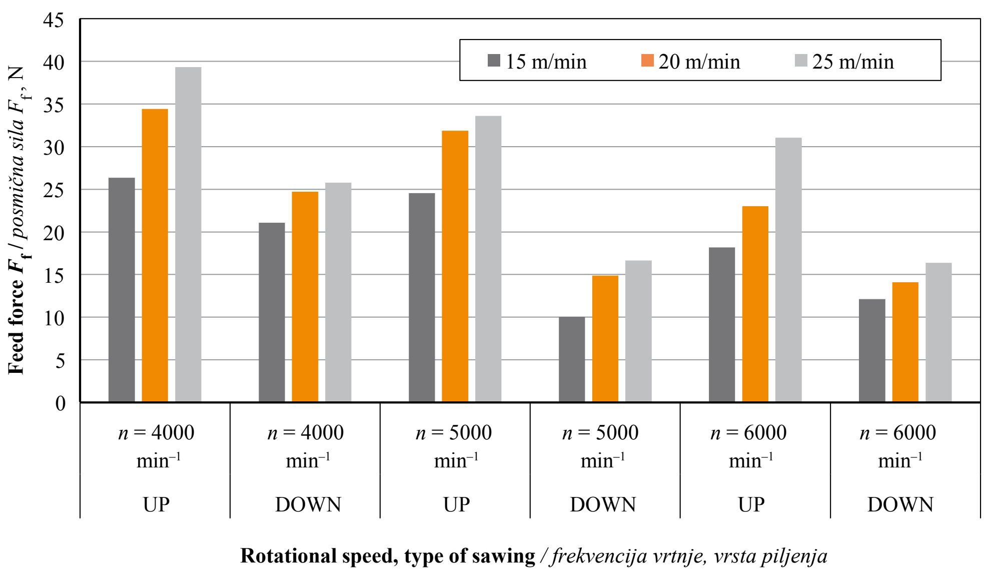



**Figure 7** Influence of feed speed $v_f$, revolutions $n$ and type of cutting to feed force $F_f$ (SD1; $z$ = 16; γ = 10°); pine wood
**Slika 7.** Utjecaj posmične brzine $v_f$, frekvencije vrtnje $n$ i vrste piljenja na posmičnu silu $F_f$ (SD1; $z$ = 16; γ = 10°); borovina

**Table 4** Ratio of up sawing feed force to down sawing feed force for SD1
**Tablica 4.** Omjer posmične sile pri protusmjernom piljenju u usporedbi s istosmjernim piljenjem za pilu SD1

| **Feed speed $v_f$, m/min** *Posmična brzina* $v_f$, m/min | **Rotational speed** $n$, **min$^{-1}$** *Frekvencija vrtnje* $n$, min$^{-1}$ | **Up sawing** *Protusmjerno piljenje* **Feed force $F_f$, N** *Posmična sila* $F_f$, N | **Down sawing** *Istosmjerno piljenje* **Feed force $F_f$, N** *Posmična sila* $F_f$, N | **Ratio: Up sawing feed force to down sawing feed force** *Omjer posmične sile pri protusmjernom piljenju u usporedbi s istosmjernim piljenjem* |
|---|---|---|---|---|
| 15 | 4000 | 26.36 | 21.07 | 1.25 |
| | 5000 | 24.5 | 10.1 | 2.42 |
| | 6000 | 18.7 | 12.13 | 1.54 |
| 20 | 4000 | 34.44 | 24.71 | 1.39 |
| | 5000 | 31.87 | 14.88 | 2.14 |
| | 6000 | 23.03 | 14.10 | 1.63 |
| 25 | 4000 | 39.32 | 25.77 | 1.52 |
| | 5000 | 33.61 | 16.64 | 2.02 |
| | 6000 | 31.04 | 16.39 | 1.89 |

*Influence of sawing type (valid for SD4, z=24, γ=10°), Figure 8*

Analogous to saw disk SD1 that has 16 teeth and rake angle of 10°, the results of a similar analysis for saw disc SD4 with rake angle of 10° but 24 teeth are displayed in Table 5. In this case the ratio between feed force during up sawing and feed force during down sawing oscillates within the range from 1.30 to 1.83 (Table 5 or Figure 8). The maximal difference is 0.50 compared to 1.17 for SD1. It seems that increasing of teeth number from 16 to 24 made the process more even.

### 3.2 Influence of feed speed (valid for SD1, z = 16, γ = 10°; Figure 9, Figure 10)
### 3.2. Utjecaj posmične brzine (vrijedi za SD1, z = 16, γ = 10°; sl. 9. i 10.)

The analysis of values displayed in Figure 9 and 10 shows partial results based on interactions of dependent variables: ratio between feed forces and different feed speeds during up and down sawing is:

- for up sawing, revolutions 4000 min$^{-1}$, feed speed 15 m/min, feed force $F_{f\,(Up,4000,15)}$ = 26.36 N and for feed speed 20 m/min, up sawing and the same revolutions feed force $F_{f\,(Up,4000,20)}$ = 34,44 N, i.e. ratio is 1.30;
- for up sawing, revolutions 4000 min$^{-1}$, feed speed 20 m/min, feed force $F_{f\,(Up,4000,20)}$ = 34.44 N and for feed speed 20 m/min, up sawing and the same revolutions feed force $F_{f\,(Up,4000,25)}$ = 39.32 N i.e. ratio is 1.14.

More detailed information for other conditions are presented in Table 4 and 5.

For both cases (down and up sawing), the slope of a straight line is quite similar.

The ratio between feed speeds $v_f$=20 m/min and $v_f$=15 m/min is 1.33; ratio between $v_f$=25 m/min and $v_f$=20 m/min is 1.25; ratio between $v_f$= 25 m/min and $v_f$=15 m/min is 1.66.

The ratio between revolution $n_2$ = 5000 min$^{-1}$ and $n_1$= 4000 min$^{-1}$ is 1.25; ratio between $n_3$=6000 min$^{-1}$ and $n_2$=5000 min$^{-1}$ is 1.2; ratio between $n_3$=6000 min$^{-1}$ and $n_1$=4000 min$^{-1}$ is 1.5.

As shown in Table 7 and 8, the rate of feed force is not the same as the rate of feed speed. The reason may lie in the fact that there are other force components, such as the depth of workpiece, etc.

**Table 5** Ratio of up sawing feed force to down sawing feed force for SD4
**Tablica 5.** Omjer posmične sile pri protusmjernom piljenju u usporedbi s istosmjernim piljenjem za pilu SD4

| **Feed speed $v_f$, m/min** *Posmična brzina* $v_f$, m/min | **Rotational speed** $n$, **min$^{-1}$** *Frekvencija vrtnje* $n$, min$^{-1}$ | **Up sawing** *Protusmjerno piljenje* **Feed force $F_f$, N** *Posmična sila* $F_f$, N | **Down sawing** *Istosmjerno piljenje* **Feed force $F_f$, N** *Posmična sila* $F_f$, N | **Ratio: Up sawing feed force to down sawing feed force** *Omjer posmične sile pri protusmjernom piljenju u usporedbi s istosmjernim piljenjem* |
|---|---|---|---|---|
| 15 | 4000 | 28.4 | 18.5 | 1.53 |
| | 5000 | 21.23 | 14.85 | 1.43 |
| | 6000 | 19.96 | 11.56 | 1.72 |
| 20 | 4000 | 32.61 | 19.71 | 1.65 |
| | 5000 | 31.7 | 17.33 | 1.83 |
| | 6000 | 23.28 | 16.43 | 1.41 |
| 25 | 4000 | 39.65 | 27.37 | 1.44 |
| | 5000 | 36.83 | 23.10 | 1.59 |
| | 6000 | 27.2 | 20.83 | 1.30 |

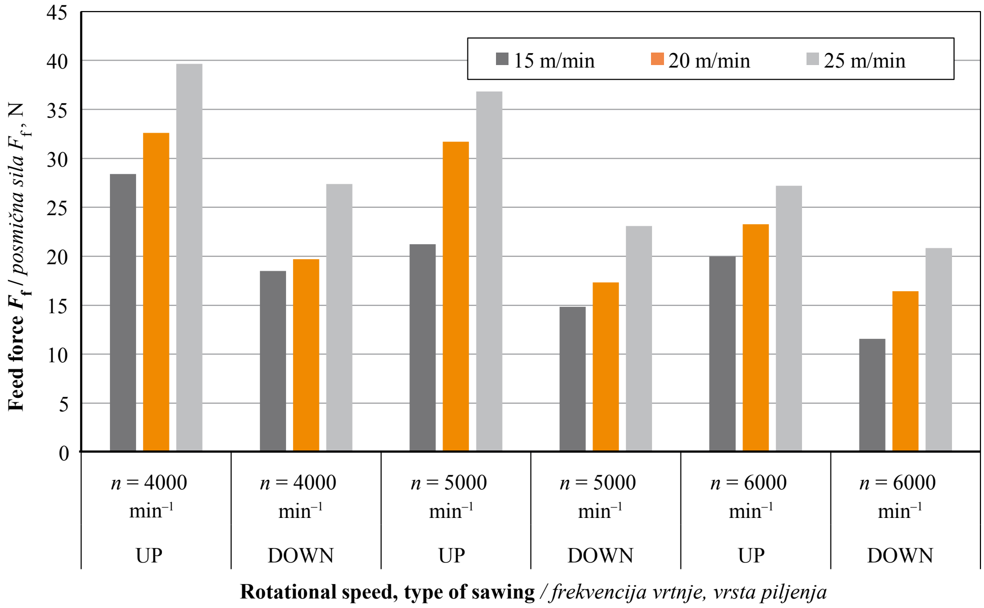



**Figure 8** Influence of feed speed $v_f$, revolutions $n$ and type of cutting to feed force $F_f$ (SD4; $z$ = 24; $\gamma$ = 10°); pine wood
**Slika 8.** Utjecaj posmične brzine $v_f$, frekvencije vrtnje $n$ i vrste piljenja na posmičnu silu $F_f$ (SD4; $z$ = 24; $\gamma$ = 10°); borovina

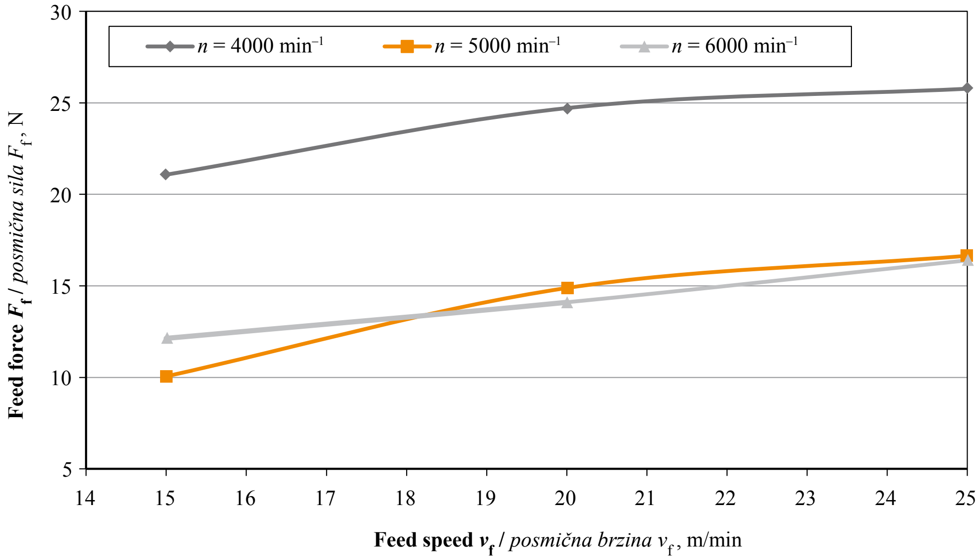



**Figure 9** Influence of feed speed $v_f$ and revolutions $n$ on feed force $F_f$ (SD1; $z$ = 16; $\gamma$ = 10°); down sawing
**Slika 9.** Utjecaj posmične brzine $v_f$ i frekvencije vrtnje $n$ na posmičnu silu $F_f$ (SD1, $z$ = 16, $\gamma$ = 10°); istosmjerno piljenje

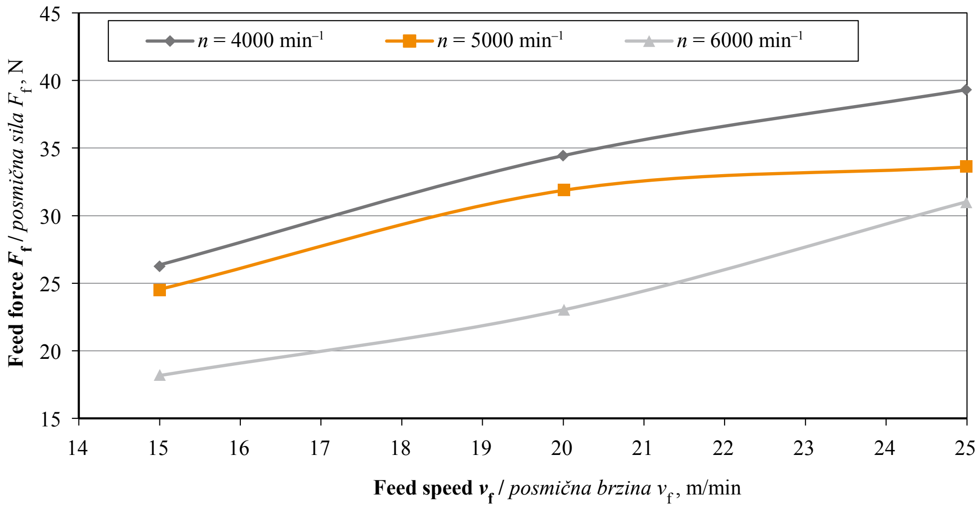



**Figure 10** Influence of feed speed $v_f$ and revolutions $n$ on feed force $F_f$ (SD1; $z$ = 16; $\gamma$ = 10°); up sawing
**Slika 10.** Utjecaj posmične brzine $v_f$ i frekvencije vrtnje $n$ na posmičnu silu $F_f$ (SD1, $z$ = 16, $\gamma$ = 10°); protusmjerno piljenje

**Table 6** Influence of feed speed $v_f$, revolutions $n$ and type of cutting on feed force $F_f$ (SD1; $z$ = 16; $\gamma$ = 10°); pine wood
**Tablica 6.** Utjecaj posmične brzine $v_f$, frekvencije vrtnje $n$ i vrste piljenja na posmičnu silu $F_f$ (SD1; $z$ = 16; $\gamma$ = 10°); borovina

| **Feed speed $v_f$, m/min** *Posmična brzina $v_f$,* m/min | **Type of sawing** / *Vrsta piljenja* | | | | | |
|---|---|---|---|---|---|---|
| | **Up** *Protusmjerno* | **Down** *Istosmjerno* | **Up** *Protusmjerno* | **Down** *Istosmjerno* | **Up** *Protusmjerno* | **Down** *Istosmjerno* |
| | **Revolutions *n*** / *Frekvencija vrtnje n*, min$^{-1}$ | | | | | |
| | 4000 | 4000 | 5000 | 5000 | 6000 | 6000 |
| | **Feed force $F_f$** / *Posmična sila $F_f$*, N | | | | | |
| 15 | 26.36 | 21.07 | 24.54 | 10.05 | 18.17 | 12.13 |
| 20 | 34.44 | 24.71 | 31.87 | 14.88 | 23.03 | 14.1 |
| 25 | 39.32 | 25.77 | 33.61 | 16.64 | 31.04 | 16.39 |

**Table 7** Increased rate of feed force due to increase of feed speed (SD1; $z$ = 16; $\gamma$ = 10°); pine wood
**Tablica 7.** Povećanje posmične sile zbog povećanja posmične brzine (SD1; $z$ = 16; $\gamma$ = 10°); borovina

| | **Type of sawing** / *Vrsta piljenja* | | | | | |
|---|---|---|---|---|---|---|
| | **Up** *Protusmjerno* | **Down** *Istosmjerno* | **Up** *Protusmjerno* | **Down** *Istosmjerno* | **Up** *Protusmjerno* | **Down** *Istosmjerno* |
| | **Revolutions *n*** / *Frekvencija vrtnje n*, min$^{-1}$ | | | | | |
| | 4000 | 4000 | 5000 | 5000 | 6000 | 6000 |
| **Ratio** / *Omjer* | | | | | | |
| $F_{f\,(vf=20)} / F_{f\,(vf=15)}$ | 1.31 | 1.17 | 1.30 | 1.48 | 1.27 | 1.16 |
| $F_{f\,(vf=25)} / F_{f\,(vf=20)}$ | 1.14 | 1.04 | 1.05 | 1.12 | 1.35 | 1.16 |
| $F_{f\,(vf=25)} / F_{f\,(vf=15)}$ | 1.49 | 1.22 | 1.37 | 1.66 | 1.71 | 1.35 |

**Table 8** Increased rate of feed force due to increase of feed speed (SD4; $z$ = 24; $\gamma$ = 10°); pine wood
**Tablica 8.** Povećanje posmične sile zbog povećanja posmične brzine (SD4; $z$ = 24; $\gamma$ = 10°); borovina

| | **Type of sawing** / *Vrsta piljenja* | | | | | |
|---|---|---|---|---|---|---|
| | **Up** *Protusmjerno* | **Down** *Istosmjerno* | Up *Protusmjerno* | **Down** *Istosmjerno* | **Up** *Protusmjerno* | **Down** *Istosmjerno* |
| | **Revolutions *n*** / *Frekvencija vrtnje n*, min$^{-1}$ | | | | | |
| | 4000 | 4000 | 5000 | 5000 | 6000 | 6000 |
| **Ratio** / *Omjer* | | | | | | |
| $F_{f\,(vf=20)} / F_{f\,(vf=15)}$ | 1.15 | 1.07 | 1.49 | 1.17 | 1.17 | 1.42 |
| $F_{f\,(vf=25)} / F_{f\,(vf=20)}$ | 1.22 | 1.39 | 1.16 | 1.33 | 1,17 | 1.27 |
| $F_{f\,(vf=25)} / F_{f\,(vf=15)}$ | 1.40 | 1.48 | 1.73 | 1.56 | 1.36 | 1.80 |

### 3.3 Influence of rake angle (valid for SD1, z = 16, $\gamma$ = 10°; SD2, z = 16, $\gamma$ = 20°; Figure 11, Figure 12)
### 3.3 Utjecaj prsnog kuta (vrijedi za SD1, z = 16, $\gamma$ = 10°; SD2, z = 16, $\gamma$ = 20°; sl. 11. i 12.)

Saw discs SD1 and SD2 have the same number of teeth but different rake angle. The graph in Figure 11 shows the values for up sawing and in Figure 12 for down sawing.

When comparing the results obtained during up and down sawing separately, there are small differences for various revolutions and feed speeds within limits from 1.36 N to 5.75 N (Figure 11) and from 0.24 N to 5.43 N (Figure 12). The results show that the rake angle has some influence but, as there are many influencing factors such as wood structure, grains orientation, position of samples in tree trunk, it is very difficult to make explicit conclusions.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The aim of this experiment was to confirm that feed force practically depends on feed speed proportionally, but the ratio of feed forces is not the same as the ratio of feed speeds.

The line slope depends on the type of sawing; it is higher for up (conventional) sawing than for down (climb) cutting.

The absolute value of feed force is higher for up sawing compared to down cutting. (On the other hand, the force perpendicular to feed force is higher for down cutting.)

The results of this experiment did not confirm the hypothesis that higher rake angle generally leads to the decrease of the feed force.

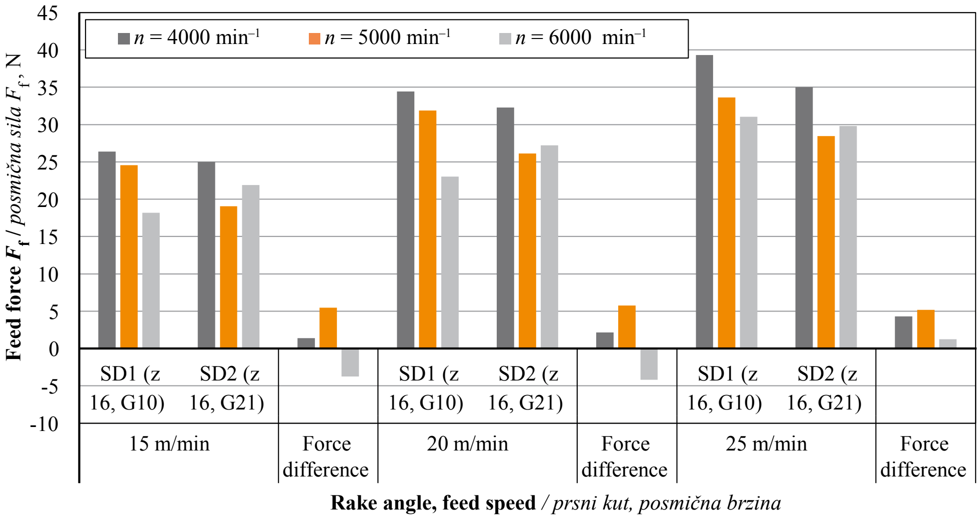



**Figure 11** Influence of feed speed $v_f$, revolutions $n$, rake angle γ on feed force $F_f$ (SD1 γ = 10°; SD2 γ = 20°; z = 16); up sawing
**Slika 11.** Utjecaj posmične brzine $v_f$, frekvencije vrtnje $n$ i prsnog kuta γ na posmičnu silu $F_f$ (SD1 γ = 10°; SD2 γ = 20°; $z$ = 16); protusmjerno piljenje

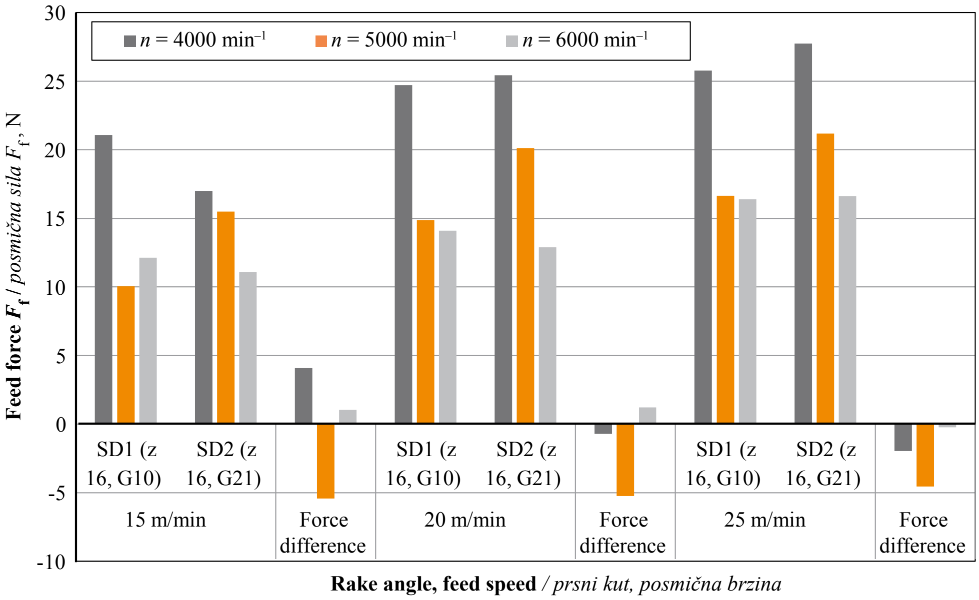



**Figure 12** Influence of feed speed $v_f$, revolutions $n$, rake angle γ on feed force $F_f$ (SD1 γ = 10°; SD2 γ = 20°; $z$ = 16); down sawing
**Slika 12.** Utjecaj posmične brzine $v_f$, frekvencije vrtnje $n$ i prsnog kuta γ na posmičnu silu $F_f$ (SD1 γ = 10°; SD2 γ = 20°; $z$ = 16); istosmjerno piljenje

### Acknowledgements – Zahvala

A part of this article was created within the framework of Grand Project No. APVV-20-0403 "FMA analysis of potential signals suitable for adaptive control of nesting strategies for milling wood-based agglomerates" as a result of the author's research activity with the support of the agency APVV-SR.

## 5 REFERENCES
## 5. LITERATURA

1. Aguilera, A., 2011: Cutting energy and surface roughness in medium density fibreboard rip sawing. European Journal of Wood and Wood Products, 69: 1-18. https://doi.org/10.1007/s00107-009-0396-z
2. Aquilera, A., 2011: Surface roughness evaluation in medium density fibreboard rip sawing. European Journal of Wood and Wood Products, 69: 489-493. https://doi.org/10.1007/s00107-010-0481-3
3. Aguilera, A.; Martin, P., 2001: Machining qualification of solid wood of *Fagus silvatica* L. and *Picea excelsa* L.: Cutting forces, power requirements and surface roughness. European Journal of Wood and Wood Products, 59 (6): 483-488. https://doi.org/10.1007/s001070100243
4. Beer, P., 2002: Obróbka skrawaniem obwodowym drewna nowo opracowanymi narzędziami (In English: Wood peeling with new elaborated tools). Roczniki Akademii Rolniczej w Poznaniu, Rozprawy Naukowe, Zeszyt 330. Wydawnictwo Akademii Rolniczej im. Augusta Cieszkowskiego w Poznaniu, Poznań.
5. Beljo Lučić, R.; Goglia, V.; Pervan, S.; Đukić, I.; Risović, S., 2004: The influence of wood moisture content on the process of circular rip-sawing. Part I: Power require-

ments and specific cutting forces. Wood Research, 49 (1): 41-49.
6. Dange, A. R.; Thakare, S. K.; Rao, I. B., 2011: Cutting energy and force as required for Pigeon pea stems. Journal of Agricultural Technology, 7 (6): 1485-1493.
7. Fekiac, J.; Svoren, J.; Gaborik, J.; Nemec, M., 2022: Reducing the Energy Consumption of Circular Saws in the Cutting Process of Plywood. Coatings, 12: 55. https://doi.org/10.3390/coatings12010055
8. Fischer, R., 1979: Orientierende Versuche zur Reibung beim Schneiden von Holz. Holztechnologie, 20 (2): 111-115.
9. Goli, G.; Porankiewicz, B., 2014: Cutting forces by Oak and Douglas Fir machining. Maderas. Ciencia y tecnología, 16 (2): 199-216. https://doi.org/10.4067/S0718-221X2014005000016
10. Hlaskova, L.; Kopecky, Z.; Solař, A.; Patočka, Z., 2019: Cutting test as a source of fracture toughness and shear yield strength for axial-perpendicular model of wood cutting. Wood and Fiber Science, 51 (1): 1-11
11. Hlaskova, L.; Orlowski, K. A.; Kopecky, Z.; Jedinak, M., 2015: Sawing processes as a Way of Determoning Fracture Toughness and shear Yield stresses of Wood. BioResources, 10 (3): 5351-5394.
12. Ioras, H.; Nicholls, T.; Perkins, M. C.; Münz, V.; Larmann, A., 2002: A Review for Cutting Forces and Stresses in Circular Saws. Holz als Roh- und Werkstoff, 60: 55-59.
13. Kivimaa, E., 1950: The cutting force in woodworking. Report No. 18. The State Institute of Technical Research, Helsinki, Finland, pp. 103.
14. Klement, I.; Réh, R.; Detvaj, J., 2011: Základné charakteristiky lesných drevín – spracovanie drevnej suroviny v odvetví spracovania dreva (In English: The basic characteristics of forest wood species – the processing of wood raw in wood industry). Národné lesnícke centrum, pp. 82.
15. Kopecky, Z.; Hlaskova, L.; Orlowski, K., 2014: An innovative approach to prediction energetic effects of woo cutting process with circular-saw blades. Wood Research, 59 (5): 827-834.
16. Kopecky, Z.; Rousek, Z., 2006: Determination of cutting forces in cutting wood Materials. Drvna industrija, 56 (4):171-176.
17. Nasir, V.; Cool, J., 2018: A review on wood machining: characterization, optimization, and monitoring of the sawing process. Wood Material Science and Engineering, 15 (1): 1-16. https ://doi.org/10.1080/17480272.2018.1465465
18. Naylor, A.; Hackney, P.; Perera, N.; Clahr, E., 2012: A predictive model for the cutting force in wood machining developed using mechanical properties. BioResources, 7 (3): 2883-2894.
19. Orlowski, K. A.; Ochrymiuk, T.; Atkins, A.; Chuchala, D., 2013: Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Science and Technology, 47 (5): 949-963.
20. Orlowski, K. A.; Ochrymiuk, T.; Sandak, J.; Sandak, A., 2017: Estimation of fracture toughness and shear yield stress of orthotropic materials in cutting with rotating tools. Engineering Fracture Mechanics, 178: 433-444.
21. Palubicki, B., 2021: Cutting Forces in Peripheral Up-Milling of Particleboard. Materials, 14, 2208. https://doi.org/10.3390/ma14092208
22. Piispanen, V., 1948: Theory of Formation of Metal Chips. Journal of Applied Physics, 19: 876. https://doi.org/10.1063/1.1697893
23. Porankiewicz, B.; Axelsson, B.; Gronlund, A.; Marklund, B., 2011: Main and normal cutting forces by machining wood of Pinus sylvestris. BioResources, 6 (4): 3687-3713.
24. Porankiewicz, B.; Goli, G., 2014: Cutting forces by Oak and Douglas Fil machining. Ciencia y tecnología, 16 (2): 199-216. https://doi.10.4067/S0718-221X2014005000016
25. Teng, Y.; Ding, J.; Wang, B.; Guo, X.; Cao, P., 2014: Cutting forces and Chip Morphology in Medium Density Fiberboard Orthogonal Cutting. BioResources, 9 (4): 5845-5857.
26. ***EN 847-1, 2017: Tools for Woodworking – Safety Requirements. Part 1: Milling Tools, Circular Saw Blades.
27. ***RANC 207 AMW – technical data.

**Corresponding address:**

**ĽUBOMÍR JAVOREK**
Technical University in Zvolen, T. G. Masaryka 24, 960 00 Zvolen, SLOVAKIA, e-mail: lubomir.javorek@tuzvo.sk

Ladislav Dzurenda, Michal Dudiak[1]

# Colour Change of Steamed Alder Wood Caused by UV Radiation

# Promjena boje parenog drva johe uzrokovana UV zračenjem

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 23. 2. 2022.
Accepted – prihvaćeno: 30. 3. 2022.
UDK: 535.349; 551.521.17; 630*84
https://doi.org/10.5552/drvind.2022.0019



**ABSTRACT** • *Alder wood (<u>Alnus glutinosa</u> L.) was steamed with a saturated steam-air mixture at a temperature of t = 95 °C, or saturated steam at t = 115 °C and t = 135 °C to obtain a pale brown colour, a light red-brown colour and a dark brown-grey colour. Subsequently, samples of unsteamed and steamed alder wood were irradiated with a UV lamp in a Xenotest Q-SUN Xe-3-HS after drying in order to test the colour stability of steamed alder wood. The colour change of the wood surface was evaluated by means of measured values on the coordinates of the colour space CIE L*a*b*. The results show that the surface of unsteamed alder wood as well as steamed alder wood with a steam-air mixture at t = 95 °C and saturated steam at t = 115 °C darkened and browned due to photochemical reactions caused by UV radiation. The opposite tendency was recorded at the surface of alder wood steamed with saturated steam with a temperature of t = 135 °C, where the deep dark-brown-grey colour lightened to a brown-reddish colour shade under the influence of UV radiation. The analysis of the changes in the coordinates of the colour space CIE L*a*b* shows that the greater the darkening and browning of the alder wood by steaming, the smaller the changes in the values of ΔL*, Δa*, Δb* of the steamed alder wood caused by UV radiation. The positive effect of steaming on UV resistance is evidenced by the decrease in the overall colour difference ΔE*. While the value of the total colour difference of unsteamed alder wood caused by UV radiation is ΔE* = 10.9, it decreased to ΔE* = 8.7 for alder wood steamed with steam-air mixture at t = 95 °C, which is a decrease of 20.2 %; for alder wood steamed at t = 115 °C it decreased to ΔE* = 6.5, which is a decrease of 40.3 %; and for alder wood steamed with saturated water steam with the temperature t = 135 °C it decreased to ΔE* = 5.7, which is a decrease of 47.7 %.*

**KEYWORDS***: alder wood; colour difference; steaming; saturated water steam; UV radiation*

**SAŽETAK** • *Za potrebe ispitivanja drvo johe (<u>Alnus glutinosa</u> L.) pareno je smjesom zasićene pare i zraka na 95 °C odnosno zasićenom parom na 115 i 135 °C kako bi se dobila blijedosmeđa, svijetla crvenosmeđa i tamna smeđosiva boja. Nepareni i pareni uzorci drva johe nakon sušenja su ozračeni UV lampom u uređaju Xenotest Q-SUN Xe-3-HS kako bi se ispitala stabilnost boje parenog drva. Promjena boje površine drva procijenjena je uz pomoć vrijednosti izmjerenih u koordinatnom sustavu boja CIE L*a*b*. Rezultati su pokazali da je površina neparenog drva johe i drva johe parenog smjesom pare i zraka na 95 °C te drva parenog zasićenom parom na 115 °C zbog fotokemijskih reakcija uzrokovanih UV zračenjem potamnjela i posmeđila. Suprotna je promjena zabilježena na površini drva johe parenoga zasićenom parom na 135 °C, na kojemu je tamna smeđosiva boja pod utjecajem UV zračenja posvijetlila i poprimila smeđocrvenkasti ton. Analiza promjena u koordinatnom sustavu boja CIE L*a*b**

[1] Authors are researchers at Technical University in Zvolen, Faculty of Wood Sciences and Technology, Zvolen, Slovakia.

*pokazuje da UV zračenje uzrokuje niže vrijednosti ΔL*, Δa*, Δb* parenog drva johe što je tamnjenje i smeđenje drva johe zbog parenja jače. Pozitivan učinak parenja na otpornost prema UV zračenju vidljiv je po smanjenju ukupne promjene boje ΔE*. Tako je vrijednost ukupne promjene boje neparenog drva johe nakon UV zračenja parenjem smjesom pare i zraka na 95 °C smanjena s ΔE* = 10,9 na ΔE* = 8,7 (smanjenje od 20,2 %), parenjem zasićenom parom na 115 °C smanjena je na ΔE* = 6,5 (smanjenje od 40,3 %), a parenjem zasićenom parom na 135 °C zabilježeno je smanjenje od ΔE* = 5,7 (smanjenje je iznosilo 47,7 %).*

**KLJUČNE RIJEČI:** *drvo johe; promjena boje; parenje; zasićena vodena para; UV zračenje*

## 1 INTRODUCTION
## 1. UVOD

The colour of wood is a basic physical-optical property, which belongs to the group of macroscopic features on the basis of which the wood of individual woody plants differs visually. The colour of the wood is formed by chromophores, i.e., functional groups of the type: >C=O, -CH=CH-CH=CH-, -CH=CH-, aromatic nuclei found in the chemical components of wood (lignin and extractives such as dyes, tannins, resins, and others), which absorb some components of the electromagnetic radiation of daylight and thus create the colour of the wood surface perceived by human eye.

The colour of wood changes in thermal processes such as: wood drying, wood steaming, thermo-wood production technologies. The wood darkens and depending on the wood, acquires new shades of colour. Depending on the steaming conditions, beech wood acquires a pale pink to red-brown colour shade (Deliiski, 1991; Bekhta and Niemz, 2003; Molnar and Tolvaj, 2004; Cividini *et al.,* 2007; González *et al.,* 2009; Todaro *et al.,* 2012; Dzurenda, 2014; Milić *et al.,* 2015; Barcík *et al.,* 2015; Baranski *et al.,* 2017; Dzurenda and Dudiak, 2021; Dzurenda, 2022). Oak wood, as reported by Tolvaj and Molnar (2006), Todaro *et al.* (2012), Dzurenda (2018a), acquires colour shades from a pale brown-yellow colour to a dark brown-grey colour. The light white-yellow colour of maple wood in the process of steaming wood with saturated water steam acquires shades of pale pink-brown to brown-red colour (Dzurenda, 2018b; Dudiak, 2021).

Alder wood in the process of steaming with saturated steam-air mixture or saturated water steam is heated and changes its physical, mechanical and chemical properties. The action of heat initiates chemical reactions in wet wood, such as: extraction of water-soluble substances, degradation of polysaccharides, cleavage of free radicals and phenolic hydroxyl groups in lignin, resulting in the formation of new chromophoric groups that cause a change in the colour of the wood. These facts are used for full-volume modification of wood colour into non-traditional colour shades of alder wood. Depending on the length of the steaming time and the temperature of the steaming medium, the alder wood acquires a pale brown colour, through shades of a soft red-brown colour to a dark brown-grey colour (Dudiak and Dzurenda, 2021).

The colour on the surface of native wood, as well as thermally modified wood, changes due to long-term exposure to sunlight. The surface of the wood darkens and mostly yellows and browns. This fact is also referred to in the professional literature as natural aging (Hon, 2001; Reinprecht, 2008; Baar and Gryc, 2012).

Solar radiation falling on the wood surface is partly absorbed by and partly reflected from the surface. The absorbed spectrum of infrared electromagnetic radiation is converted into heat and the photon flux of ultraviolet and part of visible radiation of wavelengths λ = 200 – 400 nm is the source of initiation of photolytic and photooxidation reactions with lignin, polysaccharides and accessory substances of wood. Of the chemical components of wood, lignin is the most subject to photodegradation, which captures 80 – 85 % of UV radiation, while carbohydrates absorb 5 – 20 % and 2 % of the accessory substance (Gandelová, 2009). These reactions cleave the lignin macromolecule with the simultaneous formation of phenolic hydroperoxides, free radicals, carbonyl and carboxyl groups and to a lesser extent depolymerize polysaccharides to polysaccharides with a lower degree of polymerization to form carbonyl, carboxyl groups and gaseous products ($CO$, $CO_2$, $H_2$). Although photodegradation of natural wood is a phenomenon that has been widely studied by Hon (2001), Müller *et al.* (2003), Pandey (2005), Persze and Tolvaj (2012), Baar and Gryc (2012), Denes and Lang (2013), Zivkovic *et al.* (2013), Geffert *et al.* 2017; Geffertová *et al.* (2018), less attention has been paid to the issue of photodegradation and colour stability of steamed wood.

The aim of the work is to investigate the stability of the pale brown colour of alder wood obtained by the process of steaming with a saturated steam-air mixture with a temperature of $t$ = 95 °C, or gentle red-brown and deep dark-brown-grey colour of alder wood steamed with saturated steam at temperatures $t$ = 115 °C and $t$ = 135 °C through a simulated aging process - UV radiation in Xenotest Q-SUN Xe-3-HS. The colour fastness of the wood is evaluated through changes in the coordinates $L^*$, $a^*$, $b^*$ of the colour space CIE $L^*a^*b^*$ and the total colour difference $\Delta E^*$.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

Wet wood of alder blanks with dimensions 40 mm × 100 mm × 800 mm and moisture content $w$ = (58.3±3.2) % was thermally treated with a saturated steam-air mixture at a temperature of $t$ = 95 °C, or saturated water steam at $t$ = 115 °C and $t$ = 135 °C for $\tau$ = 9 h in order to obtain a pale brown colour, a light red-brown colour and a dark-brown-grey colour in a pressure autoclave: APDZ 240 in Sundermann s.r.o. Banská **Štiavnica** (Slovakia). The alder wood steaming mode is shown in Figure 1. The temperatures of the saturated steam-air mixture and saturated water steam in individual steaming modes are given in Table 1. The values of temperatures $t_{max}$ and $t_{min}$ are the temperatures for controlling the regulation of the supply of saturated water steam to the pressure autoclave for the implementation of the technological process. The temperature $t_4$ is a parameter of the saturated water steam pressure in the autoclave to which the pressure in the autoclave must be reduced before the pressure device can be opened safely.

Steamed and unsteamed alder wood blanks were dried with a low temperature drying mode of Dzurenda (2021) to moisture content of $w$ = 10 ± 0.5 %. Samples measuring 100 mm × 50 mm × 15 mm (L × R × T) were made to test the colour fastness of the wood. Colour measurement was performed on a radial surface machined by planing.

The colour coordinates of alder wood samples in the colour space CIE $L^*a^*b^*$, before irradiation are given in Table 2.

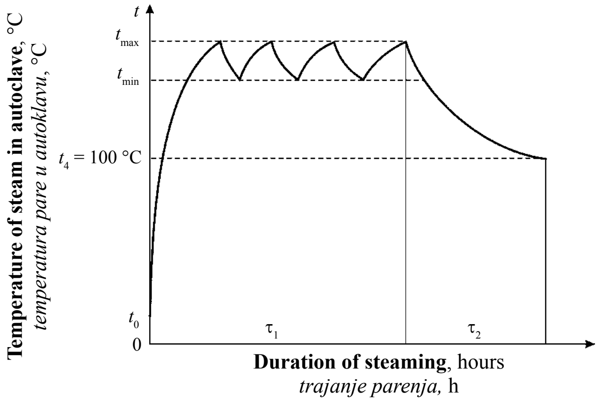



**Figure 1** Mode of colour modification of alder wood with a saturated steam-air mixture or saturated water steam
**Slika 1.** Način promjene boje drva johe smjesom zasićene pare i zraka ili zasićenom vodenom parom

In the Q-SUN Xe-3-HS xenon test chamber (Q-Lab Corporation, USA), alder wood samples were irradiated for $\tau$ = 298 h. During the exposure, the colour of the irradiated surface was measured regularly at $\tau$ = 24 h intervals. The mode for simulating outdoor conditions was used, i.e., the wood was exposed to radiation outdoors but was protected from rain (Table 3). The samples placed in the Xenotest chamber were regularly and systematically relocated according to the recommended scheme to ensure the same irradiation intensity and temperature (Kúdela and Kubovský, 2016).

According to ASTM G 155, the radiation intensity was set to 0.35 W/m$^2$ at a radiation wavelength $\lambda$ = 340 nm. This is the average annual radiation intensity

**Table 1** Mode of colour modification of alder wood with a saturated steam-air mixture or saturated water steam
**Tablica 1.** Način promjene boje drva johe smjesom zasićene pare i zraka ili zasićenom vodenom parom

| **Mode** / *Način* | **Temperature in autoclave, °C** *Temperatura u autoklavu,* °C | | | **Time of operation, h** *Trajanje postupka,* h | | |
|---|---|---|---|---|---|---|
| | $t_{min}$ | $t_{max}$ | $t_4$ | $\tau_1$ – phase I | $\tau_2$ – phase II | Total time *Ukupno vrijeme* |
| $t_I$ = 95 ± 2.5 °C | 92.5 | 97.5 | - | 8.0 | 1.0 | 9.0 |
| $t_{II}$ = 115 ± 2.5 °C | 112.5 | 117.5 | 100 | 7.5 | 1.5 | 9.0 |
| $t_{III}$ = 135 ± 2.5 °C | 132.5 | 137.5 | 100 | 7.5 | 1.5 | 9.0 |

**Table 2** Coordinate values of colour space CIE L*a*b* of unsteamed and steamed alder wood
**Tablica 2.** Vrijednosti koordinata u CIE *L*a*b** sustavu boje neparenoga i parenog drva johe

| **Labeling of samples** *Označivanje uzoraka* | **Colour coordinates in colour space CIE *L*a*b**** *Koordinate boje u CIE L*a*b*sustavu boje* | | |
|---|---|---|---|
| | *L** | *a** | *b** |
| unsteamed alder wood *npareno drvo johe* | 79.0 ± 2.3 | 9.6 ± 1.6 | 22.5 ± 1.2 |
| steamed at $t$ = 95 ± 2.5 °C *pareno na t = 95 ± 2,5 °C* | 70.4 ± 1.8 | 11.8 ± 1.4 | 21.5 ± 1.1 |
| steamed at $t$ = 115 ± 2.5 °C *pareno na t = 115 ± 2,5 °C* | 62.9 ± 1.3 | 12.1 ± 0.9 | 19.1 ± 1.1 |
| steamed at $t$ = 135 ± 2.5 °C *pareno na t = 135 ± 2,5 °C* | 51.9 ± 1.4 | 12.3 ± 0.8 | 16.5 ± 0.9 |

**Table 3** Aging parameters set according to ASTM G 155
**Tablica 3.** Parametri starenja postavljeni prema ASTM G 155

| **Step** *Korak* | **Mode** *Način rada* | **Radiation intensity, W/m²** *Intenzitet zračenja, W/m²* | **Black panel temperature,** °C *Temperatura crne ploče,* °C | **Air temperature,** °C *Temperatura zraka,* °C | **Relative humidity, %** *Relativna vlažnost zraka,* % | **Time, min** *Vrijeme,* min |
|---|---|---|---|---|---|---|
| 1 | Radiation *zračenje* | 0.35 | 63 | 48 | 30 | 102 |
| 2 | No radiation *bez zračenja* | – | – | 38 | – | 18 |

in the temperate zone. The temperature, checked on the black panel, signals the maximum surface temperature. The specified air temperature is intended to accelerate changes in the wood surface. The colour was measured on each body in ten places, which means that 30 measurements were always made for one set of bodies.

The colour of the irradiated unsteamed and steamed alder wood surface samples, in the colour space CIE $L^*a^*b^*$, was measured with a Colour Reader CR-10 colorimeter (Konica Minolta, Japan). A D65 light source was used and the diameter of the optical scanning aperture was 8 mm. The total colour difference $\Delta E^*$ of the colour change of the surface of alder wood samples due to UV radiation is determined according to the following equation (ISO 11 664-4):

$$\Delta E^* = \sqrt{\left(L^*_{298} - L^*_0\right)^2 + \left(a^*_{298} - a^*_0\right)^2 + \left(b^*_{298} - b^*_0\right)^2} \qquad (1)$$

Where: $L_0^*$, $a_0^*$, $b_0^*$ - values at the surface colour coordinates of the dried milled unsteamed and steamed alder wood prior to exposure,

$L_{298}^*$, $a_{298}^*$, $b_{298}^*$ - values on the surface colour coordinates of the dried milled unsteamed and steamed alder wood during UV exposure.

The measured values on the brightness coordinate $L^*$ and the chromatic coordinates red colour $a^*$ and yellow colour $b^*$, as well as the calculated values of the total colour differences $\Delta E^*$ during the observed exposure periods were statistically and graphically evaluated using EXCEL and STATISTICA 12 programmes (V12.0 SP2, USA).

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The colour of unsteamed and steamed alder wood before and after UV irradiation in the Q-SUN Xe-3-HS test chamber is shown in Figure 2. According to the visual evaluation of the colour of alder wood before and after UV radiation, it can be stated that while the light white-grey colour with a touch of yellow colour of unsteamed alder wood darkens under UV radiation and acquires a brown-reddish colour, the light red-brown colour of alder wood steamed with the steam-air mixture at the temperature $t$ = 95 °C slightly darkened under the influence of UV radiation and took on a pale yellow-brown colour. The dark brown-grey colour of alder wood steamed with saturated water steam with a temperature of $t$ = 135 °C under the influence of UV radiation brightened to a paler brown-grey shade.

The course of colour changes of unsteamed and steamed alder wood in the colour space CIE $L^*a^*b^*$ under the influence of UV radiation in Xenotest Q-SUN Xe-3-HS for 298 h at the individual coordinates $L^*$, $a^*$, $b^*$ is shown in Figure 3 to 5.

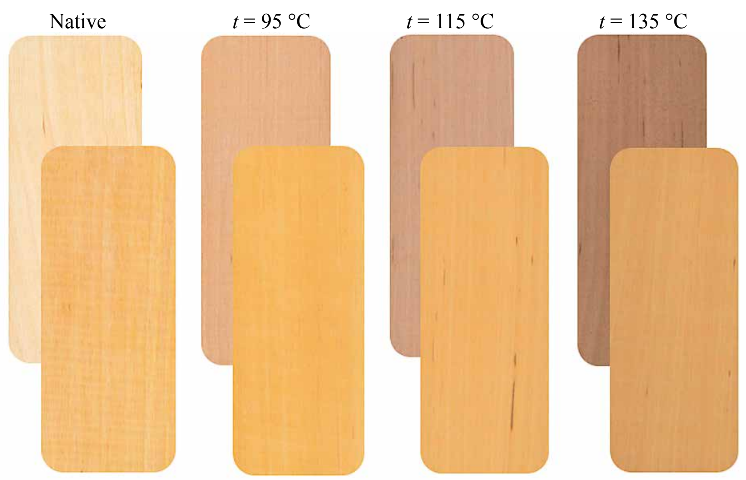



**Figure 2** View of alder wood before and after UV irradiation: native; steamed at $t$ = 95 °C; steamed at $t$ = 115 °C and steamed at $t$ = 135 °C
**Slika 2.** Izgled drva johe prije i nakon UV zračenja: prirodno drvo, pareno na 95 °C, pareno na 115 °C i pareno na 135 °C

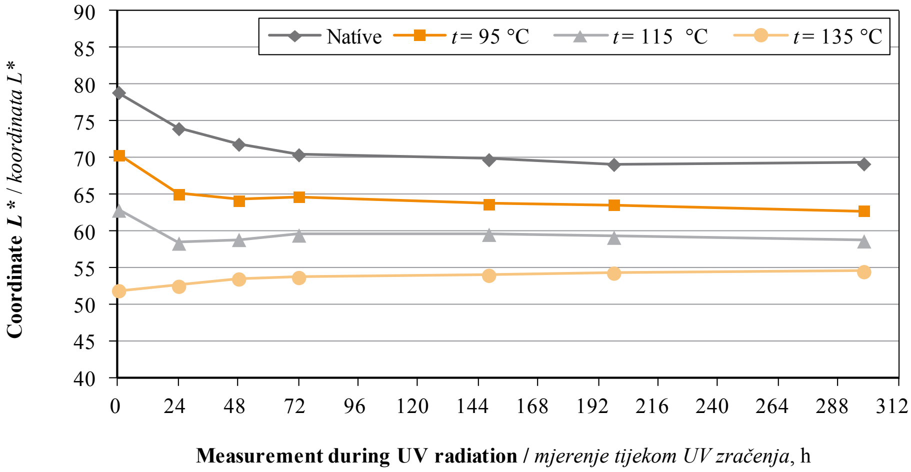



**Figure 3** The course of changes of values on brightness coordinate *L** in the process of UV irradiation of samples of unsteamed and steamed alder wood
**Slika 3.** Promjena vrijednosti koordinate svjetline *L** tijekom UV zračenja uzoraka neparenoga i parenog drva johe

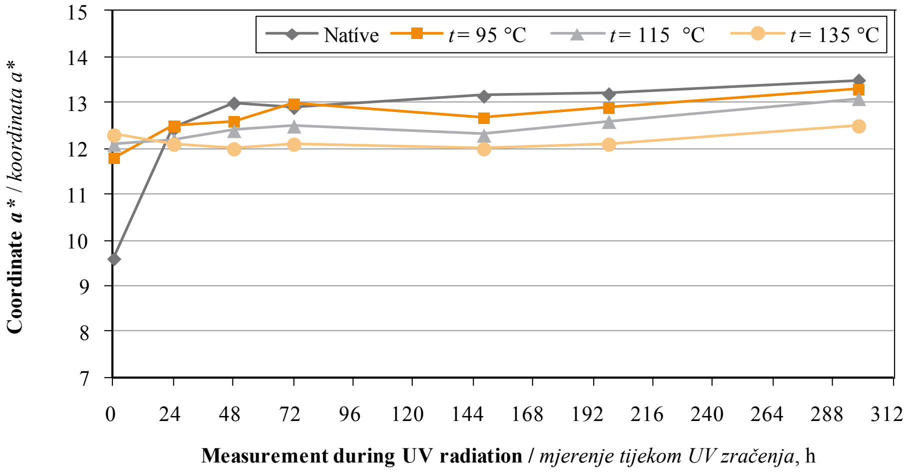



**Figure 4** The course of changes of values on the coordinate of red colour *a** in the process of UV irradiation of samples of unsteamed and steamed alder wood
**Slika 4.** Promjena vrijednosti koordinate crvenog tona *a** tijekom UV zračenja uzoraka neparenoga i parenog drva johe

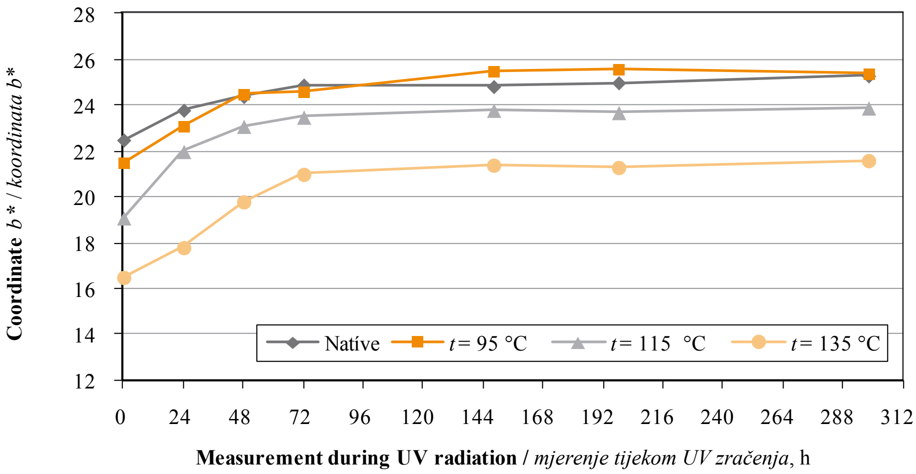



**Figure 5** The course of changes of values on the coordinate of yellow colour *b** in the process of UV irradiation of samples of unsteamed and steamed alder wood
**Slika 5.** Promjena vrijednosti koordinate žutog tona *b** tijekom UV zračenja uzoraka neparenoga i parenog drva johe

From the course of changes in individual colour spaces CIE $L^*a^*b^*$ during the action of UV radiation on the wood surface in Xenotest Q-SUN Xe-3-HS, it follows that the colour change of the surface of irradiated wood is not uniform. Significant changes in the colour of the wood occur in the first 72 h of UV radiation. Similar findings were recorded when testing the resistance of maple wood to UV radiation present in the oven (Dzurenda *et al.* 2022).

The degree of darkening and browning of unsteamed and steamed alder wood induced by UV radiation during 298 h of irradiation in the colour space CIE $L^*a^*b^*$ is shown by the shifts on the individual coordinates.

Unsteamed alder wood darkened due to photochemical reactions induced by UV radiation and a decrease in the brightness coordinate was recorded from $L_0^* = 79.0$ to $L_{298}^* = 69.2$ i.e. by the value $\Delta L^* = -9.7$; it turned brown by the increase of points on the chromatic coordinate of red colour from $a_0^* = 9.6$ to $a_{298}^* = 13.5$, i.e. $\Delta a^* = +3.9$; and on the yellow coordinate from $b_0^* = 22.5$ to $b_{298}^* = 25.3$, i.e. the value of $\Delta b^* = +3.8$. The above findings on the darkening of native - thermally untreated alder wood are in accordance with the opinions of experts dealing with changes in the properties of native wood of individual trees due to solar radiation, or UV radiation (Hon, 2001; Müller *et al.*, 2003; Pandey, 2005; Chang *et al.*, 2010; Baar and Gryc, 2011; Kúdela and Kubovský, 2016; Geffertová *et al.*, 2018; Dzurenda *et al.*, 2020).

Compared to unsteamed alder wood, steamed alder wood shows smaller changes on the coordinates of brightness $L^*$ and red $a^*$, except for changes on the chromatic coordinate of yellow $b^*$. Numerically, this is documented by changes in the individual coordinates of the colour space CIE $L^*a^*b^*$. While the darkness of thermally treated alder wood increased with steam-air mixture at the temperature $t = 95$ °C due to UV radiation, the values decreased from $L_0^* = 70.4$ to $L_{298}^* = 62.8$ i.e. $\Delta L^* = -7.6$ and the darkness of alder wood treated with saturated water steam at $t = 115$ °C decreased due to UV radiation by decreasing values by $\Delta L^* = -4.2$, so the brightness of steamed alder wood with saturated water steam at the temperature $t = 135$ °C increased from $L_0^* = 51.2$ to $L_{298}^* = 54.3$, i.e. the value of $\Delta L^* = +2.6$.

At the chromatic coordinates of the colour space CIE $L^*a^*b^*$, the colour changes of alder wood steamed with a steam-air mixture with the temperature $t = 95$ °C increased on the coordinate red colour $a^*$ from the value $a_0^* = 11.8$ to $a_{298}^* = 13.1$ i.e., $\Delta a^* = +1.5$, and on the yellow coordinate $b^*$ from the value $b_0^* = 21.5$ on $b_{298}^* = 25.4$ i.e., $\Delta b^* = +3.9$. The soft red-brown colour of steamed alder wood formed by steaming with saturated water steam with the temperature $t = 115$ °C due to UV radiation changed to a pale yellow-brown colour with an increase in values on the coordinate red colour by values $\Delta a^* = +1.0$ and on the coordinate yellow by values $\Delta b^* = +4.8$. Changes in the values of alder wood steamed with saturated water steam with the temperature $t = 135$ °C under the influence of UV radiation recorded an increase in the values on the red coordinate from $a_0^* = 12.3$ to $a_{298}^* = 12.5$, i.e., $\Delta a^* = +0.2$ and on the yellow coordinate from the value $L_0^* = 16.5$ to $L_{298}^* = 21.6$, i.e. by the value $\Delta b^* = +5.1$.

Figure 6 shows, in the form of a bar graph, the magnitudes of changes $\Delta L^*$, $\Delta a^*$, $\Delta b^*$ on the coordinates of the colour space CIE $L^*a^*b^*$ of the analysed alder wood samples induced by UV radiation during 298 h in Xenotest Q-SUN Xe-3-HS.

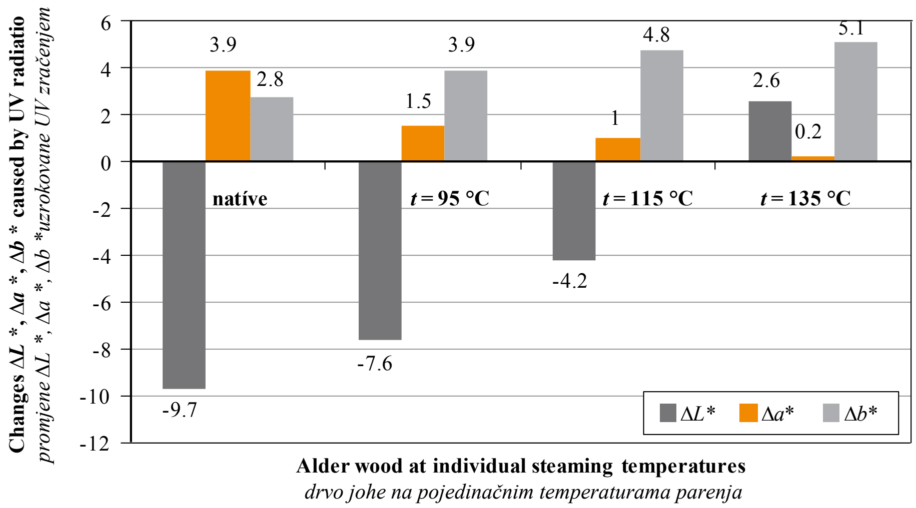



**Figure 6** Values of total changes $\Delta L^*$, $\Delta a^*$, $\Delta b^*$ generated by the action of UV radiation on the surface of alder wood in Xenotest Q-SUN Xe-3-HS during 298 h irradiation
**Slika 6.** Vrijednosti ukupnih promjena $\Delta L^*$, $\Delta a^*$, $\Delta b^*$ nastalih djelovanjem UV zračenja na površinu drva johe u Xenotest Q-SUN Xe-3-HS tijekom 298 sati zračenja

From the presented values of changes Δ*L**, Δ*a**, Δ*b** caused by UV radiation, it follows that the values on the brightness coordinates *L** and red *a** in the colour space CIE *L*a*b** of unsteamed wood are higher than those of steamed alder. The values of Δ*L**, Δ*a**, decrease with increasing darkness acquired by the steaming process at higher steaming temperatures. Changes in the chromaticity coordinate of the yellow colour *b** have the opposite tendency, and they increase due to UV radiation.

The darker surface of steamed alder wood due to the decomposition of functional groups of alder wood chromophores performed in the steaming process absorbs to a lesser extent electromagnetic radiation spectra with a wavelength of red 630 – 750 nm and yellow 570 – 590 nm (Dudiak and Dzurenda, 2021), but is also more resistant to photochemical reactions of functional groups of chromophores in alder wood under UV radiation causing a change in the colour of the wood surface.

The fact that steamed wood, unlike unsteamed wood, is more resistant to UV radiation is also pointed out in the works of Dzurenda (2020), Varga *et al.* (2021) and Dzurenda *et al.* (2022).

In the work of Dzurenda (2019) "*The effect of UV radiation in Xenotest 450 on the color of steamed beech wood during the process of simulated aging"*, presented in the journal Annals of Warsaw University of Life Sciences - SGGW, it is stated that the lightening of the surface colour of steamed beech wood occurs after its irradiation with xenon lamp emitting UV radiation with a wavelength of 340 nm and intensity (42±2) W/m$^2$ for 7 days. The lightening of the red-brown colour of steamed beech wood is shown by the increase of the values on the brightness coordinate from $L_0^*$ = 62.6 to the value of $L_{168}^*$ = 69.3, i.e. Δ*L** = + 6.7; the increase of the value on the chromatic coordinate of the yellow colour from $b_0^*$ = 17.1 to the value of $b_{168}^*$ = 29.4, i.e. Δ*b** = +12.3, and with a slight change in the value from $a_0^*$ = 10.9 to $a_{168}^*$ = 10.8, i.e. Δ*a** = - 0.1.

The influence of UV radiation on steamed agate wood is discussed in Varga *et al.* (2021) who state that while the surface of steamed agate wood darkened slightly at a steaming temperature *t* = 100 °C, the surface of agate wood brightened at a steaming temperature *t* = 120 °C.

The positive effect of the steaming process on the decomposition of functional groups of maple wood chromophores manifested by darkening and browning of maple wood on the elimination of photochemical reactions caused by UV radiation is also described by Dzurenda *et al.* (2022). They point to the fact that the greater the darkening of the maple wood in the steaming process, the smaller the colour changes on the surface of the irradiated steamed maple wood by UV radiation. This is shown by the decrease of the total colour difference from the value Δ*E** = 18.5 for unsteamed maple wood to Δ*E** = 7.2 for steamed maple wood with saturated water steam at the temperature *t* = 135 °C, and with the results of FTIR analyses.

A complex view of the colour change of unsteamed and steamed alder wood induced by UV radiation in the form of the total colour difference Δ*E** is shown in Figure 7.

The lower values of the total colour difference Δ*E** of steamed alder wood caused by UV radiation are a quantitative expression of the degree of resistance of steamed wood to the absorption of UV wavelengths, which cause photochemical reactions causing changes in the colour of the wood. While the colour change of unsteamed alder wood irradiated during 298 h reaches the value Δ*E** = 10.9, alder wood steamed with a steam-air mixture at a temperature of *t* = 95 °C reaches the value Δ*E** = 8.7, which is a decrease of 20.2 %; for

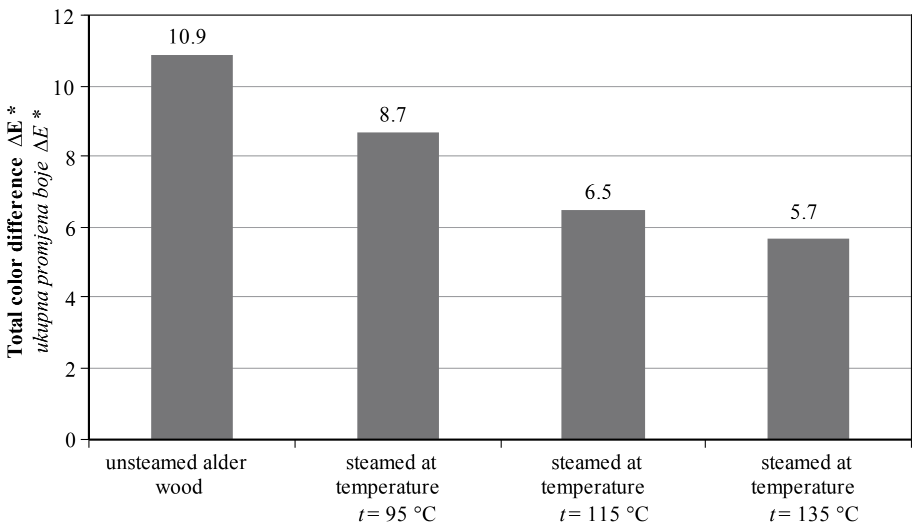



**Figure 7** Influence of UV radiation on values of total colour difference Δ*E** of unsteamed and steamed alder wood
**Slika 7.** Utjecaj UV zračenja na vrijednosti ukupne promjene boje Δ*E** neparenoga i parenog drva johe

alder wood steamed with saturated water steam at the temperature $t$ = 115 °C it reaches the value $\Delta E^*$ = 6.5, which is a decrease of 40.3 %; and for alder wood steamed with saturated steam at the temperature $t$ = 135 °C the value of the total colour difference is $\Delta E^*$ = 5.7, which is a decrease of 47.7 %.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The paper presents the results of surface colour changes of unsteamed and steamed alder wood due to UV radiation in Xenotest Q-SUN Xe-3-HS during 298 h irradiation of the surface of alder wood samples.

The surface colour of unsteamed alder wood changes colour under the influence of UV radiation more than the surface of steamed alder wood.

The measured changes in the values at the coordinates of the colour space CIE $L^*a^*b^*$ caused by UV radiation on unsteamed alder wood are: $\Delta L^*$ = - 9.7; $\Delta a^*$ = + 3.9; $\Delta b^*$ = + 2.8.

Changes in the values of the colour space CIE $L^*a^*b^*$ coordinates caused by UV radiation in steamed alder wood at a steaming temperature $t$ = 95 °C are: $\Delta L^*$ = - 7.6; $\Delta a^*$ = + 1.5; $\Delta b^*$ = + 3.9; at steam temperature $t$ = 115 °C: $\Delta L^*$ = - 4.2; $\Delta a^*$ = + 1.0; $\Delta b^*$ = + 4.8; and at a steam temperature $t$ = 135 °C: $\Delta L^*$ = + 2.6; $\Delta a^*$ = + 0.2; $\Delta b^*$ = + 5.1.

The rate of colour change of alder wood induced by UV radiation expressed in terms of the total colour difference $\Delta E^*$ shows that while the value of the total colour difference of unsteamed alder wood $\Delta E^*$ = 10.9, for alder wood steamed at a temperature $t$ = 95 °C $\Delta E^*$ = 8.7, for alder wood steamed with saturated water steam with a temperature of $t$ = 115 °C $\Delta E^*$ = 6.5 and for alder wood steamed with saturated water steam with a temperature of $t$ = 135 °C $\Delta E^*$ = 5.7, which is a decrease of 47.7 % compared to unsteamed alder wood

The decrease in changes in values $\Delta L^*$, $\Delta a^*$, $\Delta b^*$ and the overall colour difference $\Delta E^*$ of steamed alder wood caused by UV radiation indicate a positive effect of alder wood steaming - decomposition of functional groups of chromophores shown by darkening and browning of wood and increasing resistance of steamed alder wood to photochemical reactions of functional groups of alder wood chromophores with UV radiation shown by colour changes.

**Acknowledgements** – Zahvala

This experimental research was prepared within the grant project: APVV-17-0456 "Termická modifikácia dreva sýtou vodnou parou za účelom cielenej a stabilnej zmeny farby drevnej hmoty" as the result of the author's work and the considerable assistance of the APVV agency.

## 5 REFERENCES
## 5. LITERATURA

1. Baar, J.; Gryc, V., 2011: The analysis of tropical wood discoloration caused by simulated sunlight. Europen Journal of Wood and Wood Products, 70 (1-3): 263-269.
2. Barański, J.; Klement, I.; Vilkovská, T.; Konopka, A., 2017: High temperature drying process of beech wood (*Fagus sylvatica L.*) with different zones of sapwood and red false heartwood. BioResources, 12 (1): 1861-1870. https://doi.org/10.15376/biores.12.1.1861-1870
3. Barcík, Š.; Gašparík, M.; Razumov, E. Y., 2015: Effect of thermal modification on the colour changes of oak wood. Wood Research, 60 (3): 385-396.
4. Bekhta, P.; Niemz, P., 2003: Effect of high temperature on the change in colour, dimensional stability and mechanical properties of spruce wood. Holzforschung, 57 (5): 539-546. https://doi.org/10.1515/HF.2003.080
5. Chang, T. C.; Chang, H. T.; Chang, S. T., 2010: Influences of extractives on the photodegradation of wood. Polymer Degradation and Stability, 95: 516-521. https://doi.org/10.1016/j.polymdegradstab.2009.12.024
6. Cividini, R.; Travan, L.; Allegretti, O., 2007: White beech: A tricky problem in drying process. In: Proceeding of International Scientific Conference on Hardwood processing. Quebec City, Canada.
7. Deliiski, N., 1991: Metod dlja ocenki stepeni oblagoraživania bukovych pilomaterialov vo vremja ich proparki. Current problems and perspectives of beech lumber drying. ES-VŠLD, Zvolen, Slovakia, pp. 37-44.
8. Denes, L.; Lang, E. M., 2013: Photodegradation of heat-treated hardwood veneers. Journal of Photochemistry and Photobiology B: Biology, 118: 9-15. https://doi.org/10.1016/j.jphotobiol.2012.09.017
9. Dudiak, M., 2021: Modification of maple wood colour during the process of thermal treatment with saturated water steam. Acta Facultatis Xylologiae Zvolen, 63: 25-34. https://doi.org/10.17423/afx.2021.63.1.03
10. Dudiak, M.; Dzurenda, L., 2021: Changes in the physical and chemical properties of alder wood in the process of thermal treatment with saturated water steam. Coatings, 11: 898. https://doi.org/10.3390/coatings11080898
11. Dzurenda, L., 2014: Colouring of Beech Wood during Thermal Treatment using Saturated Water Steams. Acta Facultatis Xylologiae Zvolen, 56 (1): 13-22.
12. Dzurenda, L., 2018a: The shades of color of *Quercus robur L.* wood obtained through the processes of thermal treatment with saturated water vapor. BioResources, 13 (1): 1525-1533.
13. Dzurenda, L., 2018b: Hues of *Acer platanoides L.* resulting from processes of thermal treatment with saturated steam. Drewno, 61 (202): 165-176. https://doi.org/10.12841/wood.1644-3985.241.11
14. Dzurenda, L., 2019: The effect of UV radiation in Xenotest 450 on the colour of steamed beech wood during the process of simulated ageing. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology, 106, 114-119.
15. Dzurenda, L.; Dudiak, M.; Banski, A., 2020: Influence of UV radiation on color stability of natural and thermally treated maple wood with saturated water steam. Innovation in Woodworking Industry and Engineering Design, 1: 36-41.
16. Dzurenda, L., 2021: Mode for hot air drying of alder blanks that retain the color acquired during the steaming

process. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology, 114: 86-92.
17. Dzurenda, L.; Dudiak, M., 2021: Cross-correlation of color and acidity of wet beech wood in the process of thermal treatment with saturated steam. Wood Research, 66 (1): 105-116. https://doi.org/10.37763/wr.1336-4561/66.1.105116
18. Dzurenda, L.; Dudiak, M.; Výbohová E., 2022: Influence of UV Radiation on the Color Change of the Surface of Steamed Maple Wood with Saturated Water Steam. Polymers, 14 (1): 217. https://doi.org/10.3390/polym14010217
19. Gandelová, L.; Horáček.; P.; Šlezingerová, J., 2009: The science of wood. Mendel University of Agriculture and Forestry in Brno, pp. 176.
20. Geffert, A.; Vybohová, E.; Geffertová, J. 2017: Characterization of the changes of colour and some wood components on the surface of steamed beech wood. Acta Facultatis Xylologiae Zvolen, 59 (1): 49-57. https://doi.org/10.17423/afx.2017.59.1.05
21. Geffertová, J.; Geffert, A.; Vybohová, E., 2018: The effect of UV irradiation on the colour change of the spruce wood. Acta Facultatis Xylologiae Zvolen, 60 (1): 41-50. https://doi.org/10.17423/afx.2018.60.1.05
22. Gonzalez-Pena, M. M; Hale, M. D. C., 2009: Colour in thermally modified wood of beech, Norway spruce and Scots pine. Part 1: Colour evolution and colour changes. Holzforschung, 63 (4): 385-393. https://doi.org/10.1515/HF.2009.078
23. Hon D. S. N., 2001: Weathering and photochemistry in wood. In: Wood and cellulosic chemistry, 2nd ed. New York: Marcel Dekker, pp. 513-546.
24. Kúdela, J.; Kubovský, I., 2016: Accelerated-ageing-induced photo-degradation of beech wood surface treated with selected coating materials. Acta Facultatis Xylologiae Zvolen, 2. 27-36. https://doi.org/10.17423/afx.2016.58.2.03
25. Milić, G.; Todorović, N.; Popadić, R., 2015: Influence of steaming on drying quality and colour of beech timber. Glasnik Šumarskog fakulteta, pp. 83-96. https://doi.org/10.2298/GSF1512083M
26. Molnar, S.; Tolvaj, L., 2002: Colour homogenisation of different wood species by steaming. In: Interaction of Wood with Various Forms of Energy, Technical University in Zvolen, Zvolen, Slovakia, pp. 119-122.
27. Müller, U.; Rätzsch, M.; Schwanninger, M.; Steiner, M.; Zöbl, H., 2003: Yellowing and IR-changes of spruce wood as result of UV-irradiation. Journal of Photochemistry and Photobiology B: Biology, (69): 97-105. https://doi.org/10.1016/S1011-1344(02)00412-8
28. Pandey, K. K., 2005: Study of the effect of photo-irradiation on the surface chemistry of wood. Polymer Degradation and Stability, 90: 9-20. https://doi.org/10.1016/j.polymdegradstab.2005.02.009
29. Persze, L.; Tolvaj, L. Photodegradation of wood at elevated temperature: Colour change. Journal of Photochemistry and Photobiology B: Biology, 108: 44-47. https://doi.org/10.1016/j.jphotobiol.2011.12.008
30. Reinprecht, L., 2008: Wood protection. Technical University in Zvolen, pp. 450.
31. Todaro, L.; Zuccaro, L.; Marra, M.; Basso, B.; Scopa, A., 2012: Steaming effects on selected wood properties of Turkey oak by spectral analysis. Wood Science Technology, 46 (1-3): 89-100.
32. Tolvaj, L.; Molnár, S., 2006: Colour homogenisation of hardwood species by steaming. Acta Silvatica et Lignaria Hungarica, 105-112.
33. Varga, D.; Tolvaj, L.; Molnar, Z.; Pasztory, Z., 2020: Leaching efect of water on photodegraded hardwood species monitored by IR spectroscopy. Wood Science and Technology, 54: 1407-1421. https://doi.org/10.1007/s00226-020-01204-2
34. Zivkovic, V.; Arnold, M.; Radmanovic, K.; Richter, K.; Turkulin, H., 2014: Spectral sensitivity in the photodegradation of fir wood (*Abies alba Mill.*) surfaces: colour changes in natural weathering. Wood Science and Technology, 48: 239-252.

**Corresponding address:**

**LADISLAV DZURENDA, MICHAL DUDIAK**

Faculty of Wood Sciences and Technology, Technical University in Zvolen, 960 01 Zvolen, SLOVAKIA,
e-mail: dzurenda@tuzvo.sk; xdudiak@tuzvo.sk

Jerzy Majka[1], Maciej Sydor[2], Jakub Prentki[3], Magdalena Zborowska[4]

# Initial Desorption of Reaction Beech Wood

# Inicijalna desorpcija reakcijskog drva bukovine

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 24. 2. 2022.
Accepted – prihvaćeno: 8. 4. 2022.
UDK: 674.031.632.2; 674.04
https://doi.org/10.5552/drvind.2022.0021



**ABSTRACT** • *The research aimed to obtain empirical data for modeling the initial desorption in reaction wood from the cross-section of the green beech (Fagus sylvatica L.) log. Firstly, we analyzed the chemical composition, macro and microscopic structure of tension and opposite wood tissue. Then, the Equilibrium Moisture Content (EMC) was measured by the Dynamic Vapor Sorption method during the initial desorption. The used air parameters were specific for the mild drying schedule of green beech timber (t = 20, 35, and 50 °C, Relative Humidity (RH) ranging from 95 to 0 %). Relationships between the EMC of reaction wood and drying parameters were modeled using the Response Surface Method (RSM). The tests revealed: different hygroscopic properties of tension and opposite wood, the dependence of EMC value on temperature, and differences between EMC values for initial (first) and second desorption. Moreover, it was confirmed that, during initial desorption, the EMCs of reaction wood are significantly higher than reference EMC data. The differences in the EMC value are up to 0.14 kg/kg (for air with RH above 90 %). The presented polynomial model of the initial desorption of reaction beech wood can improve drying schedules for beech sawn timber with a high amount of reaction tissue.*

**KEYWORDS***: equilibrium moisture content; kiln-drying; response surface methodology; Fagus sylvatica L.; sorption isotherms; reaction wood; tension wood; opposite wood*

**SAŽETAK** • *Cilj je ovog istraživanja modeliranje inicijalne desorpcije poprečnog presjeka reakcijskog drva bukve (Fagus sylvatica L.) na temelju empirijskih podatka. Najprije je istražen kemijski sastav drva te je analizirana makroskopska i mikroskopska struktura reakcijskoga i opozitnog drva. Zatim je metodom dinamičke sorpcije pare izmjeren ravnotežni sadržaj vode tijekom inicijalne desorpcije. Drvo je podvrgnuto blagom režimu sušenja (t = 20, 35 i 50 °C, te relativnoj vlažnosti zraka u rasponu od 95 do 0 %). Odnosi između ravnotežnog sadržaja vode reakcijskog drva i parametara sušenja modelirani su metodom odzivne površine. Ispitivanjem su dobivena različita higroskopska svojstva reakcijskoga i normalnog drva, ovisnost ravnotežnog sadržaja vode o temperaturi sušenja te razlike između vrijednosti ravnotežnog sadržaja vode pri inicijalnoj (prvoj) i drugoj desorpciji. Također je potvrđeno da je ravnotežni sadržaj vode reakcijskog drva tijekom inicijalne desorpcije znatno veći od referentnih vrijednosti ravnotežnog sadržaja vode normalnog drva. Razlike u vrijednostima ravnotežnog sadržaja vode kreću se do 0,14 kg/kg (pri relativnoj vlažnosti zraka većoj od 90 %). Prikazani poli-*

[1] Author is researcher at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Wood Science and Thermal Techniques, Poznań, Poland. https://orcid.org/0000-0002-6713-8077
[2] Author is researcher at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Woodworking and Fundamentals of Machine Design, Poznań, Poland. https://orcid.org/000-0003-0076-3190
[3] Author is researcher at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Wood Science and Thermal Techniques, Poznań, Poland.
[4] Author is researcher at Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Chemical Wood Technology, Poznań, Poland. https://orcid.org/0000-0003-3028-5134

*nomski model inicijalne desorpcije reakcijskog drva bukve može poslužiti za poboljšanje režima sušenja bukove piljene građe s velikim udjelom reakcijskog drva.*

**KLJUČNE RIJEČI:** *ravnotežni sadržaj vode; sušenje u sušioniku; metoda odzivne površine; Fagus sylvatica L.; sorpcijske izoterme; reakcijsko drvo; tenzijsko drvo; opozitno drvo*

## 1 INTRODUCTION
## 1. UVOD

The equilibrium moisture content (EMC) depends on the wood species and the variation of its structure (Kollmann, 1936; Skaar, 1988). The most frequently used method of measuring the EMC is the procedure based on the Hailwood-Horrobin sorption model (1946). Simpson fitted this model to empirical EMC data provided by the "Forest Products Laboratory" (Simpson, 1973). These data are averaged values for desorption and adsorption and, by this simplification, have limited suitability for modeling a wood water relation in kiln-drying of timber (Wengert, 1976; Langrish and Walker, 1993; Salin, 2011; Glass *et al.*, 2014; Redman *et al.*, 2016). The EMC data is most often applied to relate air parameters and expected drying intensity during kiln-drying of timber. The relation is given by drying schedules for different wood species, usually using a Drying Gradient (DG) concept, which is defined as a ratio of the actual moisture content of timber and EMC values appropriate for drying parameters (Brunner, 1987). The EMC based on the initial desorption isotherms can significantly improve the accuracy of the drying gradient determination (Majka and Olek, 2013). Most published data on the hygroscopic properties of wood are the result of research on the phenomenon of the second desorption, occurring after drying the wood (Spalt, 1958; Weichert, 1963; Böhner, 1996; Ahmet *et al.*, 1999; Jannot *et al.*, 2006; Popper *et al.*, 2009; Popper and Niemz, 2009; Jankowska, 2018). However, the second desorption process differs from the initial (first) desorption. The second desorption of beech wood gives lower EMC than the initial desorption, especially in higher air relative humidity (RH) (Barkas, 1936; Skaar, 1988).

The beech can form up to 25 % of the reaction tissue (Kúdela and Čunderlík, 2012). Reaction wood is a structure of wood tissue that takes the form of compression wood and tension wood. This type of reaction wood induces the desired displacement of the stem towards a more favorable position by tensile force (Côté, 1964; Scurfield G., 1973; Tulik and Jura-Morawiec, 2011; Felten and Sundberg, 2013; Groover, 2016). An indicator of reaction wood in a log is a pith eccentricity. The eccentricity is caused by wider annual increases on the tension side. On a microscopic scale, the reaction wood of beech is characterized by lower content of vessels with smaller diameter and length and significantly elongated tracheids with thickened walls. Changes in the $S_2$ and $S_3$ cell layers are a typical feature of the microscopic structure of reaction wood in beech (Côté *et al.*, 1969; Wardrop and Davies, 1964). However, the essential factor influencing wood drying may be a non-lignified gelatinous layer (G-layer). Bound water diffusion in the G-layer causes an almost always higher in tension wood than in normal wood, despite similar density values. The fibers of reaction wood have a greater longitudinal shrinkage than normal wood (Scurfield and Wardrop, 1962; Tarmian *et al.*, 2012). The reaction tissue of beech wood dries more slowly and has a higher final moisture content after drying than the opposite and normal tissue (Klement *et al.*, 2019, 2020). The typical drying behavior of beech reaction wood is more evident during drying above Fiber Saturation Point (FSP) when liquid-free water is removed (Tarmian *et al.*, 2009). Beech timber produced from logs with a high content of tension tissue shows a greater risk of developing defects during kiln-drying (Tarmian and Perré, 2009). As far as the authors are aware, there are no published data describing the relationship between the EMC of reaction wood and air parameters in the range corresponding to the kiln-drying schedules of sawn beech timber. Therefore, the aim of the research was to provide empirical EMC data and use them to develop a model of the initial desorption in the reaction beech wood.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Material
### 2.1. Materijal

The research material was primarily sawn in February 2020 from a green 105-year-old beech (*Fagus sylvatica* L.) log with a distinctly eccentric pith. The test tree was selected from a fresh mixed deciduous forest located in the Forest District Rzepedź (in the Subcarpathian province of south-east Poland, close to the border with Slovakia). The 100 mm disc (at breast height) was cut and uncontrolled changes in moisture content were prevented. Two sections of the research material were selected for laboratory tests, located on the cross-section of the trunk on opposite sides of the eccentric pith. The strip axis ran along the line marked

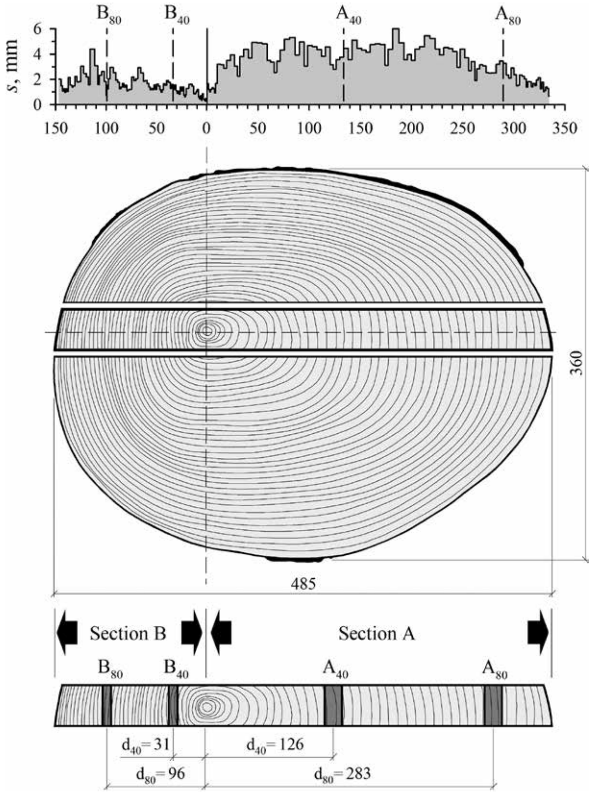



**Figure 1** Disc cross-section with location of test samples and measurement results of width of annual rings (s) along trunk diameter (A – tension wood, B – opposite wood, d – distance from pith; all dimensions in millimeters)
**Slika 1.** Poprečni presjek diska s položajem ispitnih uzoraka i rezultatima mjerenja širine goda (*s*) duž promjera debla (A – reakcijsko drvo, B – opozitno drvo, d – udaljenost od srčike; sve su dimenzije iskazane u milimetrima)

by the highest difference in the width of annual increments (Figure 1). The test samples were prepared from two sections of the strip: A – tension wood and B – opposite wood. Both sections included 40 ± 1 and 80 ± 1 annual rings (the sections inner and outer cross-section zones).

## 2.2 Macro and microstructure
## 2.2. Makroskopska i mikroskopska struktura drva

The annual tree ring widths (*s*) were measured with an optical device with a computer image analyzer (BEPD-19, BIOtronik, Warsaw, Poland) with a measuring range of 470 mm and measurement uncertainty of 0.01 mm. According to the measurement results, the difference of about three times was found in the average width of annual rings between sections A and B. The average values of the annual ring widths in Section A (tension wood) are 1.40 ± 0.71 mm, and in Section B (opposite wood) 3.19 ± 1.30 mm. The width measurements of all annual rings are presented in Figure 1.

The microtome samples were photographed using a biological microscope with a computer image analyzer (B3 Professional, Motic, Hong-Kong, China).

## 2.3 Chemical composition of wood
## 2.3. Kemijski sastav drva

Firstly, each prepared wood sample was ground (0.5-1.0 mm fraction, mass ca. 50 g) in a Fritsch Pulverisette 15 laboratory mill (Fritsch GmbH, Germany). The cellulose content was measured according to Seifert's method using a mixture of acetylacetone, 1.4-dioxane, and hydrochloric acid to isolate cellulose (Browning, 1966). According to the chlorite method, the holocellulose content was measured using $NaClO_2$ as a reagent (Browning, 1966). The pentosane content was measured using hydrochloric acid and phloroglucinol according to the TAPPI standard method T 223 cm-01. Acid-insoluble lignin was assessed according to T 222 om-06 standard TAPPI method. The content of extractives soluble in alcohol was measured according to TAPPI standard method T 204 cm-97. All tests were carried out with three replicates for each option of samples.

## 2.4 Sorption experiments
## 2.4. Eksperimenti sorpcije

Sorption experiments were carried out using a dynamic vapor sorption (DVS) apparatus (DVS Advantage 2 from Surface Measurement Systems, London, UK). The appropriate air RH levels were achieved by mixing dry and saturated air streams. The EMC values for air humidity (RH) in the range of 95 to 0 % were measured. It was assumed that the hygroscopic equilibrium was obtained at a given RH value when the mass change was less than 0.0005 % $min^{-1}$ for at least 60 min. The procedure was repeated for each RH step and the EMC values were calculated. Samples for measuring the EMC variability of the tension and opposition wood were produced in two stages. In the first stage, four fragments were separated from Section A (tension wood) and B (opposite wood), each containing three annual rings, i.e., 39-41 and 79-81. Then, the prepared fragments with dimensions of 20 mm in the tangential (T) and longitudinal (L) direction were divided in the radial plane into final samples with a thickness of ca. 1 mm. The initial mass of each investigated sample was 12 ± 0.5 mg.

The sorption experiments consisted of air parameters, specific for mild kiln-drying beech sawn wood schledue, which saves the natural color. Three air temperature values were used, i.e. 20, 35, and 50 °C and five relative air humidity (RH) values, i.e. 95, 80, 65, 50 and 35 %. After the parameters were measured during the initial desorption, an additional sorption experiment was performed, consisting of water adsorption and second desorption. An additional experiment compared the EMC values with the available literature data. The list of all variants of air parameters in the sorption experiments is presented in Table 1.

**Table 1** Summary of air parameters in sorption experiments
**Tablica 1.** Pregled parametara zraka pri istraživanju sorpcije

| **Sorption phase** *Faza sorpcije* | *t*, °C | | |
|---|---|---|---|
| | 20 | 35 | 50 |
| Initial desorption / *inicijalna desorpcija* | **95, 80, 65, 50, 35**, *20, 5, 0* | **95, 80, 65, 50, 35** | **95, 80, 65, 50, 35** |
| Adsorption / *adsorpcija* | *0, 5, 20, 35, 50, 65, 80, 95* | – | – |
| Second desorption / *druga desorpcija* | *95, 80, 65, 50, 35, 20, 5, 0* | – | – |

bold – RH values (%) included during experiments for initial desorption, italic – RH values (%) included during additional experiments / *podebljana slova – vrijednosti relativne vlažnosti zraka (%) tijekom istraživanja početne desorpcije, kurziv – vrijednosti relativne vlažnosti zraka (%) tijekom dodatnih istraživanja*

## 2.5 Sorption modeling
## 2.5. Modeliranje sorpcije

The Response Surface Methodology (RMS) was used to generalize the relationship between the EMC for initial desorption and the characteristic air parameters of the kiln-drying schedule (Box and Draper, 2007). The levels of independent variables used for the sorption experiments are presented in Table 2.

According to the following formulas, the independent variables were coded: $x_1 = (t - 35)/15$, and $x_2 = (\mathrm{RH} - 65)/15$. The third-order polynomial equation approximated the results:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1x_2 + \\ + b_6x_1^3 + b_7x_2^3 + b_8x_1^2x_2 + b_9x_1x_2^2 \quad (1)$$

Where *y* is the predicted response (i.e. equilibrium moisture content for initial desorption), $b_0$-$b_9$ are estimated coefficients. The fitting algorithm (Levenberg-Marquardt approach) was used to estimate the coefficients of the response models of the initial desorption. Due to the possible linear dependence of the variables, backward stepwise regression was applied to exclude statistically insignificant model parameters (Chatterjee and Hadi, 2013). The experimental input data for RSM modeling are presented in Table 3. The results are supplemented by EMC values calculated from the Hailwood-Horrobin equation as applied by Simpson (1973) to the data from the Forest Products Laboratory (Wood Handbook, 2010).

## 2.6 Statistical analysis
## 2.6. Statistička analiza

The experimental data were analyzed using STATISTICA 13.3 software (TIBCO Software Inc., Palo Alto, CA, USA). A one-factor analysis of variance (ANOVA) was performed to determine significant differences between the components of the average content

**Table 2** Levels of independent variables used for sorption experiments
**Tablica 2.** Razine neovisnih varijabli primijenjenih u istraživanju sorpcije

| **Independent variables** *Nezavisne varijable* | **Actual levels** *Stvarne vrijednosti* |
|---|---|
| Dry-bulb temperature *t* ($x_1$), °C / *temperatura suhog termometra t* ($x_1$), °C | 20 (-1); 35 (0); 50 (1) |
| Relative humidity RH ($x_2$), % / *relativna vlažnost zraka RVZ* ($x_2$), % | 95 (-2); 80 (-1); 65 (0); 50 (1); 35 (2) |

**Table 3** Experimental (input) data for modeling initial desorption
**Tablica 3.** Eksperimentalni (ulazni) podatci za modeliranje početne desorpcije

| ***t*, °C** | **RH, %** | **EMC, kg/kg** | | | | |
|---|---|---|---|---|---|---|
| **($x_1$)** | **($x_2$)** | **$A_{40}$** | **$A_{80}$** | **$B_{40}$** | **$B_{80}$** | **FPL data** |
| 20 (–1) | 95 (–2) | 0.377 | 0.401 | 0.379 | 0.301 | 0.260 |
| 20 (–1) | 80 (–1) | 0.208 | 0.219 | 0.212 | 0.219 | 0.184 |
| 20 (–1) | 65 (–0) | 0.152 | 0.158 | 0.154 | 0.155 | 0.148 |
| 20 (–1) | 50 (–1) | 0.114 | 0.118 | 0.116 | 0.117 | 0.127 |
| 20 (–1) | 35 (–2) | 0.082 | 0.085 | 0.084 | 0.084 | 0.112 |
| 35 (–0) | 95 (–2) | 0.373 | 0.388 | 0.365 | 0.280 | 0.248 |
| 35 (–0) | 80 (–1) | 0.188 | 0.199 | 0.193 | 0.197 | 0.173 |
| 35 (–0) | 65 (–0) | 0.136 | 0.143 | 0.138 | 0.140 | 0.138 |
| 35 (–0) | 50 (–1) | 0.102 | 0.107 | 0.103 | 0.105 | 0.118 |
| 35 (–0) | 35 (–2) | 0.073 | 0.078 | 0.074 | 0.077 | 0.104 |
| 50 (–1) | 95 (–2) | 0.249 | 0.251 | 0.228 | 0.204 | 0.235 |
| 50 (–1) | 80 (–1) | 0.157 | 0.156 | 0.154 | 0.155 | 0.161 |
| 50 (–1) | 65 (–0) | 0.123 | 0.123 | 0.122 | 0.123 | 0.128 |
| 50 (–1) | 50 (–1) | 0.097 | 0.097 | 0.094 | 0.096 | 0.109 |
| 50 (–1) | 35 (–2) | 0.073 | 0.072 | 0.072 | 0.072 | 0.096 |

A, B – tension and opposite wood, respectively; 40, 80 – number of annual rings / *A – reakcijsko drvo, B – opozitno drvo; 40, 80 – broj godova* of the chemical composition of the examined wood samples. The post-hoc HSD Tukey's test was used to test the significance of differences between the average values of the mean. Significance was established at $p<0.05$.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Microscopic structure
### 3.1. Mikroskopska struktura drva

The microstructure of the investigated samples is shown in Figure 2. Microscopic images presented the features typical of tension and opposite wood. Gelatin fibers are mainly seen in the tension wood section (signed $A_{40}$ and $A_{80}$). The lower content of gelatin fibers in the near pith zone ($A_{40}$) of the tension wood than the content of gelatin fibers in the outer zone ($A_{80}$) confirms previous information that asymmetric growth is not always accompanied by the formation of reactive tissue across the width of the tree trunk (Kojs *et al.*, 2012). The microscopic images of the test samples taken from the pith area and peripheral parts of section B (marked $B_{40}$ and $B_{80}$) are characteristic of the structure of the opposite wood. The anatomical elements have smaller lumen with a thicker wall than normal wood.

### 3.2 Chemical composition
### 3.2. Kemijski sastav drva

Table 4 summarizes the experimentally measured chemical composition of the tension wood (Section A) and opposition wood (Section B). These data were compared with the literature data for normal wood. The cellulose content is similar, but substances soluble in alcohol content in the tension wood samples (Section A) and opposition wood are ca. twice as

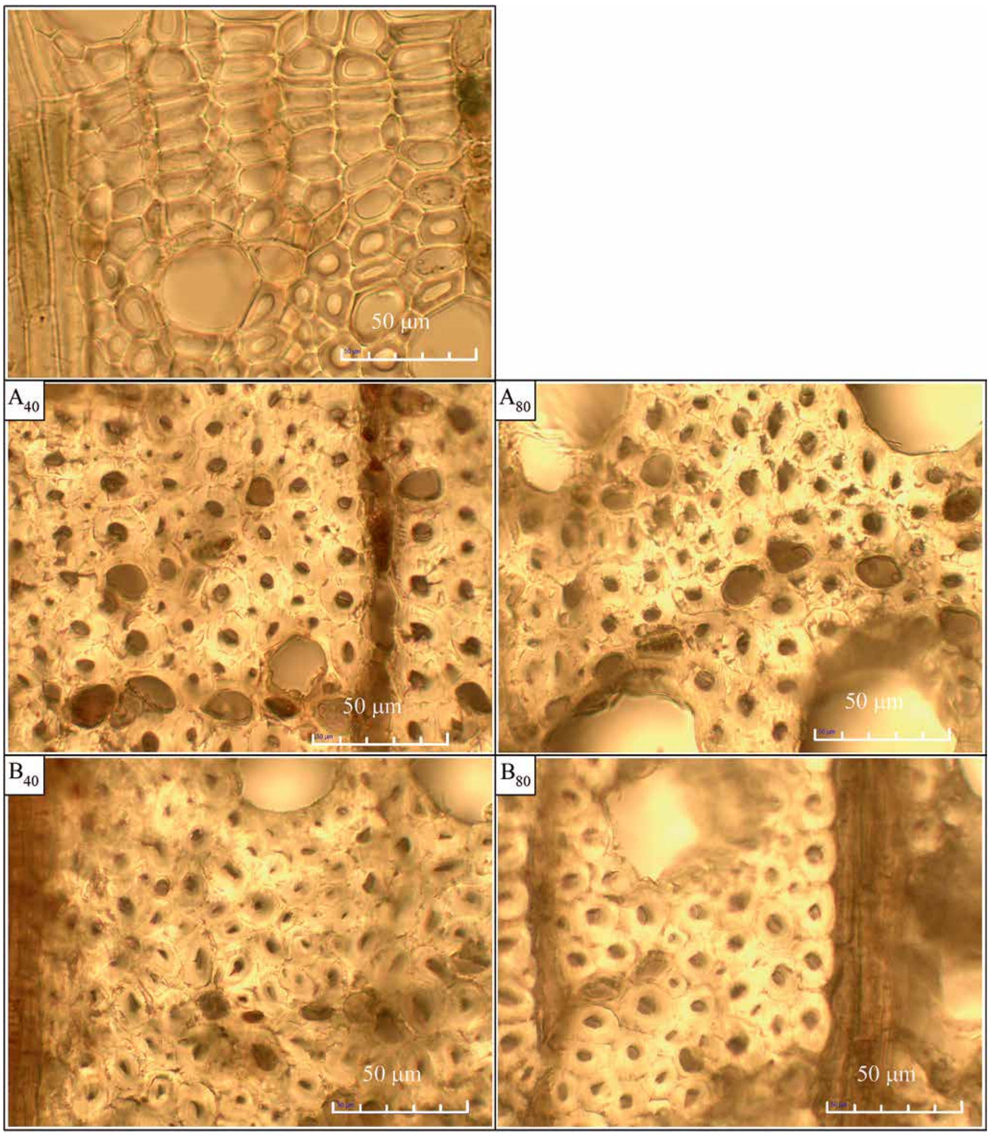



**Figure 2** Microstructure of normal (above) and reaction (bottom) green beech (*Fagus sylvatica* L.) at a 40-fold magnification: A, B – tension and opposite wood, respectively, 40, 80 – number of annual rings
**Slika 2.** Mikrostruktura normalne (gore) i reakcijske (dolje) bukovine (*Fagus sylvatica* L.) pri povećanju 40 puta: A – reakcijsko drvo, B – opozitno drvo, 40, 80 – broj godova

**Table 4** Chemical composition of beech reaction and normal wood (*Fagus sylvatica* L.)
**Tablica 4.** Kemijski sastav reakcijskoga i normalnog drva bukve (*Fagus sylvatica* L.)

| **Wood samples** *Uzorak drva* | **Annual ring** *God* | **Symbol** *Oznaka* | **Holocellulose** *Holoceluloza* | **Cellulose** *Celuloza* | **Pentosans** *Pentozani* | **Lignin** *Lignin* | **Substances soluble in alcohol**[1] *Tvari topljive u alkoholu*[1] |
|---|---|---|---|---|---|---|---|
| Section A (Tension wood) *sekcija A (reakcijsko drvo)* | 40±1 | $A_{40}$ | 78.9 $^{b}$± 1.4 | 40.0 $^{a}$± 0.1 | 29.3 $^{b}$± 1.4 | 22.8 $^{a}$± 0.3 | 1.56$^{a}$± 0.21 |
| | 80±1 | $A_{80}$ | 68.7 $^{a}$± 1.7 | 40.2 $^{a}$± 0.4 | 28.6 $^{ab}$± 0.6 | 22.8 $^{a}$± 0.3 | 1.54$^{a}$± 0.09 |
| Section B (Opposite wood) *sekcija B (opozitno drvo)* | 40±1 | $B_{40}$ | 76.7 $^{b}$± 4.2 | 42.6 $^{b}$± 0.4 | 27.2 $^{a}$± 0.1 | 21.2 $^{a}$± 1.4 | 1.87 $^{ab}$± 0.07 |
| | 80±1 | $B_{80}$ | 70.0$^{a}$± 0.6 | 39.7 $^{a}$± 0.3 | 28.8 $^{ab}$± 0.2 | 22.9 $^{a}$± 0.8 | 1.93$^{b}$± 0.12 |
| Literature data for normal wood[2] *vrijednosti iz literature*[2] | | | – | 49.1 | 22.0 | 23.8 | 0.8 |

[1] substances soluble in alcohol – benzene 1:1, [2]according to (Fengel and Wegener, 1983), mean value ($n$ = 3) ± standard deviation; identical superscripts (a, b, c) denote no significant difference ($p$ < 0.05) between mean values according to post-hoc Tukey's HSD test
*[1] tvari topljive u otopini alkohola i benzena u omjeru 1:1, [2]prema: Fengel i Wegener, 1983., srednja vrijednost (n = 3) ± standardna devijacija; identični superskripti (a, b, c) označavaju da prema post-hoc Tukeyjevu HSD testu nema značajne razlike (p < 0,05) među srednjim vrijednostima*

high as in normal wood. Moreover, a higher hemicellulose content (in Sections A and B) was found than in normal beech wood.

### 3.3 Sorption isotherms
### 3.3. Sorpcijske izoterme

The sorption isotherms of the reaction beech wood for the successive phases: initial (first) desorption, adsorption, and second desorption at a temperature of 20 °C are shown in Figure 3.

For all tension and opposite wood samples, it was confirmed as follows: the sorption hysteresis occurrence (desorption differs from the subsequent adsorption), differences between the first (initial) and second water desorption, the EMC value in the initial desorption was higher than the EMC value in the second desorption in the range of RH air above 70 %. The usefulness of the FPL data, which is presented as an additional isotherm (dot line, Figure 3), was confirmed only for adsorption. For this reason, the FPL data have limited suitability for determining the technological parameters of drying beech lumber with a high amount of "reaction wood". In our research, significantly lower EMC values were observed in the first desorption of

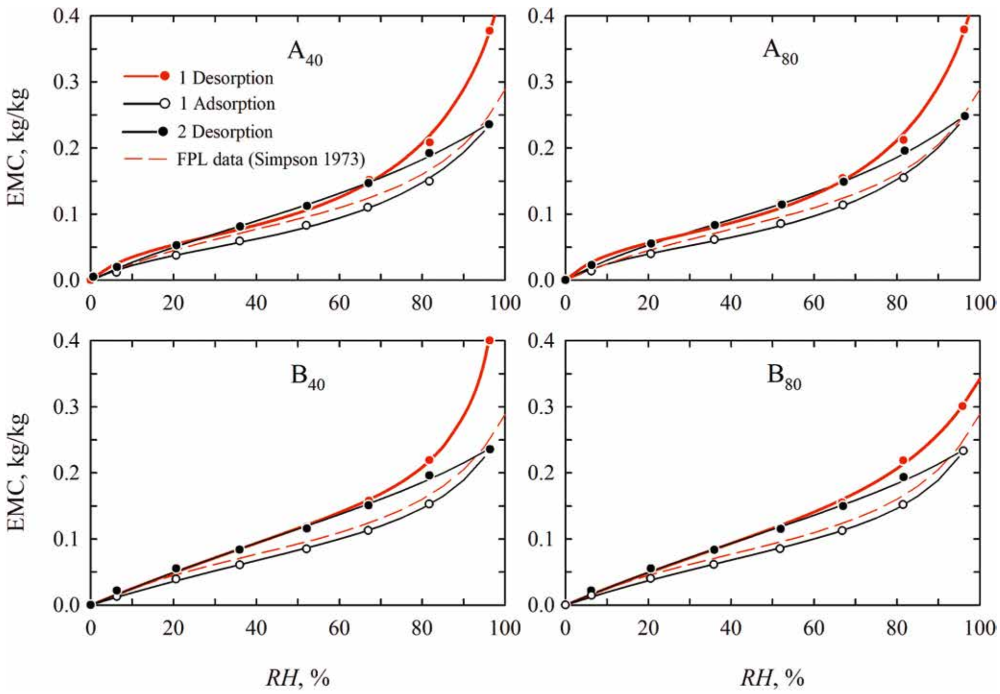



**Figure 3** Sorption isotherms of green beech wood (*Fagus sylvatica* L.) at a temperature of 20 °C (A, B – samples of tension and opposite wood, respectively, 40, 80 – samples from inner and outer zone of trunk cross-section, respectively, FPL data – literature data for normal wood)
**Slika 3.** Sorpcijske izoterme drva bukve (*Fagus sylvatica* L.) pri temperaturi od 20 °C (A – reakcijsko drvo, B – opozitno drvo, 40, 80 – uzorci od srčike prema kori na poprečnom presjeku debla, FPL podatci – podatci iz literature za normalno drvo)

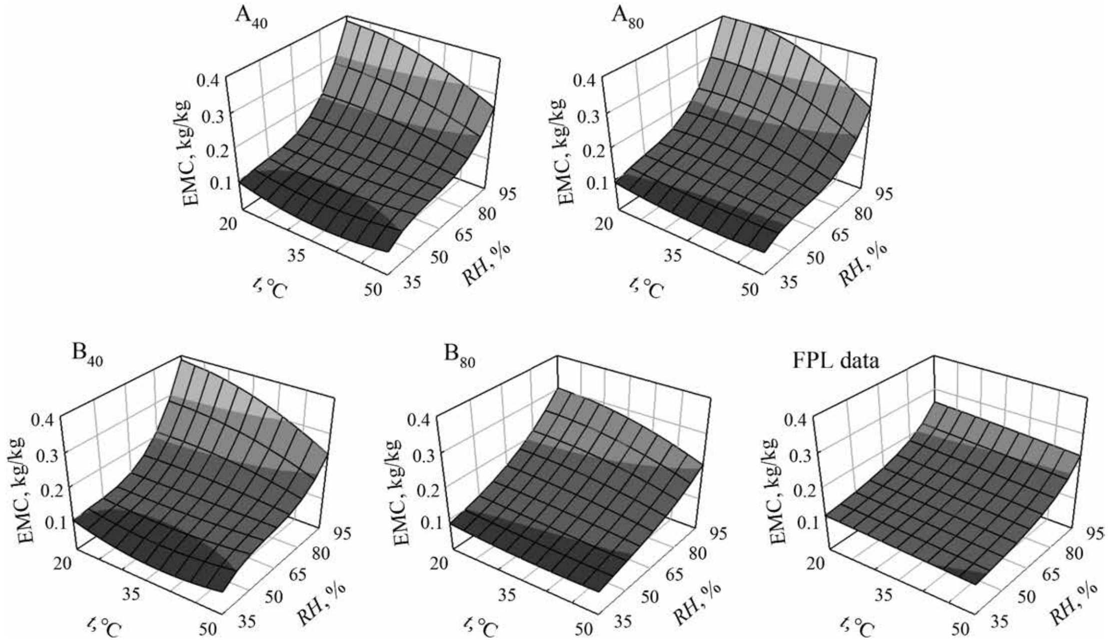



**Figure 4** Effect of air parameters on equilibrium moisture content (EMC) of green beech wood during initial desorption: A, B – samples of tension and oposition wood, respectively, 40, 80 – samples from inner and outer zone of trunk cross-section, respectively, FPL data –reference

**Slika 4.** Utjecaj parametara zraka na ravnotežni sadržaj vode (RSV) u bukovini tijekom inicijalne desorpcije: A – reakcijsko drvo, B – normalno drvo, 40, 80 – uzorci od srčike prema kori na poprečnom presjeku debla, FPL podatci – podatci iz literature

the reaction wood sample with the highest extractive substance content, i.e. 1.93 % (sample $B_{80}$). The results of sorption experiments and chemical composition analysis confirmed a significant influence of the substances soluble in alcohol on the sorption phenomena. The influence of extractives on the sorption phenomenon was described previously, and it was pointed out that their higher content causes a decrease in EMC (Simón *et al*., 2015; Jankowska *et al*., 2016). The results of sorption experiments confirm earlier literature reports that wood containing more substances soluble in alcohol achieved lower EMC, especially when air RH is above 50 % (Hernández, 2007).

## 3.4 Initial desorption modeling
## 3.4. Modeliranje inicijalne desorpcije

Figure 4 presents a comparison of the EMC response surfaces for initial desorption as observed for reaction green beech wood and the FPL reference EMC data. The maximum difference between the estimated EMC of the reaction beech wood and the reference FPL data for the highest RH values included in the experiments is up to 0.14 kg/kg (for air RH above 90 %).

The responses models (Figure 4) present the differences in the hygroscopic properties of the tension and opposite wood tissues. The most significant differences in the EMC value occur in the air RH range above 70 %. The EMC of the tension wood (Section A) was significantly higher than that of the opposite wood (Section B). Moreover, responses models for the reaction tissue show that the EMC values are much more temperature-dependent for the initial desorption than can be calculated using the Simpson procedure, taking into account the FPL data (Simpson, 1973). In extreme cases, an increase in temperature from 20 to 50 °C, for RH near saturation reduces the EMC of the reaction beech wood by even 0.010 to 0.15 kg/kg. The EMC reduction for the same conditions calculated from the FPL data is only 0.025 kg/kg.

Table 5 shows the estimated coefficients of response models developed in this study.

**Table 5** Estimated coefficients of response models
**Tablica 5.** Procijenjeni koeficijenti modela odziva

| **Coefficients** *Koeficijenti* | **Response** *Odziv* | | | |
|---|---|---|---|---|
| | $A_{40}$ | $A_{80}$ | $B_{40}$ | $B_{80}$ |
| $b_0$ | 0.130 | 0.145 | 0.132 | 0.145 |
| $b_1$ | – | -0.0161 | – | -0.0176 |
| $b_2$ | 0.0411 | 0.0425 | 0.0435 | 0.0456 |
| $b_3$ | – | -0.015 | – | -0.00729 |
| $b_4$ | 0.0182 | 0.0192 | 0.0168 | 0.00741 |
| $b_5$ | -0.0137 | -0.0158 | -0.0156 | -0.0105 |
| $b_6$ | – | – | – | – |
| $b_7$ | 0.00809 | 0.00843 | 0.00697 | 0.00129 |
| $b_8$ | -0.0137 | -0.0137 | -0.0142 | -0.007 |
| $b_9$ | -0.00909 | -0.00609 | -0.0108 | -0.00249 |
| $R^2$ | 0.984 | 0.993 | 0.980 | 0.999 |
| Adj $R^2$ | 0.971 | – | 0.966 | – |
| Standard error | 0.0167 | 0.0132 | 0.0179 | 0.00408 |

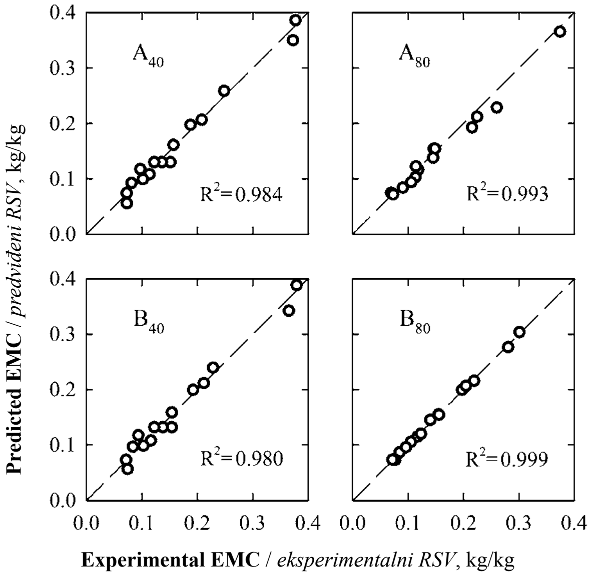



**Figure 5** Experimental versus predicted equilibrium moisture content (EMC) using response models
**Slika 5.** Usporedba eksperimentalnoga i predviđenoga ravnotežnog sadržaja vode (RSV) primjenom modela odziva

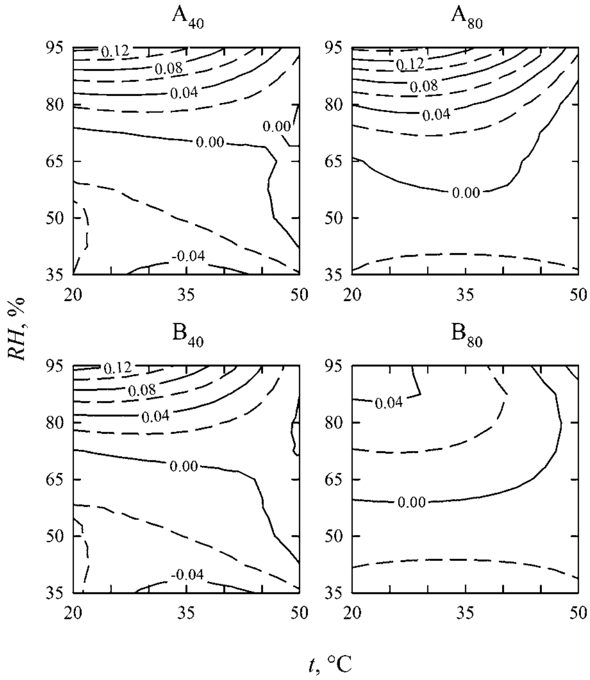



**Figure 6** Calculated absolute differences between values of reaction wood EMC for initial desorption and FPL data for normal wood (Simpson, 1973)
**Slika 6.** Izračunane apsolutne razlike između vrijednosti RSV reakcijskog drva za početnu desorpciju i FPL podataka za normalno drvo (Simpson, 1973.)

Figure 5 compares the predicted EMC to the experimental EMC.

Figure 6 shows calculated absolute differences between reaction wood EMC for initial desorption and normal wood EMC according to FPL data (Simpson, 1973).

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

Taken together, these findings demonstrate that:

1. The research results show the possible range of variability of the hygroscopic properties of the raw beech wood containing pathological tissue. The dependence of the hygroscopic properties of the examined wood on the type of pathological tissue (tension wood, opposite wood) and chemical composition was confirmed. The experimental results show lower EMC values of tension beech wood in higher air RH values. The higher extractives content in reaction wood than in normal tissue is the most likely cause of the lower EMC.
2. It was confirmed that the EMC value for the initial desorption is higher than for the second desorption (in the range of RH above 70 %).
3. The EMC values for the initial desorption for investigated tissues are much more dependent on the temperature than in the Wood Handbook data, which does not consider the anomalous properties of the reaction wood.
4. The calculated EMC value corresponding to the initial desorption can verify kiln-drying schedules for beech sawn timber with a high content of reaction tissue. Applying the developed initial desorption models can significantly improve the accuracy of the drying gradient determination. It can be concluded that there is a potential to improve the efficiency and drying quality of beech kiln-drying.

## 5 REFERENCES
## 5. LITERATURA


1. Ahmet, K.; Dai, G.; Jazayeri, S.; Tomlin, R., 1999: Experimental procedures for determining the equilibrium moisture content of twenty timber species. Forest Products Journal, 49: 88-93.
2. Barkas, W. W., 1936: Wood-water relationships, 2: The fibre saturation point of beech wood. Proceedings of the Physical Society, 48: 576-588. https://doi.org/10.1088/0959-5309/48/4/305
3. Böhner, G., 1996: Überlegungen und Ergänzungen zum „Keylwerth-Diagramm". Holz als Roh-und Werkstoff, 54: 73-79. https://doi.org/10.1007/s001070050139
4. Box, G. E. P.; Draper, N. R., 2007: Response surfaces, mixtures, and ridge analyses, 2nd ed., Wiley Series in Probability and Statistics. Wiley, Hoboken, NJ, USA.
5. Browning, B. L., 1966: The chemistry of wood. Interscience Publishers Inc., New York, USA.
6. Brunner, R., 1987: Die Schnittholztrocknung, 5th ed. Brunner-Hildebrand Gmbh, Hannover, Germany.
7. Chatterjee, S.; Hadi, A. S., 2013: Regression analysis by example, 5th ed. Wiley, Somerset, UK.
8. Côté, W. A., 1964: Anatomy and ultrastructure of reaction wood. In: Cellular Ultrastructure of Woody Plants. Presented at the Advanced Science Seminar, Syracuse University Press, Upper Saranac Lake, New York, Sept. 1964.

9. Côté, W. A.; Day, A. C.; Timell, T. E., 1969: A contribution to the ultrastructure of tension wood fibers. Wood Science and Technology, 3: 257-271. https://doi.org/10.1007/BF00352301
10. Felten, J.; Sundberg, B., 2013: Biology, chemistry and structure of tension wood. In: Cellular Aspects of Wood Formation, Plant Cell Monographs. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 203-224. https://doi.org/10.1007/978-3-642-36491-4_8
11. Fengel, D.; Wegener, G., 1983: Wood: Chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin. https://doi.org/10.1515/9783110839654
12. Glass, S. V.; Zelinka, S. L.; Johnson, J. A., 2014: Investigation of historic equilibrium moisture content data from the Forest Products Laboratory (No. FPL-GTR-229). Forest Products Laboratory, Madison, WI, USA.
13. Groover, A., 2016: Gravitropisms and reaction woods of forest trees – evolution, functions and mechanisms. New Phytol, 211: 790-802. https://doi.org/10.1111/nph.13968
14. Hailwood, A. J.; Horrobin, S., 1946: Absorption of water by polymers: analysis in terms of a simple model. Transactions of the Faraday Society, 42: B084. https://doi.org/10.1039/tf946420b084
15. Hernández, R. E., 2007: Moisture sorption properties of hardwoods as affected by their extraneous substances, wood density, and interlocked grain. Wood and Fiber Science, 39: 132-145.
16. Jankowska, A., 2018: Assessment of sorptive properties of selected tropical wood species. Drvna industrija, 69: 35-42. https://doi.org/10.5552/drind.2018.1733
17. Jankowska, A.; Drożdżek, M.; Sarnowski, P.; Horodeński, J., 2016: Effect of extractives on the equilibrium moisture content and shrinkage of selected tropical wood species. BioResources, 12: 597-607. https://doi.org/10.15376/biores.12.1.597-607
18. Jannot, Y.; Kanmogne, A.; Talla, A.; Monkam, L., 2006: Experimental determination and modelling of water desorption isotherms of tropical woods: afzelia, ebony, iroko, moabi and obeche. Holz als Roh- und Werkstoff, 64: 121-124. https://doi.org/10.1007/s00107-005-0051-2
19. Klement, I.; Vilkovská, T.; Uhrín, M.; Barański, J.; Konopka, A., 2019: Impact of high temperature drying process on beech wood containing tension wood. Open Engineering, 9: 428-433. https://doi.org/10.1515/eng-2019-0047
20. Klement, I.; Vilkovská, T.; Vilkovský, P.; Hýsek, Š., 2020: Structural differences between reaction wood and opposite wood with different drying temperatures. Bioresources, 15: 4407-4416. https://doi.org/10.15376/biores.15.2.4407-4416
21. Kojs, P.; Malik, I.; Wistuba, M.; Stopka, R.; Trabka, K., 2012: Mechanizmy wzrostu ekscentrycznego i formowania się drewna reakcyjnego w kontekście badań dendrogeomorfologicznych – wprowadzenie do nowej hipotezy / Model of eccentric growth and reactive wood formation in the context of dendrogeomorphological research – introduction to a new hypothesis. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej, 14: 147-156.
22. Kollmann, F., 1936: Technologie des Holzes, 1st ed. Springer, Berlin.
23. Kúdela, J.; Čunderlík, I., 2012: Bukové drevo, štruktúra, vlastnosti, použitie / Beech wood, structure, properties, use. Technická univerzita vo Zvolene, Zvolen.
24. Langrish, T. A. G.; Walker, J. C. F., 1993: Transport processes in wood. In: Primary Wood Processing: Principles and Practice. Springer Netherlands, Dordrecht, pp. 121-152. https://doi.org/10.1007/978-94-015-8110-3_5
25. Majka, J.; Olek, W., 2013: The influence of equilibrium moisture content data on accurate control of timber kiln drying intensity. In: Procedings of 4th European Drying Conference (EuroDrying'2013). Presented at the 4th European Drying Conference (EuroDrying'2013), European Federation of Chemical Engineering, Paris, France.
26. Popper, R.; Niemz, P., 2009: Wasserdampfsorptionsverhalten ausgewählter heimischer und überseeischer Holzarten. Bauphysik, 31: 117-121. https://doi.org/10.1002/bapi.200910017
27. Popper, R.; Niemz, P.; Croptier, S., 2009: Adsorption and desorption measurements on selected exotic wood species: Analysis with the Hailwood-Horrobin model to describe the sorption hysteresis. Wood Research, 54: 43-56. https://doi.org/10.3929/ethz-a-006104740
28. Redman, A. L.; Bailleres, H.; Turner, I.; Perré, P., 2016: Characterisation of wood-water relationships and transverse anatomy and their relationship to drying degrade. Wood Science and Technology, 50: 739-757. https://doi.org/10.1007/s00226-016-0818-0
29. Salin, J.-G., 2011: Inclusion of the sorption hysteresis phenomenon in future drying models. Some basic considerations. Maderas: Ciencia y Tecnologia, 13: 173-182. https://doi.org/10.4067/S0718-221X2011000200005
30. Scurfield, G., 1973: Reaction wood: Its structure and function. Science, 179: 647-655. https://doi.org/10.1126/science.179.4074.647
31. Scurfield, G.; Wardrop, A., 1962: The nature of reaction wood. VI. The reaction anatomy of seedlings of woody perennials. Australian Journal of Botany, 10: 93. https://doi.org/10.1071/BT9620093
32. Simón, C.; Esteban, L. G.; de Palacios, P.; Fernández, F. G.; Martín-Sampedro, R.; Eugenio, M. E., 2015: Thermodynamic analysis of water vapour sorption behaviour of juvenile and mature wood of *Abies alba* Mill. Journal of Materials Science, 50: 7282-7292. https://doi.org/10.1007/s10853-015-9283-7
33. Simpson, W. T., 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber Science, 5: 41-49.
34. Skaar, C., 1988: Wood-water relations. Springer-Verlag, Berlin; New York.
35. Spalt, H., 1958: Water vapor sorption by wood. Forest Products Journal, 8: 288-295.
36. Tarmian, A.; Perré, P., 2009: Air permeability in longitudinal and radial directions of compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Holzforschung, 63: 352-356. https://doi.org/10.1515/HF.2009.048
37. Tarmian, A.; Remond, R.; Dashti, H.; Perré, P., 2012: Moisture diffusion coefficient of reaction woods: compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Wood Science and Technology, 46: 405-417. https://doi.org/10.1007/s00226-011-0413-3
38. Tarmian, A.; Remond, R.; Faezipour, M.; Karimi, A.; Perré, P., 2009: Reaction wood drying kinetics: tension wood in *Fagus sylvatica* and compression wood in *Picea abies*. Wood Science and Technology, 43: 113-130. https://doi.org/10.1007/s00226-008-0230-5
39. Tulik, M.; Jura-Morawiec, J., 2011: Drewno reakcyjne a architektura korony drzewa / Reaction wood and tree crown architecture. Sylwan, 155: 808-815.
40. Wardrop, A.; Davies, G., 1964: The nature of reaction wood. VIII. The structure and differentiation of compres-

sion wood. Australian Journal of Botany, 12: 24. https://doi.org/10.1071/BT9640024
41. Weichert, L., 1963: Untersuchungen über das Sorption- und Quellungsverhalten von Fichte, Buche und Buchen-Preßvollholz bei Temperaturen zwischen 20° und 100°C. Holz als Roh-und Werkstoff, 21: 290-300. https://doi.org/10.1007/BF02610962
42. Wengert, E. M., 1976: Predicting average moisture content of wood in a changing environment. Wood and Fiber Science, 7: 264-273.
43. ***Wood Handbook (General Technical Report No. FPL-GTR-190), 2010., Wood as an Engineering Material. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

**Corresponding address:**

**MACIEJ SYDOR**
Poznań University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Woodworking and Fundamentals of Machine Design, ul. Wojska Polskiego 28, Poznań, POLAND,
e-mail: maciej.sydor@up.poznan.pl

Kazimierz A. Orlowski[1], Daniel Chuchala[1], Gerhard Sinn[2]

# Analyses of Shear Angle in Orthogonal Cutting of Pine Wood

# Analiza kuta smicanja pri ortogonalnom rezanju borovine

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 24. 2. 2022.
Accepted – prihvaćeno: 19. 4. 2022.
UDK: 539.55; 674.82; 674.032.475.4
https://doi.org/10.5552/drvind.2022.0022



**ABSTRACT** • *The determination of energy effects for wood machining processes, such as cutting power and cutting forces, is very useful in designing of manufacture process of wooden products. A more accurate prediction of cutting forces requires a correct determination of the shear angle value, which can be determined using various models. In this article, shear angle values for an orthogonal linear cutting process of pine wood are determined. The pine wood analysed was represented by two groups of samples with different moisture content levels, 12 % and 20 %. Three different models were used to determine the shear angle values: the Merchant model, which is based on the rake angle and the angle of friction, model based on chip compression ratios and Atkins model based on material properties (elements of fracture mechanics). The values obtained have been analysed for comparison. Results showed that the values of the shearing angles determined from the chip compression ratios turned out to be higher than the values from Merchant equation. The shear angles determined from the Atkins model are, as expected, lower than those determined from the Merchant model. Furthermore, the shear angle values for moisture content of 20 % are higher than for moisture content of 12 %.*

**KEYWORDS:** *shear angle; orthogonal cutting; chip compression ratio; pine wood; fracture toughness*

**SAŽETAK** • *Određivanje energijskih veličina tijekom procesa obrade drva, poput snage rezanja i sile rezanja, vrlo je korisno pri projektiranju procesa proizvodnje drvenih predmeta. Za točnije predviđanje sila rezanja potrebno je ispravno odrediti vrijednost kuta smicanja, što se može postići primjenom različitih modela. U ovom su članku određene vrijednosti kutova smicanja za ortogonalno linearno rezanje borovine. Analizirano borovo drvo predstavljeno je dvjema skupinama uzoraka različitog udjela sadržaja vode, 12 i 20 %. Za određivanje vrijednosti kuta smicanja primijenjena su tri različita modela: Merchantov model utemeljen na prsnom kutu i kutu trenja; model zasnovan na omjerima kompresije strugotine i Atkinsov model, kojemu su glavna polazišta svojstva materijala (elementi mehanike loma). U radu je prezentirana usporedba dobivenih vrijednosti. Na temelju rezultata uočeno je da su vrijednosti kutova smicanja određene iz omjera kompresije strugotine veće od vrijednosti dobivenih Merchantovom jednadžbom. Kutovi smicanja određeni prema Atkinsovu modelu očekivano su niži od onih određenih uz pomoć Merchantova modela. Nadalje, vrijednosti kuta smicanja za uzorke sa sadržajem vode od 20 % veće su od kutova smicanja za uzorke sa sadržajem vode od 12 %.*

**KLJUČNE RIJEČI:** *kut smicanja; ortogonalno rezanje; omjer kompresije strugotine; borovina; lomna žilavost*

[1] Authors are researchers at Gdańsk University of Technology, Faculty of Mechanical Engineering and Ship Technology, Gdańsk, Poland.
[2] Author is researcher at University of Natural Resources and Life Sciences, Vienna, Institute of Physics and Materials Science, Vienna, Austria.

# 1 INTRODUCTION
# 1. UVOD

The determination of energy effects for wood machining processes is a frequently studied issue and the results are very useful for the design of machining processes (Nasir and Cool, 2020; Atanasov and Kovatchev, 2019; Atanasov, 2021). Most of the analytical modelling works aim at producing equations that can determine cutting forces, without any experimental work. This approach is useful since other parameters can be derived by cutting forces, and analysis of tool wear, surface integrity and workpiece quality can be carried out. The problem involved in the determination of the cutting effects ends up in determining a suitable relationship between the shear angle $\Phi_c$, the rake angle $\gamma_f$ and the friction coefficient μ between a chip and the rake plane $A_\gamma$ (Markopoulos, 2013). Attempting to find a unique shear angle relationship has long attracted scientific and practical interest. Ståhl *et al.* (2012) report that more than 50 relationships for determining shear angle can be found in the literature in the last 100 years. On the other hand, Markopoulos (2013) cites 13 such functions in his book.

A numerical model for orthogonal cutting using the material point method was applied by Nairn (2016) to woodcutting using a bench plane. The cutting process was modelled by accounting for surface energy associated with wood fracture toughness for crack growth parallel to the grain. The simulations were verified by comparison to an analytical model and then used to conduct virtual experiments on wood planing.

Experimental works compared to modelling of the wood cutting process is a larger group. The strain associated with orthogonal cutting with and against the grain of hinoki (*Chamaecyparis obtusa*) was measured by Matsuda *et al.* (2019). A digital image correlation (DIC) method has been used in a number of published works to measure strain distribution (Matsuda *et al.*, 2018, 2019; Ohtani and Iida, 2015; Radmanović *et al.*, 2017).

The values of shear angles determined based on the Atkins model (Atkins, 2005) for sawing wood on a frame sawing machine, a band sawing machine and a circular sawing machine have been published in the papers of Orlowski *et al.* (2013, 2014).

The goal of this work was to demonstrate how the method of determination of shear angle can affect the obtained values while pine wood (*Pinus sylvestris* L.) is cut in the orthogonal process. The new features in this paper is that the experimental values of shear angles, determined in a function of the chip compression ratio (Grzesik, 2017, 2018; Ståhl *et al.*, 2012), are compared to the values calculated from the Merchant equation (Merchant, 1945) and the values of shear angles computed based on the Atkins model (Atkins, 2005), which incorporate realistic effects of cut material properties.

# 2 THEORETICAL BACKGROUND
# 2. TEORIJSKE OSNOVE

Orthogonal cutting represents a two-dimensional mechanical problem with no side curling of the chip considered. It represents only a trickle of machining processes. Nevertheless, it is widely used in theoretical and experimental work due to its simplicity. The case of free orthogonal cutting occurs when (Grzesik, 2016, 2017; ISO 3002-4, 1984):

- cutting speed $v_c$ is perpendicular to the cutting edge,
- the cutting edge $S$ is rectilinear,
- tool cutting edge angle is $\kappa_r = 90°$, and inclination angle is $\lambda_s = 0°$,
- the width of the cut layer (sample width) $W_s$ is much greater than the uncut thickness $h$,
- the length of the active cutting edge is greater than the cutting width.

## 2.1 Prediction of shear angle with Merchant model
## 2.1. Predviđanje kuta smicanja Merchantovim modelom

The engineering approach to the description of plastic deformation in the cutting zone is simplified, including: replacing curvilinear boundaries by straight lines (shear zone is in the shape of the fan) proposed by Zorev (1966), parallel-sided shear band inclined at shear angle (Oxley, 1989), and one shear plane proposed by Merchant (1945) as presented in Figure 1. Although this 2D single shear plane model is criticised, it is usually discussed in machining handbooks due to

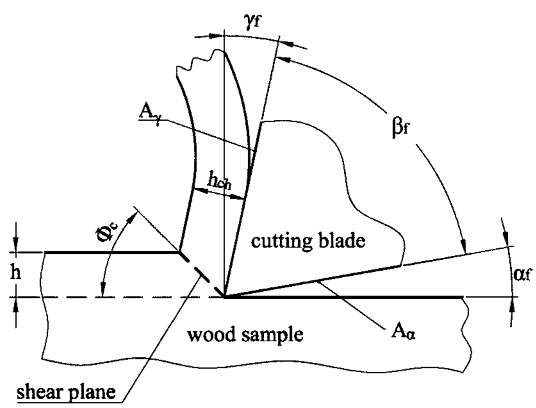



**Figure 1** Geometry of chip forming zone with one shear plane. Legend: $A_\alpha$ - flank face, $A_\gamma$ - rake face, $h$ – uncut chip thickness, $h_{ch}$ – chip thickness, $\Phi_c$ – shear angle, $\alpha_f$ – side flank (clearance) angle, $\beta_f$ - side wedge angle, $\gamma_f$ – rake angle
**Slika 1.** Geometrija zone nastanka strugotine s jednom ravninom smicanja ($A_\alpha$ – leđna površina, $A_\gamma$ – prsna površina, $h$ – debljina neodvojene strugotine, $h_{ch}$ – debljina strugotine, $\Phi_c$ – kut smicanja, $\alpha_f$ – leđni kut, $\beta_f$ – kut klina, $\gamma_f$ – prsni kut

its simplicity and it is the basis for calculating several process parameters, e.g. cutting forces (Grzesik, 2017; Markopoulos, 2013).

Merchant (1945) proposed to calculate the shear angle $\Phi_c$ considering the rake angle $\gamma_f$ of and the angle of friction $\beta_\mu$. The latter depends on the coefficient of friction μ between the rake face and the chip. The relationship by Merchant is as follows:

$$\Phi_c = \frac{\pi}{4} - \frac{1}{2}\left(\beta_\mu - \gamma_f\right) \quad (1)$$

Where: $\beta_\mu$ is a friction angle determined as $\beta_\mu = \tan^{-1}\mu$.

The coefficients of friction are going to be taken on the basis of the measured cutting forces.

### 2.2 Shear angle as a function of chip compression ratio
### 2.2. Kut smicanja kao funkcija omjera kompresije strugotine

Knowledge of the chip compression ratio $\lambda_h$ that takes place enables the shear angle $\Phi_c$ to be computed with the use of the relationship (Merchant, 1945; Grzesik, 2017, 2018; Ståhl *et al.*, 2012):

$$\tan \Phi_c = \frac{\cos \gamma_f}{\lambda_h - \sin \gamma_f} \quad (2)$$

The chip compression ratio $\lambda_h$ could be calculated as follows (Merchant, 1945; Ståhl *et al.*, 2012):

$$\lambda_h = \frac{h_{ch}}{h} \quad (3)$$

To determine the chip thickness $h_{ch}$ (Figure 2), the chips were collected after each test and immediately measured with a calliper. The digital calliper by GEDORE company was applied (GEDORE Werkzeugfabrik GmbH & Co. KG, Remscheid, Germany).

### 2.3 Prediction of shear angle with Atkins model
### 2.3. Predviđanje kuta smicanja primjenom Atkinsova modela

Atkins (2003) stated that sensible material-dependent predictions for $\Phi_c$ are obtained when proper magnitudes of separation work are incorporated in the minimisation. According to Atkins (2003) for least cutting force $F_c$, the shear angle $\Phi_c$ satisfies:

$$\left[1 - \frac{\sin\beta_\mu \sin\Phi_c}{\cos(\beta_\mu - \gamma_f)\cdot\cos(\Phi_c - \gamma_f)}\right]\cdot\left[\frac{1}{\cos^2(\Phi_c - \gamma_f)} - \frac{1}{\sin^2\Phi_c}\right] = -\left[\cot\Phi_c + \tan(\Phi_c - \gamma_f) + Z\right]\cdot \left[\frac{\sin\beta_\mu}{\cos(\beta_\mu - \gamma_f)}\left\{\frac{\cos\Phi_c}{\cos(\Phi_c - \gamma_f)} + \frac{\sin\Phi_c \sin(\Phi_c - \gamma_f)}{\cos^2(\Phi_c - \gamma_f)}\right\}\right] \quad (4)$$

in which $Z = \frac{R}{\tau_\gamma \cdot h}$ is the parameter which makes $\Phi_c$ material dependent, where: $R$ is specific work of surface separation/formation (fracture toughness), and $\tau_\gamma$ is the shear yield stress (along the shear plane). The nonlinear equation (4) (further called the Atkins Model – AM) can be solved with Newton's method (Wanat 1994), which is one of the iterative methods, in which the roots can be found.

The cutting process is a simple and exceptional way for simultaneously measuring toughness and shear yield stresses (Atkins, 2005). Cutting forces can be expressed as a linear regression function (Atkins, 2003; Orlowski and Atkins, 2007; Orlowski *et al.*, 2013; Chuchala *et al.*, 2021):

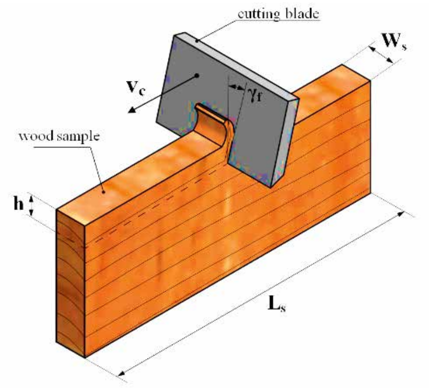
$$F_c(h) = b \cdot h + a \quad (5)$$

In this case, $a$ and $b$ correspond to the intercept and slope, respectively. From the value $a$, the value of fracture toughness $R$ could be determined (Orlowski and Atkins, 2007; Chuchala *et al.* 2021), and from the value of the slope $b$, the value of shear yield stresses $\tau_\gamma$ might be computed (Orlowski and Atkins, 2007).

## 3 MATERIALS AND METHODS
## 3. MATERIJALI I METODE

### 3.1 Materials
### 3.1. Materijali

Scots pine (*Pinus sylvestris* L.) was used to prepare the samples. One log was randomly chosen among others in the sawmill yard. From the middle part of the 4 m long log, rectangular samples with dimensions W = 60 mm × $H$ = 60 mm × $L$ = 600 mm (width × height ×length, respectively) were cut. Then, ten prepared samples were dried and conditioned under laboratory conditions assuring constant air temperature of 20 °C and relative humidity of 65 % for three months. They were divided into two group - one of the final moisture content MC obtained at the level around 20 %, and the other of about 12 % *MC*. The moisture content values were determined by use of the dryer-weight method. The 12 % MC level represents dry wood and 20 % *MC* represents wet wood but bellow the value of fibre saturation point (FSP). The density of the tested wood was 549 kg/m$^3$ for final *MC* of 20 %, and 536 kg/m$^3$ for final *MC* of 12 %. The examined pine wood was characterised by an average width of annual rings of 2.12 ±0.4 mm and an average width of the late wood in annual rings of 0.44 ±0.05 mm. These rectangular samples were sawn on the sash gang saw PRW15M into lamellae about 5 mm in thickness. The obtained lamellae were the raw material for the preparation of small samples with dimensions $W_s$ = 5 mm × $H_s$ = 30 mm × $L_s$ = 50 mm (width × height ×length, respectively). The dimensions of small samples were determined by the material holder of the microtome.




a)

b)

**Figure 2** Orthogonal cutting process on sliding microtome: a) process kinematics and b) formed chip while cutting. Legend: $L_s$ – sample length, $W_s$ – sample width, $h$ – uncut chip thickness, $v_c$ – cutting speed

**Slika 2.** Proces ortogonalnog rezanja na kliznome mikrotomu: a) kinematika procesa, b) strugotina nastala tijekom rezanja; $L_s$ – duljina uzorka, $W_s$ – širina uzorka, $h$ – debljina neodvojene strugotine, $v_c$ – brzina rezanja

### 3.2 Orthogonal cutting tests
### 3.2. Eksperimentalno ortogonalno rezanje

The orthogonal cutting process was conducted on the sliding microtome (Figure 2a and 2b) (R. Jung AG, Heidelberg, Germany) at the laboratory of the University of Natural Resources and Life Sciences (BOKU) in Vienna (Austria). The investigated linear cutting process was performed in longitudinal direction to wood fibres (direction 90°–0° according to Kivimaa (1950)) (Figure 2a). The average cutting speed $v_c$ was equal to 0.05 m·s$^{-1}$, and the uncut chip thickness $h$ was set at 4 levels: 0.075 mm, 0.1 mm, 0.15 mm and 0.2 mm. 5 repetitions were made for each $h$ level of the uncut chip thickness. Brand new sharp knife blades made of tungsten carbide (HW) (Leitz GmbH & Co KG, Oberkochen, Germany) were applied for cutting. Tool side rake angle (tool-in machine system) $\gamma_f$ was equal to 15°, and tool wedge angle was $\beta_f$ = 55°.

### 3.3 Shear angle
### 3.3. Kut smicanja

The shear angle values were determined using three methods:

- Merchant model (Eq. 1);
- chips compression ratio model (Eq. 2);
- Atkins model (Eq. 4).

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The obtained experimental results of cutting forces $F_c$ in orthogonal cutting process on the sliding microtome in longitudinal direction to pine wood fibre (direction 90°–0° according to Kivimaa (1950)) at two levels of *MC* equal to 12 % and 20 % are presented in Figure 3.

On the assumption that the cutting model includes work of separation (fracture toughness) in addi-

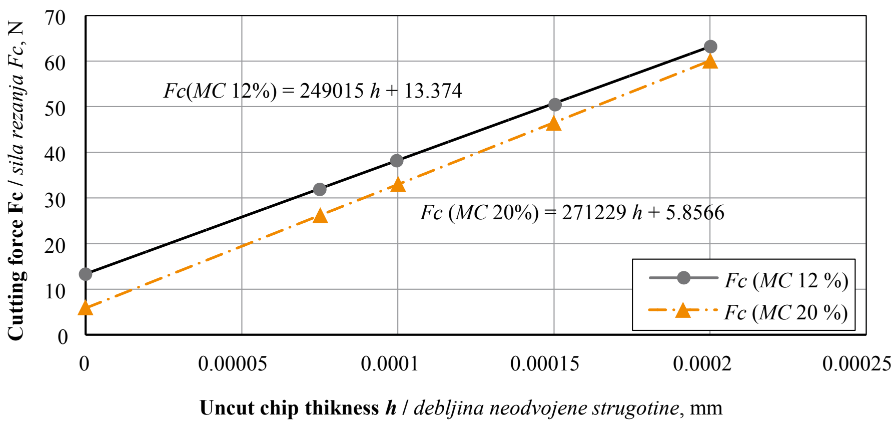



**Figure 3** Cutting forces $F_c$ in a function of uncut chip thickness $h$ and moisture content *MC* while cutting on sliding microtome in longitudinal direction to pine wood fibres

**Slika 3.** Sile rezanja $F_c$ u funkciji debljine neodvojene strugotine $h$ i sadržaja vode *MC* tijekom rezanja na kliznome mikrotomu u smjeru vlakanaca borova drva

**Table 1** Fracture toughness $R$, shear yield stresses $\tau_\gamma$ and average friction coefficients μ between rake face and chip for pine wood in a function of *MC*
**Tablica 1.** Lomna žilavost $R$, naprezanje smicanja $\tau_\gamma$ i prosječni koeficijenti trenja μ između prsne površine i strugotine borovine u ovisnosti o sadržaju vode

| *MC*, % | *R*, J/m² | $\tau_\gamma$, MPa | μ |
|---|---|---|---|
| 12 | 2674.80 | 17.21 | 0.72 |
| 20 | 1171.32 | 20.03 | 0.63 |

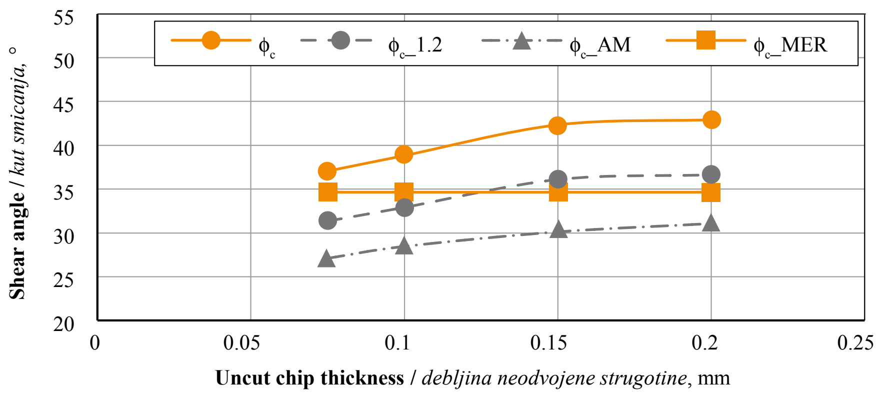
tion to plasticity and friction in the case of cutting pine wood on the sliding microtome, examined values of fracture toughness $R$ and shear yield stresses $\tau_\gamma$ have been computed from linear functions given in Figure 3. The results of computations of $R$ and $\tau_\gamma$ together with determined average friction coefficients μ between the rake face and the chip are presented in Table 1.

Cutting forces for pine wood of 12 % *MC* in a function of the uncut chip thickness are slightly higher than in the case of cutting pine of 20 % *MC* (Figure 3), and this phenomenon could be caused by differences in friction coefficient, which is smaller for pine wood of 20 % *MC*. Moreover, as the values of the uncut chip thickness increases, the differences in force values decrease. The obtained values of friction coefficients (Table 1) are in agreement with the statement that intermediate moisture content may range from 0.5 to 0.7 (Simpson and TenWolde, 1999).

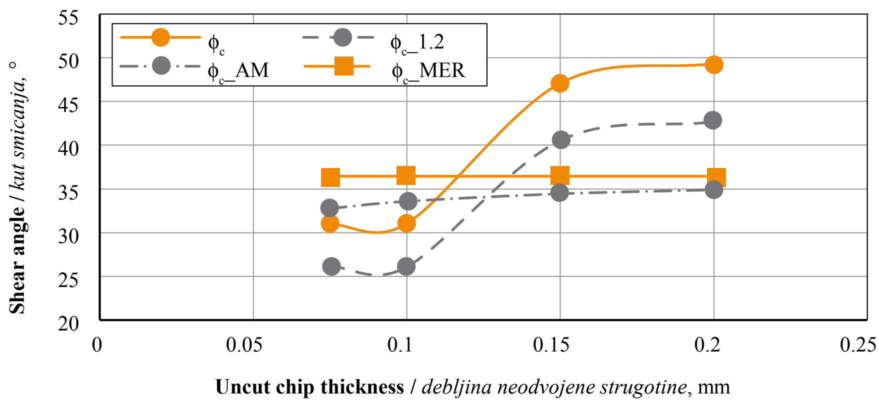
The shear angle $\Phi_c$, considering the rake angle $\gamma_f$ and the angle of friction $\beta_\mu$, computed with the use of the Merchant model (Eq. 1), for pine wood of 12 % *MC* was equal to $\Phi_c$ = 34.65°, and in case of pine wood of 20 % *MC* the shear angle $\Phi_c$ = 36.44°. The obtained results are in agreement with machining theory (Grzesik, 2018; Markopoulos, 2013; Ståhl *et al.*, 2012), since lower cutting forces are observed for larger values of the cutting angle (Figure 3). The calculated shear angle $\Phi_c$ values with the Merchant model are presented in Figure 4a and 4b as ϕ_MER.

Some collected pine chips from the orthogonal cutting on the sliding microtome in longitudinal direction to pine wood fibres are shown in Figure 5.

Measured with callipers, the chip thickness values allowed the determination of the chip compression ratio



a)



b)

**Figure 4** Shear angles $\Phi_c$ while cutting on sliding microtome in longitudinal direction to pine wood fibres for *MC* = 12 % (a) and *MC* = 20 % (b) in a function of uncut chip thickness $h$. Legend: $\phi_c$ – shear angle determined in a function of chip compression ratio $\lambda_h$, $\phi_c$_1.2 – shear angle computed in a function of chip compression ratio $\lambda_h$ while measured chip thickness $h_{ch}$ was enlarged by 20 %, $\phi_c$_AM – shear angle obtained from Atkins model, $\phi_c$_MER – shear angle calculated with Merchant model
**Slika 4.** Kutovi smicanja $\Phi_c$ tijekom rezanja na kliznome mikrotomu u smjeru vlakanaca borovine pri (a) *MC* = 12 % i (b) *MC* = 20 % u funkciji debljine neodvojene strugotine $h$ ($\phi_c$ – kut smicanja određen u funkciji omjera kompresije strugotine $\lambda_h$, $\phi_c$_1.2 – kut smicanja izračunan u funkciji omjera kompresije strugotine $\lambda_h$, a izmjerena debljina strugotine $h_{ch}$ povećana je za 20 %, $\phi_c$_AM – kut smicanja dobiven iz Atkinsova modela, $\phi_c$_MER – kut smicanja izračunan prema Merchantovu modelu)

**Figure 5** Exemplary collected chips from orthogonal cutting on sliding microtome in longitudinal direction to pine wood fibres; chips were created during cutting process with set uncut chip thickness $h$ = 0.15 mm
**Slika 5.** Primjeri strugotine skupljene pri ortogonalnom rezanju na kliznome mikrotomu u smjeru vlakanaca borovine; strugotina je nastala tijekom procesa rezanja uz definiranu debljinu neodvojene strugotine $h$ = 0,15 mm

(Eq. 3), and then the determination of shear angle $\Phi_c$ from Eq. (2). The results of the shear angle $\Phi_c$ (courses Fic) for pine wood of 12 % MC are shown in Figure 4a, and for pine wood of 20 % MC in Figure 4b. For both courses, it is noticeable that the obtained values are larger than shear angles determined with the use of the Merchant model ($\phi_c$_MER). These results are contrary to the data presented in the literature, where the values of the shear angles obtained experimentally are below the values of the Merchant model (Ståhl *et al*., 2012). The reason for this phenomenon may be local compression of thin chips by the callipers during measurement. An additional simulation was carried out for chip thicknesses increased by 20 %, and the resulting shear angles (Figure 4a, b, plots $\phi_c$_1.2) were found to be lower, although, for higher uncut chip thickness values, still above those of the Merchant model. Although the resolution of a digital calliper is 0.01 mm, its measurement error for external dimensions can be ±0.03 mm for a calliper with a measurement range of up to 150 mm (Mitutoyo, 2018). This measurement error may be another additional source of overshooting shear angle values. It is presumed that much better results could be achieved by using vision techniques in chip thickness measurement as it was done in case of wood cutting (Matsuda *et al*., 2019; Ohtani and Iida, 2015; Radmanović *et al*., 2017), and has also proved its worth in metal cutting (Venkata Ramana *et al*., 2021).

In prediction of the shear angles with the Atkins model (Eq. 4), which makes $\Phi_c$ material dependent, the values of fracture toughness $R$ and shear yield stresses $\tau_\gamma$, and values of friction coefficients μ presented in Table 1 were applied in numerical computations. The results of these calculations are shown in Figure 4a and 4b. The values obtained from the Atkins model $\phi_c$_AM are lower than the values from the Merchant model ($\phi_c$_MER) over the entire range of change. Moreover, a decrease in the cutting angle is observed for smaller values of uncut chip thickness, whereas, in the Merchant model the shear angle is constant. Furthermore, it is evident that differences between shear angles from the Merchant model and the Atkins model are larger for pine wood of 12 %.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The novel experimental analyses of shear angles proposed here provide a unique opportunity to assess the effect of the method of determining shear angles on their values.

For pine wood (*Pinus sylvestris* L.) with a moisture content of $MC$ = 20 %, lower values of the friction coefficient μ between the chip and the rake face were observed during orthogonal cutting along the wood fibre than for a moisture content level of $MC$ = 12 %. The difference is equal to 14.2 %. As a consequence of this difference, lower values of the cutting force $F_c$ were recorded over the entire range of variations in the uncut chip thickness.

The values of the shearing angles determined from the chip compression ratios turned out to be higher than the values from Merchant equation. This can be explained by the measurement error resulting from the use of digital callipers.

The shear angles determined from the Atkins model are, as expected, lower than those determined from the Merchant model. Furthermore, the shear angle values for 20 % *MC* are higher than for moisture content 12 % *MC*.

The area of shear angle analysis for wood machining processes requires deeper analysis at both modelling and experimental verification levels. Accurate determination of the shear angle for wood machining processes would allow a fairly accurate prediction of the energy demand for these cutting processes, resulting in a reduction of material waste.

### Acknowledgements – Zahvala

Financial support of NAWA (Polish National Agency for Academic Exchange) within the project PPN/BIL/2018/1/00100/U/00001 and BMBWF trough OEAD within the project PL 06/2019 is gratefully acknowledged.

The authors gratefully acknowledge the Ministry of Science and Higher Education, Poland, for supporting the maintenance of scientific and research equipment – PRW-15M frame saw, grant number 21/E-359/SPUB/SP/2019.

## 5 REFERENCES
## 5. LITERATURA


1. Atanasov, V.; Kovatchev, G., 2019: Determination of the cutting power during milling of wood-based materials. Acta Facultatis Xylologiae Zvolen, 61 (1): 93-101. https://doi.org/10.17423/afx.2019.61.1.09
2. Atanasov, V., 2021: Experimental research on the cutting force during longitunal milling of solid wood and wood-based composites. Acta Facultatis Xylologiae Zvolen, 63 (2): 73-84. https://doi.org/10.17423/afx.2021.63.2.06
3. Atkins, A. G., 2003: Modelling metal cutting using modern ductile fracture mechanics: quantitative explanations for some longstanding problems. International Journal of Mechanical Sciences, 45: 373-396. https://doi.org/10.1016/S0020-7403(03)00040-7
4. Atkins, A. G., 2005: Toughness and cutting: a new way of simultaneously determining ductile fracture toughness and strength. Engineering Fracture Mechanics, 72 (6): 849-860. https://doi.org/10.1016/j.engfracmech.2004.07.014
5. Chuchala, D.; Orlowski, K.; Sinn, G.; Konopka, A., 2021: Comparison of the fracture toughness of pine wood determined on the basis of orthogonal linear cutting and frame sawing. Acta Facultatis Xylologiae Zvolen, 63 (1): 75-83. https://doi.org/10.17423/afx.2021.63.1.07
6. Grzesik, W., 2018: Podstawy skrawania materiałów konstrukcyjnych. Wydawnictwo Naukowe PWN SA, Warszawa.
7. Grzesik, W., 2017: Advanced machining processes of metallic materials. Theory, Modelling and Applications. Second Edition. Elsevier BV, Oxford.
8. Kivimaa, E., 1950: Cutting force in woodworking. VTT Technical Research Centre of Finland. Valtion teknillinen tutkimuslaitos. Julkaisu – Publikation No. 18.
9. Markopoulos, A. P., 2013: Finite Element Method in Machining Processes. SpringerBriefs in Manufacturing and Surface Engineering. Springer, London. https://doi.org/10.1007/978-1-4471-4330-7
10. Matsuda, Y.; Fujiwara, Y.; Fujii, Y., 2018: Strain analysis near the cutting edge in orthogonal cutting of hinoki (*Chamaecyparis obtusa*) using a digital image correlation method. Journal of Wood Science, 6: 566-577. https://doi.org/10.1007/s10086-018-1724-x
11. Matsuda, Y.; Fujiwara, Y.; Fujii, Y., 2019: Effect of grain angle on the strain distribution during orthogonal cutting of hinoki (*Chamaecyparis obtusa*) measured using a digital image correlation method. Journal of Wood Science, 65: 44. https://doi.org/10.1186/s10086-019-1824-2
12. Merchant, M. E., 1945: Mechanics of the metal cutting process. I. Orthogonal cutting and a type 2 chip. Journal of Applied Physics, 16 (5): 267-275. https://doi.org/10.1063/1.1707586
13. Nairn, J. A., 2016: Numerical modelling of orthogonal cutting: application to woodworking with a bench plane. Interface Focus, 6: 20150110. http://dx.doi.org/10.1098/rsfs.2015.0110
14. Nasir, V.; Cool, J., 2020: A review on wood machining: characterization, optimization, and monitoring of the sawing process. Wood Material Science and Engineering, 15 (1): 1-16. https://doi.org/10.1080/17480272.2018.1465465
15. Ohtani, T.; Iida, R., 2015: Mechanical analysis of shear zone chip formation process of wood cutting. In: Proceedings of the 22nd International Wood Machining Seminar, Quebec City, Canada, pp. 38-45.
16. Orlowski, K. A.; Atkins, A., 2007: Determination of the cutting power of the sawing process using both preliminary sawing data and modern fracture mechanics. In: Proceedings of the Third International Symposium on Wood Machining. Fracture Mechanics and Micromechanics of Wood and Wood Composites with regard to Wood Machining, Lausanne, Switzerland. Presses Polytechniques et Universitaires Romandes, Lausanne, pp. 171-174.
17. Orlowski, K. A.; Ochrymiuk, T.; Atkins, A.; Chuchala, D., 2013: Application of fracture mechanics for energetic effects predictions while wood sawing. Wood Science and Technology, 47: 949-963.https://doi.org/10.1007/s00226-013-0551-x
18. Orlowski, K. A.; Ochrymiuk, T.; Atkins, A., 2014: An innovative approach to the forecasting of energetic effects while wood sawing. Drvna industrija, 65 (4): 273-281. https://doi.org/10.5552/drind.2014.1341
19. Oxley, P. L. B., 1989: Mechanics of machining. An analytical approach to assessing machinability. Ellis Horwood, Chichester, 1989.
20. Radmanović, K.; Đukić, I.; Merhar, M.; Šafran, B.; Jug, M.; Beljo-Lučić, R., 2017: Chip plastic deformation in orthogonal wood cutting. In: Proceedings of the 23rd International Wood Machining Seminar, Warsaw, Poland, pp. 222-231.
21. Simpson, W.; TenWolde, A., 1999: Physical properties and moisture relations of wood (Chapter 3). In: Wood handbook – wood as an engineering material. Forest Products Laboratory. Gen. Tech. Rep. FPL – GTR-113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, pp. 463.
22. Ståhl, J.-E.; Andersson, M.; Bushlya, V.; Zhou, J.; Andersson, C., 2012: Metal cutting. Theories and models. Lund University, Division of production and Materials Engineering, (in cooperation with Seco Tools). Lund, Sweden.
23. Venkata Ramana, M.; Krishna Mohana Rao, G.; Prasanth, G.; Sagar, B.; Ravi Kumar, P.; Raja Ravi Kumar, B. V., 2021: Effect of machining conditions on shear angle in turning of A286 iron based nickel super alloy. Materials Today: Proceedings, 44, (1): 2319-2324. https://doi.org/10.1016/j.matpr.2020.12.407
24. Wanat, K., 1994: Numerical algorithms. Gliwice, Helion (in Polish).
25. Zorev, N. N., 1966: Metal cutting mechanics. Pergamon, Headington Hill Hall, Oxford, England.
26. ***Mitutoyo, 2018. Accuracy and Calibration of Calipers (online), https://www.mitutoyo.com/webfoo/wp-content/uploads/15003A.pdf (Accessed Feb. 13, 2022).
27. *** ISO 3002-4, 1984: Basic quantities in cutting and grinding. Part 4: Forces, energy, power.



**Corresponding address:**

**DANIEL CHUCHALA**

Gdańsk University of Technology, Faculty of Mechanical Engineering and Ship Technology, 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk, POLAND, e-mail: daniel.chuchala@pg.edu.pl

Dušan Jokanović[1], Tatjana Ćirković-Mitrović[2], Vesna Nikolić Jokanović[1], Radoslav Lozjanin[1], Iva Ištok[3]

# Wood Fibre Characteristics of Pedunculate Oak (*Quercus R obur* L.) Growing in Different Ecological Conditions

# Svojstva drvnih vlakanaca hrasta lužnjaka sa staništa različitih ekoloških uvjeta

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 28. 2. 2022.
Accepted – prihvaćeno: 29. 4. 2022.
UDK: 630*81; 674.031.632.2;
https://doi.org/10.5552/drvind.2022.0023



**ABSTRACT** • *Anatomical properties of pedunculate oak (Quercus robur L.) wood have not been previously investigated in Serbia, so bearing in mind economic-productive and ecological significance of this species, it was one of the main reasons why this research was conducted. In this paper, fibre length (FL), double cell-wall thickness (DCWT) and fibre lumen diameter (FLD) were measured in pedunculate oak wood from two different sites. The study was conducted at two sites (Donji Srem – MU „Raškovica-Smogvica" and Gornji Srem – MU „Kupinske grede"), situated along the Sava River and characterised by different ecological conditions, including flooding regimes. Measurements were conducted in radial direction, from pith to bark, in order to assess variation of investigated characteristics with cambial age, between two sites and between individual trees within each site. All measured characteristics from both sites increase going from pith to bark apart from FL in the area of Donji Srem – MU „Kupinske grede" that reaches maximum value in the central part of xylem and then decreases. Hydrological site conditions affect the dimensions of pedunculate oak wood fibres and these values are a bit higher in Gornji Srem – MU „Raškovica-Smogvica", due to a greater quantity of available water.*

**KEYWORDS:** *pedunculate oak (Quercus robur L.); fibre characteristics; Gornji Srem; Donji Srem; wood variation*

**SAŽETAK** • *Anatomska svojstva drva hrasta lužnjaka (Quercus robur L.) do sada nisu istraživana na području Srbije, a imajući na umu golemo značenje te vrste u ekonomsko-proizvodnome i ekološkom smislu, to je bio jedan od glavnih razloga za provedbu ovog istraživanja. U radu je izmjerena duljina vlakanaca (DV), dvostruka debljina stijenki (DDS) i promjer lumena vlakanaca (PLV) drva hrasta lužnjaka s dva različita staništa. Istraživanje je provedeno na staništima Gornji Srem – GJ „Raškovica-Smogvica" i Donji Srem – GJ „Kupinske grede", koja se prostiru duž rijeke Save, a karakteriziraju ih različiti ekološki uvjeti, uključujući i režim plavljenja. Mjerenja su provedena u radijalnom smjeru, od srčike prema kori, kako bi se utvrdile varijacije istraživanih svojstava ovisno*

[1] Authors are associate professors and doctoral student at Belgrade University, Faculty of Forestry, Belgrade, Serbia.
[2] Author is senior research associate at Institute of Forestry, Belgrade, Serbia.
[3] Author is assistant professor at University of Zagreb, Faculty of Forestry and Wood Technology, Institute of Wood Science, Zagreb, Croatia.

*o starosti kambija, o različitosti dvaju lokaliteta te o razlikama među stablima unutar istog lokaliteta. Utvrđeno je da se sve izmjerene vrijednosti drva s oba lokaliteta povećavaju u smjeru od srčike prema kori, osim DV-a na području Donjeg Srema – GJ „Kupinske grede", koji maksimalnu vrijednost dosežu u središnjem dijelu ksilema i potom se smanjuju. Hidrološki uvjeti staništa uvelike utječu na dimenzije drvnih vlakanaca hrasta lužnjaka i te su vrijednosti zbog veće količine raspoložive vode nešto veće u Gornjem Sremu, u GJ „Raškovica-Smogvica".*

**KLJUČNE RIJEČI:** *hrast lužnjak (Quercus robur L.); svojstva drvnih vlakanaca; Gornji Srem, Donji Srem; varijabilnost drva*

## 1 INTRODUCTION
## 1. UVOD

Pedunculate oak (*Quercus robur* L.) forests in the area of Ravni Srem (Serbia) are of exceptional importance from ecology and economic point of view (Nikolić, 2016). Its wood is considered to be of high quality and is used for different purposes, mainly veneer, floor-boards, furniture and construction wood. The entire complex of hygrophilous forests in this area is divided into two spatial-geographical units: Gornji Srem, where a defensive embankment was built in the 1930s so that the impact of flooding is excluded, and Donji Srem, which is not defended and where, in addition to atmospheric precipitation and groundwater, additional watering through flooding also has a significant influence on development characteristics of pedunculate oak. In Serbia, both pedunculate (*Q. robur* L.) and sessile oak (*Q. petraea* (Matt.) Liebl.) have been investigated in terms of growth and development (Letić *et al*., 2017; Nikolić Jokanović *et al*., 2019; Nikolić Jokanović *et al*., 2020; Radaković and Stajić, 2021). From these studies, it was concluded that water is the main ecological factor related to pedunculate and sessile oak growth and development. Its shortage can affect the decline of the species. Feuillat *et al.* (1997) emphasised that pedunculate and sessile are two major oak species in European forests (27 % of the area of European broad-leaved forests). They are seldom distinguished during management operations and never after felling.

Wood density and shrinkage are lower in pedunculate oak (Deret-Varcin, 1983; Nepveu, 1984; Levy *et al.,* 1992), heartwood formation is quicker, thus leading to a thinner sapwood zone (Deret-Varcin, 1983; Levy *et al.,* 1992), while wood colour is slightly different (Klumpers *et al*., 1993). On the other hand, vessel dimensions in oak wood structure have been studied in more detail (Tumajer and Tremsl, 2016; Levanič *et al*., 2011). Levanič *et al.* (2011) linked growth and anatomical properties of pedunculate oak to its mortality rate and claimed that variability in anatomical properties affects transpiration potential and other physiological parameters of this species. Xylem anatomy has direct implications on tree ecophysiology. The hydraulic functioning of trees largely depends on anatomical features (Zimmermann, 1983). Jacobsen *et al.* (2005) examined the connection between xylem fibres and vessels cavitation resistance by different hardwoods. At the cellular level, they found that increased cavitation resistance and stem mechanical strength were associated with increased thickness of fibre cell walls. Increased vessel wall thickness was not correlated to xylem density, while xylem conductive efficiency was correlated with increased hydraulic vessel lumen diameter and decreased fibre wall area. Hacke *et al.* (2001) established that fibre and vessel properties are indeed correlated and found a possible role for fibres in increased vessel implosion resistance.

Wood anatomical characteristics greatly influence its properties and quality. Regarding mechanical elements in the structure of pedunculate oak wood, in addition to wood fibres (libriforms), fibrous tracheids are also present (Vilotić, 2000). Fibres have the greatest area in the structure of pedunculate oak wood (40-60 %). In line with that, the vessel area in the earlywood is 40 % and in the latewood 8 %, while the ray area is 15-30 % (Wagrenführ and Scheiber, 2006).

Radial variation of anatomical characteristics from pith to bark shows a big influence of cambial age on wood structure (Tsoumis, 1991). This could point to transition from juvenile to mature wood on the cross-section of wood. In a certain site, variation is very high, generally higher than between sites, and for Serbian Pedunculate oak populations this assumption was confirmed by DNA markers (Kesić *et al*., 2021).

Some papers (Mladenova *et al*., 2017; Nazari *et al*., 2020; Keleş and Savaci, 2021) investigated fibre characteristics, mainly fibre length in wood of different oak species. Obtained results showed a big dependence of its dimensions on site conditions. Vilotić (1992), established some differences related to the anatomical structure inside the genus *Quercus* and claimed that these differences are quantitatively caused by genotype, pedology, climate, topography, and features of plant associations. However, little attention has been given to determining different patterns of fibre characteristics variation.

The aim of this research is to provide preliminary results on the intra- and inter-population variability of wood fibre characteristics (fibre length – FL, double cell wall thickness – DCWT and fibre lumen diameter

– FLD) of pedunculate oak on the territory of Serbia, as well as to determine how these traits change with age, going from pith to bark of the tree.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Study area
### 2.1. Istraživana staništa

For the purpose of this research, a total of six trees were selected and harvested. Three trees were located in the area of Gornji Srem, within the Management Unit (MU) „Raškovica-Smogvica", while the other three were located in the area of Donji Srem, within the Management Unit (MU) „Kupinske grede". It should be emphasised that all stems were planted from the seed.

The first site, in the area of Forestry Holding (FH) „Morović", within the MU „Raškovica-Smogvica" is situated on flat terrain, the dead cover is poorly represented, the humification process is very favourable and there is no flooding. This is a type of ash and pedunculate oak forest with maple and hornbeam and a rich floor of shrubs in the non-flooded part of Gornji Srem on the driest options of marsh blackberries and meadow blackberries with signs of leaching. The mechanical texture of the soil is lighter (clay + powder are represented with about 75 %), which affects the content of air in the soil increases, and the amount of total water decreases.

The second site is situated in the lowland belt area of Forestry Holding (FH) „Kupinovo", within the MU „Kupinske grede". The dead cover is moderately represented, while the humification process is favourable. The site is characterised by regular flooding, the shrubs are medium dense present, with some weeds cover. As for the forest type, it is ash and pedunculate oak association on moderately moist marsh blackberries. There is also a high forest of ash and poplar, a two-story, ripening stand. The stand is medium endangered by wind, and its quality is very high. It is primarily intended for the production of technical wood.

### 2.2 Laboratory work
### 2.2. Laboratorijsko istraživanje

Discs, approximately 5 cm thick, were cut at breast height (1.3 m). Radial segments were taken from the north-south section along the entire radius, starting from pith to bark. To analyse the wood anatomical characteristics (FL (mm), DCWT (μm) and FLD (μm)), half the length of the test tube (one radius) was used which includes the segment from pith to bark (Figure 1).

In order to perform the necessary microscopic analyses and determine the dimensions of wood fibres, a maceration procedure was applied. It is a process of chemical decomposition of wood mass in order to dis-

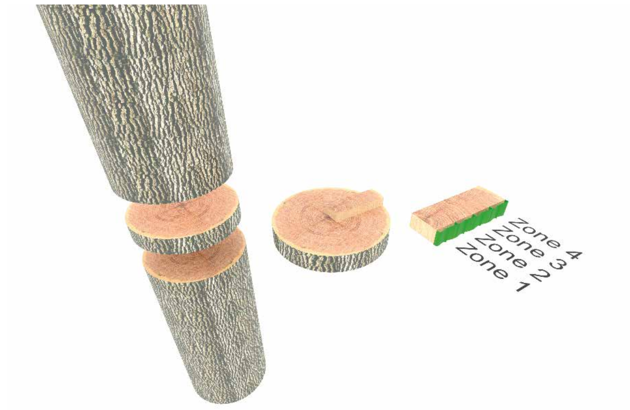



**Figure 1** Scheme of disc sampling and test tube preparation
**Slika 1.** Shema uzimanja ispitnih kolutova i izrade ispitnih uzoraka

integrate intercellular spaces and perform the necessary measurements. Using Franklin's reagent (1945), the intercellular substance was decomposed, and individual cells suitable for measurements were isolated. The maceration solution consists of 30% hydrogen peroxide and glacial acetic acid in a volume ratio of 1:1. Samples of wood primarily chopped to the size of a stick were placed in a test tube and treated with the prepared reagent. The material thus prepared was thermally treated in an oven at 65°C for 24 hours until it turned into pulp. After rinsing with distilled water, measurable single xylem cells were obtained.

Within each tree, four zones were selected – first near the pith, second in the juvenile part of the tree, third including the central part of the xylem and fourth located in the sapwood zone. Thirty undamaged wood fibres were sampled in each zone, meaning 120 per tree, or 720 fibres within the entire study area. Trees from the first site were 122, 121 and 119 years old, while trees from the second site were 120, 180 and 175 years old. In this research, the juvenile wood includes about 40 annual rings apart from two trunks from MU „Kupinske grede" (Donji Srem) that are 180 years old, so by these trees juvenile wood occupies about 60-70 growth rings. All investigated characteristics were measured using „Boeco" microscope, connected with specialised software with appropriate calibration. FL was measured at 40x magnification, while DCWT and FLD were measured at 400x magnification.

Statistical analyses were performed using the statistical program STATISTICA 7.0 (StatSoft Inc. 2004). Factorial analysis of variance (ANOVA) was used to test significance of differences in selected fibre characteristics between sites and in pith to bark direction. The one-way analysis of variance (ANOVA) was used to test significance of differences between tress within each site and Tukey's post hoc test for comparison between four zones within populations.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

Statistical values of fibre characteristics of pedunculate oak wood from both sites are given in Table 1.

In MU „Raškovica-Smogvica" within Gornji Srem, the groundwater level is quite deep, usually 2-2.5 m and 3-3.5 m (Nikolić, 2016). However, nearby is the River Bosut, which presumably contributes to additional wetting of this habitat, provides favourable water-air properties of humogley soil (Nikolić, 2016). The humus-accumulative horizon goes to a depth of 55 cm, and the ratio of the total sand fraction to the total clay and powder fraction is 1: 2.5 (Nikolić, 2016).

On the other hand, MU „Kupinske grede" is characterized by fluvisol-type soil, whose humus-accumulative horizon (0-35 cm) is shallower than humogley, which means that this soil is poorer in nutrients than the previous one (Nikolić, 2016). Also, MU „Kupinske grede" is in a depression where, due to the granulometric composition of fluvisol and low permeability, water stagnates (anaerobic conditions) and its uptake by pedunculate oak is difficult. The ratio of the total sand fraction to the total clay and powder fraction is 1:19, which means that the water-air properties of this soil and water capacity are much worse than those of the humogley present in MU „Raškovica-Smogvica" (Nikolić, 2016). Based on the mentioned habitat conditions prevailing in the two investigated sites, it can be concluded that ecological, primarily hydrological conditions in the area of MU „Raškovica-Smogvica" are more favourable for pedunculate oak development than site conditions in the area of MU „Kupinske grede". As a result, greater dimensions of wood fibres were determined in Gornji Srem – MU „Raškovica-Smogvica".

**Table 1** Statistical values of fibre characteristics of pedunculate oak wood from studied sites
**Tablica 1.** Statističke vrijednosti svojstava vlakanaca drva hrasta lužnjaka s oba staništa

| Site / *Stanište* | Value / *Vrijednost* | FL / *DV*, mm | DCWT / *DDS*, mm | FLD / *PLV*, mm |
|---|---|---|---|---|
| Gornji Srem | $N_{mean}$ | 1.35 | 13.16 | 20.14 |
| | $N_{min}$ | 0.71 | 6.98 | 12.08 |
| | $N_{max}$ | 1.97 | 22.19 | 28.93 |
| | $S_d$ | 0.25 | 2.57 | 3.09 |
| | Cv | 18.52 | 19.53 | 15.34 |
| Donji Srem | $N_{mean}$ | 1.33 | 12.66 | 19.76 |
| | $N_{min}$ | 0.65 | 5.62 | 9.90 |
| | $N_{max}$ | 1.96 | 19.90 | 31.12 |
| | $S_d$ | 0.22 | 2.52 | 3.90 |
| | Cv | 16.54 | 19.91 | 19.74 |

$N_{mean}$ – mean value / *aritmetička sredina*, $N_{min}$ – minimum value / *minimum*, $N_{max}$ – maximum value / *maksimum, Sd* – standard deviation / *standardna devijacija*, *Cv* – coefficient of variation / *koeficijent varijacije*, FL – fibre length / *DV – duljina vlakanaca*, DCWT – double cell wall thickness / *DDS – dvostruka debljina stijenki*, FLD – fibre lumen diameter / *PLV – promjer lumena vlakanaca*

Based on the results shown in Table 1, we can conclude that mean values of all investigated characteristics were greater in the area of Gornji Srem, MU „Raškovica-Smogvica". From the calculated coefficient of variation (Table 1), we can deduce that FL is more variable in MU „Raškovica-Smogvica", while other two characteristics are more variable in the area of MU „Kupinske grede".

The mean values of FL are in the range reported by Mladenova *et al*. (2017), between 1.02 mm for Hungarian oak and 1.46 mm for sessile oak from different sites in Bulgaria. However, Nazari *et al*. (2020) reported fibres shorter than 1 mm in Persian oak wood (mean value was 0.87 mm). All of these differences could be explained by individual genetic and silvicultural impacts. Keleş and Savaci (2021) determined that seasonality considerably influenced fibre length in pedunculate oak wood. Longer fibres in the first growing period (1.22 mm) are closer to the results obtained from this research, although the sampling approach was different. Sousa *et al*. (2009) examined the wood anatomy of the cork oak. They established greater mean values of fibre width and double wall-thickness than in this research (approximately 23.5 μm, and 18 μm, respectively).

Significant differences in FL and DCWT were detected between two sites (Table 2). Studies by Arend and Fromm (2007) and De Micco *et al.* (2016) reported that fibre dimensions are sensitive to environmental fluctuations, indicating that their dimensions decreased with low water availability. Our results coincide with these because longer wood fibres of pedunculated oak were determined in the area with better water-air properties and more favourable water capacity (MU „Raškovica-Smogvica"), compared to another site (MU „Kupinske grede"). Those site conditions, due to water stagnation, shallower humus-accumulative horizon and less suitable ratio of the total sand fraction to the total clay and powder fraction, are less desirable for pedunculated oak development. Likewise, highly significant differences in Persian oak fibre length were observed at two sites differentiated by altitude and slope (Nazari *et al*. 2020).

As for changing of observed characteristics with cambial age (distance from pith divided into four zones) (Table 2, Figure 2, 3 and 4), we can conclude that all characteristics increased with cambial age from pith to bark in the area of MU „Raškovica-Smogvica" (Gornji Srem). On the other side, in the area of MU „Kupinske grede" (Donji Srem), there is a linear increase of an average DCWT and FLD with cambial age (Figure 3 and 4), while FL gradually increases starting

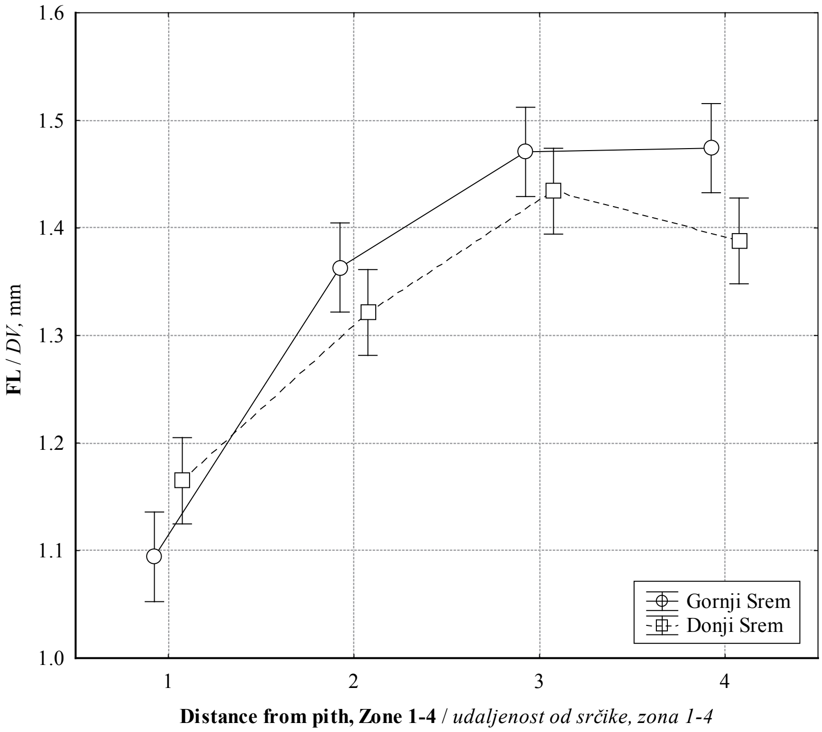



**Figure 2** Radial distribution of fibre length (FL) of pedunculate oak wood from two sites
**Slika 2.** Raspored duljine vlakanaca (DV) drva hrasta lužnjaka s dva staništa u radijalnom smjeru

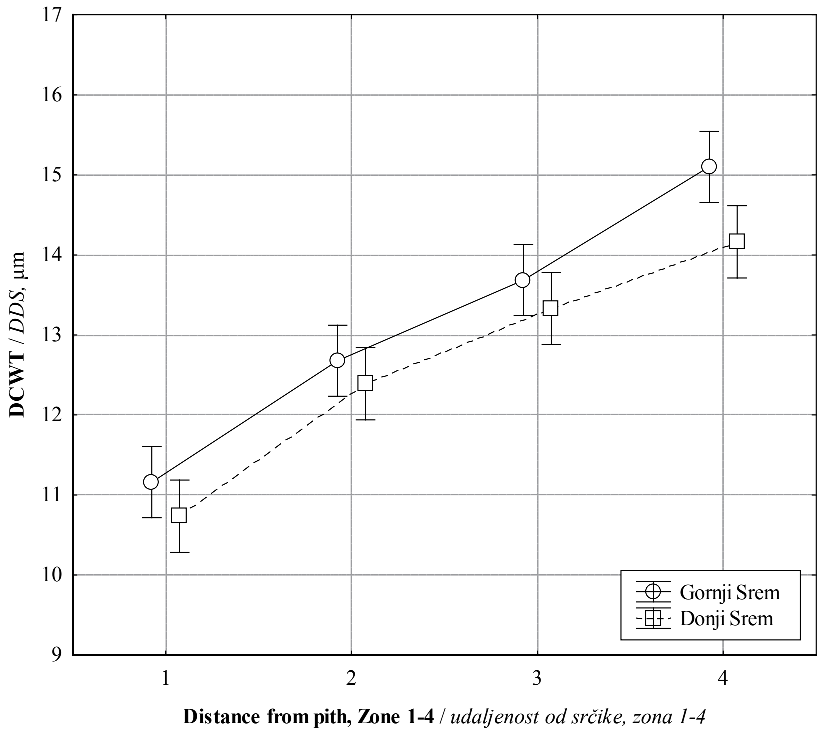



**Figure 3** Radial distribution of double cell-wall thickness (DCWT) of pedunculate oak wood from two sites
**Slika 3.** Raspored dvostruke debljine stijenki (DDS) drva hrasta lužnjaka s dva staništa u radijalnom smjeru

from the pith, and then along juvenile and central xylem zone. In the final zone (sapwood zone), a gradual reduction of FL can be noticed, bearing in mind that they previously reached their culmination (Figure 2). Panshin and de Zeeuw's (1980) early findings report that hardwood fibres exhibit appreciable postcambial elongation, considering juvenile and mature phases. The juvenile phase reflects a rapid increase in cell length, while the functioning of the mature cambium is stabilised in the mature phase. Old age in trees brings a reduction in fibre length. The same authors find a similar pattern of radial increase in cell-wall thickness.

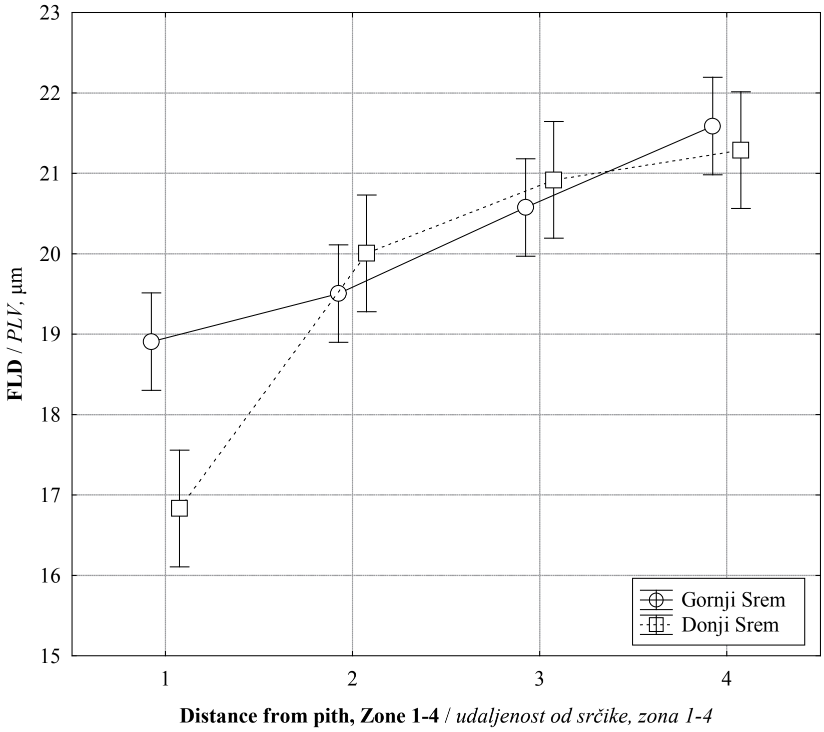



**Figure 4** Radial distribution of fibre lumen diameter (FLD) of pedunculate oak wood from two sites
**Slika 4.** Raspored promjera lumena vlakanaca (PLV) drva hrasta lužnjaka s dva staništa u radijalnom smjeru

**Table 2** Results of analysis of variance for fibre characteristics of pedunculate oak wood from two sites and in pith to bark direction, divided into 4 zones
**Tablica 2.** Rezultati analize varijance svojstava vlakanaca drva hrasta lužnjaka s dva staništa i u smjeru od srčike prema kori; podjela u četiri zone

| **Source of variation** *Izvor varijabilnosti* | **FL** / *DV*, mm | | **DCWT** / *DDS*, µm | | **FLD** / *PLV*, µm | |
|---|---|---|---|---|---|---|
| | *F* | *p* | *F* | *p* | *F* | *p* |
| Site / *stanište* | 13.57 | **0.000247** | 9.68 | **0.001932** | 2.53 | 0.111889 |
| Zones of distance from pith *zone udaljenosti od srčike* | 28.65 | **0.000000** | 94.05 | **0.000000** | 41.65 | **0.000000** |
| Site × Zones of distance from pith *stanište × zone udaljenosti od srčike* | 55.67 | **0.000000** | 0.85 | 0.468224 | 6.03 | **0.000465** |

FL –fibre length / *DV – duljina vlakanaca*, DCWT – double cell wall thickness / *DDS – dvostruka debljina stijenki*, FLD – fibre lumen diameter / *PLV – promjer lumena vlakanaca*

Rao *et al*. (1997) showed that latewood libriform fibre diameter and wall thickness in pedunculate oak increased significantly with ring number from pith. Determined mean values of fibre diameter and double cell wall thickness are a bit lower than this research results. Helinska-Raczkowska and Fabisiak (1991) concluded that fibre length in sessile oak wood increased in the first 30 growth rings. Based on the radial fibre length variation in eight oak species, other authors concluded that the juvenile wood usually comprises 30-40 annual rings (Hamilton, 1961; Farmer, 1969; Taylor, 1979; Petrić and Ščukanec, 1980; Furukawa *et al*., 1983). In this research, the juvenile wood includes about 60 annual rings bearing in mind that trees are older than 120 years apart from two trunks from MU „Kupinske grede" (Donji Srem) that are 180 years old, so in these trees, juvenile wood occupies a bit more than 60 growth rings. According to Eaton *et al*. (2016), the most valuable oak wood is produced in high mixed forests on fertile sites with long economic rotations, about 130 years for pedunculate oak. This implies that some of the used trees are possibly overmature. The same authors (Helinska-Raczkowska and Fabisiak, 1991) deduced that the length of mature anatomical elements, including wood fibres, is from 10 to 20 % greater than the length of juvenile wood anatomical elements of oak, and this coincides with our results. Variations in fibre characteristics were investigated in other hardwood species, such as poplar (Ištok *et al*., 2017), birch (Luostarinen and Möttönnen, 2010) and eucalyptus (Carrillo *et al*., 2015), showing similar differences and trends in radial variations.

Comparing mean values between individual trees inside study sites, we can establish significant differences in fibre characteristics among trees within both

**Table 3** Results of analysis of variance for fibre characteristics of pedunculate oak wood within-population from each site
**Tablica 3.** Rezultati analize varijance svojstava vlakanaca drva hrasta lužnjaka unutar populacije svakog staništa

| **Source of variation** *Izvor varijabilnosti* | **Site** *Stanište* | **FL** / *DV*, mm | | **DCWT** / *DDS*, µm | | **FLD** / *PLV*, µm | |
|---|---|---|---|---|---|---|---|
| | | *F* | *p* | *F* | *p* | *F* | *p* |
| Trees *stabla* | Gornji Srem | 6.45 | 0.001776 | 3.762 | 0.024167 | 8.81 | 0.000185 |
| | Donji Srem | 17.38 | 0.000000 | 21.88 | 0.000000 | 58.22 | 0.000000 |

FL –fibre length / *DV – duljina vlakanaca*, DCWT – double cell wall thickness / *DDS – dvostruka debljina stijenki*, FLD – fibre lumen diameter / *PLV – promjer lumena vlakanaca*

**Table 4** Fibre characteristics of pedunculate oak wood within population from each site depending on distance from pith (Post hoc Tukey's HSD test)
**Tablica 4.** Svojstva vlakanaca drva hrasta lužnjaka unutar populacije svakog staništa ovisno o udaljenosti od srčike (Post hoc Tukeyjev HSD test )

| **Site** *Stanište* | **Distance from pith, Zone 1-4** *Udaljenost od srčike, zona 1-4* | **FL** / *DV*, mm | **DCWT** / *DDS*, µm | **FLD** / *PLV*, µm |
|---|---|---|---|---|
| Gornji Srem | 1 | 1.09b | 11.16a | 18.91a |
| | 2 | 1.36c | 12.68b | 19.50ab |
| | 3 | 1.47a | 13.69c | 20.58bc |
| | 4 | 1.47a | 15.10d | 21.59c |
| Donji Srem | 1 | 1.16c | 10.69a | 16.81b |
| | 2 | 1.32a | 12.39b | 20.01a |
| | 3 | 1.43b | 13.33c | 20.92a |
| | 4 | 1.39ab | 14.16d | 21.29a |

FL –fibre length / *DV – duljina vlakanaca*, DCWT – double cell wall thickness / *DDS – dvostruka debljina stijenki*, FLD – fibre lumen diameter / *PLV – promjer lumena vlakanaca*
*Average values in the same column with different letter (a, b, c, d) are statistically different for p <0.05 (Post hoc Tukey's HSD test). / *Prosječne vrijednosti u istom stupcu s različitim slovom (a, b, c, d) statistički su različite za r <0,05 (Post hoc Tukeyjev HSD test).*

pedunculate oak populations, all highly significant in Donji Srem (Table 3). This could be explained by more differences in the microenvironment of each tree, as well as by differences in the genetic constitution of each tree (Tsoumis, 1991), especially in Donji Srem.

Observing FL in different zones from the pith outwards within sites, we can conclude that in the juvenile wood of all trees from both sites this parameter is statistically less significant compared to the other zones (Table 4). Going from pith to bark within the mature wood, FL increases in the area of MU „Raškovica-Smogvica" until the last zone. However, in trees from another site (MU „Kupinske grede"), it decreases in the last zone. DCWT statistically significantly increases from pith to bark. FLD increases significantly with cambial age in the MU „Raškovica-Smogvica", while in another site, trees have significantly narrower fibre lumens in the juvenile wood and its value is somewhat the same in the other three zones going to the bark, so there are no statistically significant differences in these three zones (Table 4).

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

In this paper, anatomical characteristics of wood fibres (FL, DCWT and FLD) of pedunculate oak in the area of Ravni Srem were investigated. All measured characteristics increase from pith to bark apart from FL in MU „Kupinske grede" – Donji Srem that reaches maximum values in the central part of the wood and then decreases towards the bark. Mean values of all three measured characteristics are greater in the area of Gornji Srem.

Based on the calculated coefficient of variation, it was concluded that FL is more variable in MU „Raškovica-Smogvica", unlike the other two characteristics, which are more variable in the area of MU „Kupinske grede". Dimensions of all measured wood fibre characteristics have greater values in the area of MU „Raškovica-Smogvica", due to more favourable hydrological conditions for growth and development of pedunculate oak.

Regarding tree age, results obtained in this study indicate the presence of too mature trees of this species, explaining radial trends in FL. More detailed information on wood properties of pedunculate oak from these two sites would better characterise wood quality and possible alternative use of too mature trees. The recommendation is to monitor fluctuations of groundwater level during longer time in order to establish complete relation between hydrological factors and anatomical characteristics of pedunculate oak wood fibres.

## 5 REFERENCES
## 5. LITERATURA


1. Arend, M.; Fromm, J., 2007: Seasonal change in the drought response of wood cell development in poplar. Tree Physiology, 27: 985-992.
2. Carrillo, I.; Aguayo, M. G.; Valenzuela, S.; Teixeira Mendonça, R.; Elissetche, J. P., 2015: Variations in wood anatomy and fiber biometry of *Eucalyptus globulus* genotypes with different wood density. Wood Research, 60 (1): 1-10.
3. De Micco, V.; Battipaglia, G.; Balzano, A.; Cherubini, P.; Arrone, G., 2016: Are wood fibres as sensitive to environmental conditions such as vessels in tree rings with intra-annual density fluctuations (IADFs) in Mediterranean species? Trees, 30: 971-983.
4. Deret-Varcin, E., 1983: Etude comparative de la qualite du bois de trois types de chenes (rouvres, pedoncules et intermediaires) en foret de Morimond. Annals of Forest Science, 40: 373-398.
5. Eaton, E.; Caudullo, G.; Oliveira, S.; de Rigo, D., 2016: *Quercus robur* and *Quercus petraea* in Europe: distribution, habitat, usage and threats. In: European Atlas of Forest Tree Species. Luxembourg, Publ. Off. EU.
6. Farmer, Jr. R. E., 1969: Phenotypic variation in specific gravity and fiber length of cherrybark oak. Tappi Journal, 52: 317-319.
7. Feuillat, F.; Dupouey, J.-L.; Sciama, D.; Keller, R., 1997: A new attempt at discrimination between *Quercus petraea* and *Quercus robur* based on wood anatomy. Canadian Journal of Forest Research, 27 (3): 343-351.
8. Franklin, G. L., 1945: Preparation of thin-wood sections of synthetic resins and wood-resin composites, and a new macerating method for wood. Nature, 155: 51.
9. Furukawa, I.; Sekoguchi, M.; Matsuda, M.; Sukano, T.; Kishimoto, J., 1983: Wood quality of small hardwoods – horizontal variations in the length of fiber and vessel elements in seventy-one species of small hardwoods. Hardwood Res. 2, Hardwood Lab.
10. Hacke, U. G.; Sperry, J. S.; Pockman, W. T.; Davis, S. D.; McCulloh, K. A., 2001: Trends in wood density and structure are linked to prevention of xylem implosion by negative pressure. Oecologia, 126: 457-461.
11. Hamilton, J. R., 1961: Variation of wood properties in southern red oak. Forest Products Journal, 11: 267-271.
12. Helinska-Raczkowska, L.; Fabisiak, E., 1991: Radial variation and growth rate in the length of the axial elements of sessile oak wood. IAWA Bulletin, 12 (3): 257-262.
13. Ištok, I.; Šefc, B.; Hasan, M.; Popović, G.; Sedlar, T., 2017: Fiber characteristics of white poplar (*Populus alba* L.) juvenile wood along the Drava river. Drvna industrija, 68 (3): 241-247. https://doi.org/10.5552/drind.2017.1729
14. Jacobsen, A. L.; Ewers, F. W.; Pratt, R. B.; Paddock, W. A.; Davis, S. D., 2005: Do xylem fibers affect vessel cavitation resistance? Plant Physiology, 139: 546-556.
15. Keleş, S. Ő.; Savaci, G., 2021: Seasonal variation of morphological traits, wood formation and soil properties differs between *Quercus robur* L. and *Robinia pesudoacacia* L. samplings. Scandinavian Journal of Forest Research, 36 (5): 344-353. https://doi:10.1080/02827581.2021.1941237
16. Kesić, L.; Cseke, K.; Orlović, S.; Stojanović, D.; Kostić, S.; Benke, A.; Borovics, A.; Stojnić, S.; Avramidou, E. V., 2021: Genetic diversity and differentiation of pedunculate oak (*Quercus robur* L.) populations at the southern margin of its distribution range – implications for conservation. Diversity, 13 (8): 371. https://doi.org/10.3390/d13080371
17. Klumpers, J.; Janin, G.; Becker, M.; Levy, G., 1993: The influences of age, extractive content and soil water on wood color in oak: the possible genetic determination of wood color. Annals of Forest Science, 50: 403-409.
18. Letić, Lj.; Nikolić, V.; Savić, R., 2017: Uticaj režima vlaženja na sušenje šuma u GJ „Raškovica-Smogvica". Šumarstvo, 1-2: 53-64 (online). http://www.srpskosumarskoudruzenje.org.rs/pdf/sumarstvo/2017_1-2/sumarstvo2017_1-2_rad04.pdf (Accessed Apr 1, 2022).
19. Levanič, T.; Čater, M.; McDowell, N. G., 2011: Associations between growth, wood anatomy, carbon isotope discrimination and mortality in a *Quercus robur* forest. Tree Physiology, 31: 298-308. https://doi:10.1051/forest:2008033.doi:10.1093/treephys/tpq111
20. Levy, G.; Becker, M.; Duhamel, D., 1992: A comparison of the ecology of pedunculate and sessile oaks: radial growth in the centre and northwest of France. Forest Ecology and Management, 55: 51-63.
21. Luostarinen, K.; Möttönnen, V., 2010: Radial variation in the anatomy of *Betula pendula* wood from different growing sites. Baltic Forestry, 16 (2): 209-216.
22. Mladenova, D.; Todorova, A.; Bardarov, N., 2017: Study on the length of fibers of oak wood. Management of Sustainable Development, 63 (19): 61-64.
23. Nazari, N.; Bahmani, M.; Kahyani, S.; Humar, M.; Koch, G., 2020: Geographic Variations of the Wood Density and Fiber Dimensions of the Persian Oak Wood. Forests, 11: 1-15. https://doi:10.3390/f11091003
24. Nepveu, G., 1984: Controle hereditaire de la densite et de la retractibilite du bois de trois especes de Chene (*Quercus petraea, Quercus robur* et *Quercus rubra*). Silvae Genetica, 33: 110-115.
25. Nikolić Jokanović, V.; Letić, Lj.; Savić, R.; Jokanović, D., 2019: Influence of groundwater level fluctuations on decline of higrophilous pedunculate oak forest. Fresenius Environmental Bulletin, 28 (8): 5989-5996.
26. Nikolić Jokanović, V.; Vulević, T.; Lazarević, K., 2020: Risk assessment of forest decline by application of geostatistics and multi-criteria analysis. Journal of Hydrology and Hydromechanics, 68: 1-8. https://doi.org/10.2478/johh-2020-0013
27. Nikolić, V., 2016: Uticaj režima vlaženja na karakteristike staništa hrasta lužnjaka (*Quercus robur* L.) u Ravnom Sremu. Doktorska disertacija u rukopisu. Šumarski fakultet Univerziteta u Beogradu.
28. Panshin, A. J.; de Zeeuw, C., 1980: Textbook of wood technology. New York, McGraw-Hill.
29. Petrić, B.; Šćukanec, V., 1980: Neke strukturne karakteristike juvenilnog i zrelog drva hrasta lužnjaka (*Quercus robur* L.). Drvna industrija, 31: 81-86.
30. Radaković, N.; Stajić, B., 2021: Climate signals in earlywood, latewood and tree-ring width chronologies of sessile oak (*Quercus petraea* (Matt.) Liebl.) from Majdanpek, North-Eastern Serbia. Drvna industrija, 72 (1): 79-87. http://dx.doi.org/10.5552/drvind.2021.2016
31. Rao, R. V.; Aebischer, D. P.; Denne, M. P., 1997: Latewood density in relation to wood fibre diameter, wall thickness, and fibre and vessel percentages in *Quercus robur* L. IAWA Journal, 18 (2): 127-138. https://doi.org/10.1163/22941932-90001474
32. Sousa, V. B.; Leal, S.; Quilho, T.; Pereira, H., 2009: Characterization of cork oak (*Quercus suber*) wood anatomy. IAWA Journal, 30 (2): 149-161.

33. Taylor, F. W., 1979: Property variation within stem of selected hardwoods growing in the Mid-South. Wood Science, 11: 193-199.
34. Tsoumis, G., 1991: Science and technology of wood: structure, properties, utilization. New York, Chapman & Hall, pp. 66-83.
35. Tumajer, J.; Treml, V., 2016: Response of floodplain pedunculate oak (*Quercus robur* L.) tree-ring width and vessel anatomy to climatic trends and extreme hydroclimatic events. Forest Ecology and Management, 379: 185-194. https://doi.org/10.1016/j.foreco.2016.08.013
36. Vilotić, D., 1992: Anatomska građa stabla virgilijskog hrasta (*Quercus virgiliana* /Ten./Ten.) na različitim staništima Deliblatske peščare. Doktorska disertacija u rukopisu. Šumarski fakultet Univerziteta u Beogradu.
37. Vilotić, D., 2000: Uporedna anatomija drveta. Univerzitetski udžbenik. Šumarski fakultet Univerziteta u Beogradu, 1-176.
38. Wagenführ, R.; Scheiber, C., 2006: HOLZATLAS. Leipzig, VEB Fachbuchverlag.
39. Zimmermann, M. H., 1983: Xylem structure and the ascent of sap. Berlin-Heidelberg-New York-Tokyo, Springer-Verlag, 1-143. https://doi.org/10.1007/BF02895041
40. ***StatSoft Inc., 2004: STATISTICA, Version 7.

**Corresponding address:**

**IVA IŠTOK**
University of Zagreb, Faculty of Forestry and Wood Technology, Institute of Wood Science,
Svetošimunska cesta 23, 10000 Zagreb, CROATIA, e-mail: iistok@sumfak.unizg.hr

Michał Słonina, Jerzy Smardzewski[1]

# Starch Impregnation Effect of Testliner Paper on Stiffness of Honeycomb Panels with Slender Cells

# Učinak impregnacije testliner papira škrobom na krutost ploča sa srednjicom od papirnog saća uskih ćelija

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 2. 3. 2022.
Accepted – prihvaćeno: 3. 4. 2022.
UDK: 547.458.61; 630*86; 676.2-027.33
https://doi.org/10.5552/drvind.2022.0024



**ABSTRACT** • *The study aimed to determine the effect of impregnation with modified starch of recycled paper (Testliner) on elasticity constants of slender core cells and the influence on the elasticity constants and strength of honeycomb with facings made of thin particleboards. The experimental tests were carried out on beams subjected to three-point bending. It was shown that slender hexagonal cells significantly differentiate their elastic properties and elastic properties of honeycomb panels in the main directions of orthotropy. Impregnation of the Testliner paper with modified starch reduces the values of the modulus of elasticity of the cells by about 8.8 % and reduces the values of the modulus of elasticity of the honeycomb panels by at least 6.9 %. Analytical solutions that do not take into account the structural form of the core cannot be used to calculate the modulus of elasticity of sandwich panels with hexagonal core cells.*

**KEYWORDS:** *honeycomb; hexagonal cell; orthotropy; impregnation; elastic properties; strength*

**SAŽETAK** • *Cilj predstavljenog istraživanja bio je utvrditi učinak impregnacije recikliranog papira (testliner papira) modificiranim škrobom na konstante elastičnosti uskih ćelija papirne jezgre i učinak na konstante elastičnosti papirnog saća obostrano obloženoga tankim pločama ivericama. Eksperimentalna su ispitivanja provedena na uzorcima podvrgnutima savijanju u tri točke. Pokazalo se da vitke heksagonalne ćelije u glavnim smjerovima ortotropije znatno diferenciraju svoja svojstva elastičnosti, kao i svojstva elastičnosti ploča s jezgrom od papirnog saća. Impregnacija testliner papira modificiranim škrobom smanjuje vrijednosti modula elastičnosti ćelija za otprilike 8,8 %, ali i vrijednosti modula elastičnosti ploča sa srednjicom od papirnog saća za najmanje 6,9 %. Analitička rješenja kojima se ne uzima u obzir strukturni oblik jezgre ne mogu se upotrijebiti za proračun modula elastičnosti tzv. sendvič-ploča, čija jezgra ima heksagonalne ćelije.*

**KLJUČNE RIJEČI:** *papirno saće; heksagonalne ćelije; ortotropija; impregnacija; elastična svojstva; čvrstoća*

[1] Authors are researchers at Poznan University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Furniture Design, Poznan, Poland.

# 1 INTRODUCTION
# 1. UVOD

Kraft paper, which is commonly used in the production of light wood-based honeycomb panels, is produced by chemical defibering with at least 80 % virgin fibers. It is widely used as a packaging material (Twede *et al.*, 2015). Paper as such can be recycled up to six times, but it is assumed that the life cycle of cellulose fiber in Europe has an average of 3.5 times (Ghinea *et al.*, 2017). As reported by European and global organizations monitoring the pulp and paper industry, in 2018, more than half of the global paper production was made of recycled paper known as Testliner. For hundreds of years, the paper industry has been using various methods of protecting paper against moisture (sizing), including impregnation. A side effect of impregnation may be a reduction in the paper strength, which was confirmed in the work of Pohl (2009). In recent years, efforts have been made to develop environmentally friendly substances that increase the hydrophobic properties of cellulose fibers. These are vegetable proteins and starch (Lagus, 2019; Ren and Li, 2005). Starch is the second most used agent in the paper industry, right after clay fillers. The usual cellulose pulp supplement is within the range of 2 % – 4 % (Maurer, 2009; Zeng, 2013). Its presence increases the mechanical resistance of the paper to tearing, improves the quality of prints, and most of all increases the resistance to moisture by filling the pores in the cellulose fiber mesh. In 2009, modified starch accounted for 66 % of the starch used for sizing (Zeng, 2013; Słonina *et al.*, 2022).

Lightweight, wood-based honeycomb boards are of great use in the production of furniture (Librescu and Hause, 2000; Michanickl, 2006). However, a significant limitation of the widespread use of honeycomb boards in the furniture industry is their low stiffness and strength, compared to classic wood materials, such as particleboard, MDF board or plywood. (Shalbafan *et al.*, 2012; Smardzewski, 2013; Smardzewski and Jasińska, 2016; Khojasteh-Khosro *et al.*, 2020). However, these boards are distinguished by an attractive quality factor (Peliński and Smardzewski, 2020; Beckers *et al.*, 2021).

Scientific research of three-point bent sandwich panels consisting of a core with hexagonal cells concerned the modeling of deflection of panels with regular hexagonal cells (Chen, 2011), facings damage, and core cell collapse (Steeves and Fleck, 2004; Crupi *et al.*, 2012; Sun *et al.*, 2017; Palomba *et al.*, 2019; Hussain *et al.*, 2019; Wang *et al.*, 2019; Ma *et al.*, 2021), damage to the paper core cells (Chen *et al.*, 2011; Chen and Yan, 2012; Hao *et al.*, 2018).

Research has also begun on protecting wood-based cellular panels against the destructive effects of variable temperature and air humidity (Bekhta *et al.*, 2006; Ozarska and Harris, 2007; Nilsson *et al.*, 2017; Słonina *et al.*, 2022).

On the other hand, the effect of the hydrophobic impregnation of paper on the orthotropic properties of slender hexagonal core cells and their influence on the mechanical properties of the cell plates was not investigated. Therefore, the study aimed to determine the effect of impregnation with modified starch of Testliner paper on the elasticity constants of slender core cells and determine the influence of these changes on the elasticity constants and strength of honeycomb panels with facings made of thin particleboards.

# 2 MATERIALS AND METHODS
# 2. MATERIJALI I METODE

## 2.1 Shape and properties of honeycomb cells
## 2.1. Oblik i svojstva ćelija papirnog saća

The method of modeling hexagonal cells has been presented in numerous scientific papers (Gibson, 2005; Peliński *et al.*, 2017; Słonina *et al.*, 2020; Słonina *et al.*, 2022). They describe in detail the method of selecting the cell geometry and its production processes. For the purposes of this study, the shape of one slender cell was designed (Figure 1). The elongated, spindle-shaped geometry was to ensure strong orthotropic properties of the cell and the core made of paper. Table 1 lists the basic dimensions of the cell influencing its elastic properties.

The cells and cores of the honeycomb boards were made of paper Testliner-2 with a thickness of 0.15 mm and basis weight of 123 g/m$^2$ (Sam-Brew *et al.*, 2011; Słonina *et al.*, 2022). Testliner-2 paper was pro-

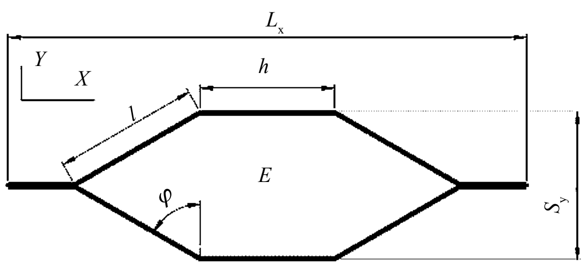



**Figure 1** Slender cell model
**Slika 1.** Model uskih ćelija

**Table 1** Geometric characteristics of test cell, where (Figure 1)
**Tablica 1.** Geometrijska svojstva ispitivanih ćelija: (sl. 1.)

| $S_y$, mm | $L_x$, mm | $l$, mm | $h$, mm | $t$, mm | $\varphi$, ° |
|---|---|---|---|---|---|
| 13.33 | 46.48 | 13.0 | 12.0 | 0.15 | 60 |

$\rho$ – relative density, $S_y$ – width, $L_x$ – length, $l$ – free wall length, $h$ – length of common wall, $t$ – wall (paper) thickness, $\varphi$ – angle of wall
*$\rho$ – relativna gustoća, $S_y$ – širina, $L_x$ – duljina, l – duljina slobodne stijenke, h – duljina kontaktne stijenke, t – debljina stijenke (papira), $\varphi$ – kut stijenke*

**Table 2** Physical and mechanical properties of materials used
**Tablica 2.** Fizička i mehanička svojstva upotrijebljenih materijala

| Code *Oznaka* | | Thickness, mm *Debljina*, mm | *MC*, % | Density, kg/m³ *Gustoća*, kg/m³ | $E_i$, MPa | | $MOE_i$, MPa | | $\upsilon_{ij}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *x* | *y* | *x* | *y* | *xy* | *yx* |
| PN | Mine | 0.15 | 5.72 | 686 | 5707 | 2188 | 46 | 16 | 0.411 | 0.147 |
| | SD | 0.01 | 0.32 | 32 | 672 | 113 | 1.8 | 0.30 | 0.043 | 0.023 |
| PS | Mine | 0.16 | 7.05 | 730 | 5190 | 2642 | 49 | 20 | 0.308 | 0.109 |
| | SD | 0.02 | 0.41 | 28 | 374 | 102 | 3.1 | 0.34 | 0.033 | 0.010 |
| PB | Mine | 2.77 | 6.76 | 942 | 4116 | 3445 | 14 | 10 | 0.161 | 0.129 |
| | SD | 0.02 | 0.53 | 18 | 276 | 210 | 2.3 | 1.50 | 0.027 | 0.026 |

PN – paper not impregnated with starch, PS – starch-impregnated paper, PB – particleboard, ($E_i$ – modulus of linear elasticity, $MOE_i$ – modulus of rupture, $\upsilon_{ij}$ – Poissons ratio, *i, j* – appropriately *x,y* – orthotropy directions, *SD* – standard deviation) / *PN – neimpregnirani papir, PS – papir impregniran škrobom, PB – ploča iverica (*$E_i$ *– modul linearne elastičnosti,* $MOE_i$ *– modul loma,* $\upsilon_{ij}$ *– Poissonov omjer, i, j – prikladnost, x,y – smjerovi ortotropije, SD – standardna devijacija)*

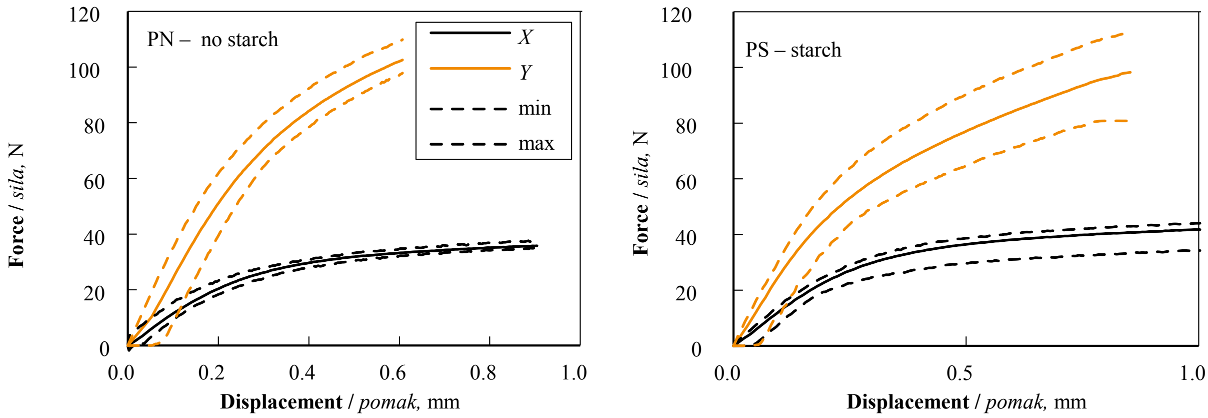



**Figure 2** Relationships between force and displacement in uniaxial tensile test of non-impregnated (PN) and impregnated (PS) paper; the dotted line marks the smallest and largest force values recorded for each type of sample
**Slika 2.** Odnos između sile i pomaka u jednoosnom vlačnom ispitivanju neimpregniranoga (PN) i impregniranoga (PS) papira; isprekidana linija označava najmanju i najveću zabilježenu silu za svaku vrstu uzorka

duced in the company HM Technology (HM Technology, Brzozowo, Poland). For cell formation, non-impregnated (PN) and impregnated (PS) papers were prepared with a 10 % aqueous solution of modified starch (patent number P.430486). The paper (Słonina *et al.*, 2020) presents in detail the method of paper impregnation, the method of forming cells, and obtaining cores. The elastic properties of the paper were determined in accordance with the standard (ISO 1924-2, 2008) and are presented in Table 2. The elastic properties of thin particleboard (PB) with a thickness of 3 mm, used to make the facings of the honeycomb boards, are also given (Egger, Rion-des-Landes, Francja). These properties were determined in accordance with the standard (ISO 13061-6, 2014). The uniaxial tensile characteristics of the papers and particleboard are shown in Figure 2 and 3.

Based on Figure 2 and the data in Table 2, it can be seen that the stiffness and strength of the paper in the machine direction (MD=*x*) is significantly higher compared to the properties in the cross-machine direction (CD=*y*). Material tests have also shown that impregnation of the paper with starch slightly reduces the modulus of elasticity in the (*x*) direction but increases its value in the (*y*) direction and slightly increases the tear strength of the paper. Therefore, it was decided to form the cells in further studies in such a way to make their orthotropy direction (*x*) (Figure 1) consistent with the cross direction (*y*) of the paper. Figure 3 also shows

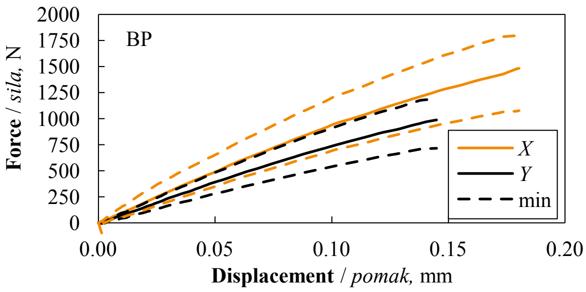



**Figure 3** Relationships between force and displacement in uniaxial tensile test of particleboard (PB); the dotted line marks the smallest and largest force values recorded for each type of sample
**Slika 3.** Odnos između sile i pomaka u jednoosnom vlačnom ispitivanju ploče iverice; isprekidana linija označava najmanju i najveću zabilježenu silu za svaku vrstu uzorka

that thin particleboards are characterized by strong orthotropy. Thus, it was decided that the direction of the orthotropy of the plate ($x$) should always coincide with the direction of the longer side of the cellular plate sample.

The cell relative density $\rho$ was calculated from the following Eq. (Peliński *et al.*, 2017):

$$\rho = 1 - \frac{F_s}{F^*} \quad (1)$$

Where: $F_s$ and $F^*$ the surface of the substance and the surface of the cell, respectively,

$$F^* = L_x \cdot S_y \quad (2)$$

$$S_y = 2\cdot(l\cdot\cos(\varphi) + t) \quad (3)$$

$$L_x = 2\cdot\left(\frac{h}{2} + l\cdot\sin(\varphi) + \frac{h}{2} - t\cot(\varepsilon)\right) \quad (4)$$

$$F^* = 4\cdot(l\cdot\cos(\varphi) + t)\left(h + l\cdot\sin(\varphi) - t\cdot\cot(\varepsilon)\right) \quad (5)$$

$$F_s = F^* - F_1 - F_2 - F_3 \quad (6)$$

$$F_1 = 2\cdot l\cdot\cos(\varphi)\cdot\left(h - 2\cdot t\cdot\cot(\varepsilon) + l\cdot\sin(\varphi)\right) \quad (7)$$

$$F_2 = 2\cdot\left(\left(l\cdot\cos(\varphi) + t\right) - 2\cdot t\right)\left(h - 2\cdot t\cdot\cot(\varepsilon)\right) \quad (8)$$

$$F_3 = 2\cdot l\cdot\sin(\varphi)\cdot\cos(\varphi)\cdot\left(l - t\cdot\cot(\varepsilon)\right) \quad (9)$$

Since it was assumed that hexagonal honeycomb cells are characterized by strong orthotropy resulting from their slender geometry, two longitudinal elasticity modules $E_x^c$, $E_y^c$, two Poisson's coefficients $\vartheta_{xy}^c$, $\vartheta_{yx}^c$, were calculated for a single cell, and Kirchhoff's module $G_{xy}^c$,

$$E_x^c = \frac{E_x\cdot t^3\cdot\left(\frac{h}{l} + \sin(\varphi)\right)}{l^3\cdot\cos^3(\varphi)} \quad (10)$$

$$E_y^c = \frac{E_x\cdot t^3\cdot\cos(\varphi)}{l^3\cdot\left(\frac{h}{l} + \sin(\varphi)\right)\cdot\sin^2(\varphi)} \quad (11)$$

$$G_{xy}^c = E_x\cdot\left(\frac{t}{l}\right)^3\cdot\frac{\frac{h}{l} + \sin(\varphi)}{\left(\frac{h}{l}\right)^2\cdot\left(1 + \frac{2\cdot h}{l}\right)\cdot\cos(\varphi)} \quad (12)$$

$$\vartheta_{xy}^c = \frac{\sin(\varphi)\cdot\left(\frac{h}{l} + \sin(\varphi)\right)}{\cos^2(\varphi)} \quad (13)$$

$$\vartheta_{yx}^c = \frac{\cos^2(\varphi)}{\left(\frac{h}{l} + \sin(\varphi)\right)\cdot\sin(\varphi)} \quad (14)$$

Table 3 presents the calculation results of the elastic properties of the core cells. It shows that the relative density of cells is constant and equal to 0.0785. In addition, the cell shows strong orthotropy; therefore, it will significantly affect the elastic properties of the modeled honeycomb panels. The influence of the impregnation with starch on Testliner paper on the elastic properties of the cells also seems to be significant. Impregnation reduces the values of the linear elasticity modulus by the Kirchhoff modulus. However, it does not change the value of the Poisson's coefficients, as these depend only on the cell geometry. With this in mind, samples of honeycomb panels with the longitudinal and transverse arrangement of the core cells were prepared for further research.

### 2.2 Honeycomb manufacturing and testing
### 2.2. Proizvodnja i ispitivanje ploče sa srednjicom od papirnog saća

On non-decorative particleboard surfaces, glue PVAc Woodmax FF12.47 class D2 delivered by Synthos Adhesives (Oświęcim, Poland) was applied in the amount of approximately 110 g/m$^2$. Then, a particleboard frame with a thickness of 16.1 mm was placed along the edges of one of the facing, and an expanded paper core with a thickness of 16.3 mm was inserted inside it. Care was taken that the longitudinal axis of the cell (x) was consistent with or perpendicular to the axis (x) of the particleboard. The assembly was closed with another particleboard to form a panel with a honeycomb core. The gluing process of the set took place in a hydraulic press Orma Macchine NPC/DIGIT 6/90 25x13 (Bergamo, Italy) for 25 minutes at a pressure of 0.7 MPa. For each type of impregnated and non-impregnated paper, six 22 mm thick panels were made. The panels were seasoned in laboratory conditions until a constant mass of samples was obtained, which proved that they maintained the hygroscopic equilibrium. After this time, the boards were cut into beams $w$=50 mm wide and 20 times their thickness plus 50 mm long. The beam samples were splitted in such a way as to obtain the longitudinal and transverse arrangement of the core cells (Fig. 4). For each type of

**Table 3** Physical and mechanical properties of non-impregnated and starch-impregnated cells
**Tablica 3.** Fizička i mehanička svojstva ćelija neimpregniranog papira i papira impregniranog škrobom

| **Code** *Oznaka* | $\rho$ | $E_i^c$, MPa | | $G_{ij}^c$, MPa | $\vartheta_{ij}^c$ | |
|---|---|---|---|---|---|---|
| | | *x* | *y* | *xy* | *xy* | *yx* |
| N | 0.0785 | 0.1255 | 0.0033 | 0.0129 | 6.1976 | 0.1614 |
| S | | 0.1141 | 0.0030 | 0.0118 | | |

$E_i^c$– modulus of linear elasticity, $\vartheta_{ij}^c$ - Poisson's ratio, $G_{ij}^c$ – Kirchhoff moduli, *i, j* – x, y, respectively - orthotropy directions) / $E_i^c$ – *modul linearne elastičnosti,* $\vartheta_{ij}^c$ – *Poissonov omjer,* $G_{ij}^c$ – *Kirchhoffovi moduli, i, j – x, y pravci ortotropije)*

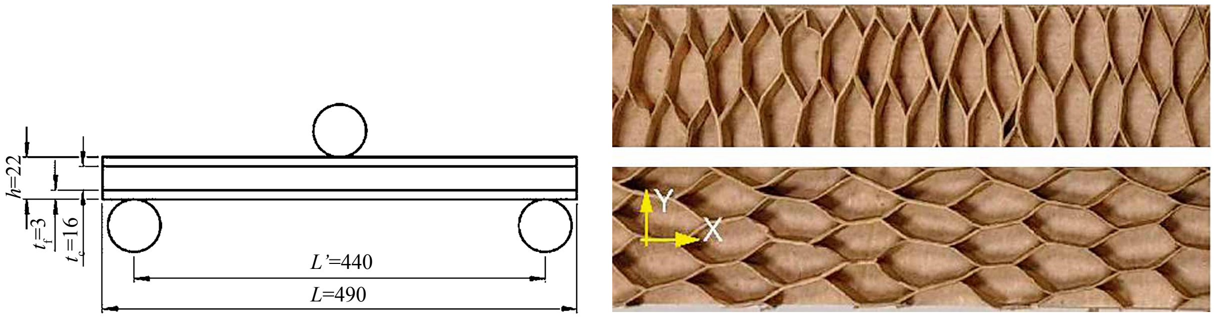



**Figure 4** Honeycomb boards samples
**Slika 4.** Uzorci ploča sa srednjicom od papirnog saća

core and impregnation, 10 samples were made, a total of 40 pieces.

The beams were subjected to a three-point bending (Fig. 4) according to the standard (EN 310, 1993) on a Zwick Z100 testing machine (Zwick GmbH, Ulm, Germany). During the tests, the value of the force was recorded with an accuracy of 2 N and the deflection of the beams in the direction of acting force with an accuracy of 0.01 mm. Then, for the test samples, based on the measured values of the maximum forces $F_{max}$ (N), modulus of rupture $MOR_{p(x,y)}$ (MPa) was calculated for each direction of orthotropy ($x$, $y$) from Eq. 15:

$$MOR_p = \frac{3 \cdot F_{max} \cdot L'^3}{2 \cdot w \cdot h^3} \tag{15}$$

Where: $F_{max}$ is the force at the fracture point (N), $L' = 20\ h$ is the length of the support span (mm), $h$ is the thickness of the beam (mm), $w$ is the width of the beam (mm). On the other hand, the linear elasticity modulus was calculated based on the relationship of force and deflection in the linear range $E_{p(x,y)}$ (MPa) for each direction of orthotropy ($x$, $y$) from Eq. 16:

$$E_{p(x,y)} = \frac{\left(0.4 \cdot F_{max} - 0.1 \cdot F_{max}\right) \cdot L'^3}{48 \cdot \left(f_{0.4Fmax} - f_{0.1Fmax}\right) \cdot I_s} \tag{16}$$

Where: $f_{0.4Fmax}$ is the deflection of the beam in mm for a load equal to $0.4 \cdot F_{max}$, $0.1 \cdot F_{max}$ (N), $I_s = \frac{w \cdot h^3}{12}$ is the crosssection moment of inertia ($mm^4$).

Bodig and Jayne (Bodig and Jayne, 1982) developed simplified equations for layered wood-based panels consisting of three orthotropic layers with symmetric facings. The equations developed by Bodig and Jayne may be used to calculate the stiffness of the sandwich panel if we assume each layer as a continuum. Of course, these equations are unable to account for cell geometry effect. Nevertheless (Chen and Yan, 2012), we tried to compare our simulated results with the estimates from Eqs. 17, 18 and 19:

$$E_{Px} = \frac{2 \cdot E_x^f \cdot t^f + E_x^c \cdot t^c}{h} \tag{17}$$

$$E_{Py} = \frac{2 \cdot E_x^f \cdot t^f + E_y^c \cdot t^c}{h} \tag{18}$$

$$G_{Pxy} = \frac{2 \cdot G_{xy}^f \cdot t^f + G_{xy}^c \cdot t^c}{h} \tag{19}$$

Where: $E_x^f$ – linear elastic modulus of the facing (PB), $E_x^c$, $E_y^c$ – core elasticity modulus in x, y direction, $G_{xy}^f$, $G_{xy}^c$ - Kirchhoff module of facing and core, $t^f$, $t^c$ – facing thickness and core thickness. The data for the calculations are summarized in Tables 2 and 3. In the case of particleboards, their Kirchhoff modulus was calculated in accordance with (Bodig and Jayne, 1982) and is equal $G_{xy}^f$ =1774 MPa.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

Figure 5 shows the method of deformation of beams subjected to three-point bending, and Figure 6 shows the relationship of force to deflection.

Figure 6 shows that the individual sample populations were characterized by high homogeneity, especially in terms of deflections corresponding to the linear elasticity of beams. Comparing the curves for the mean values, it can be seen that the maximum value of

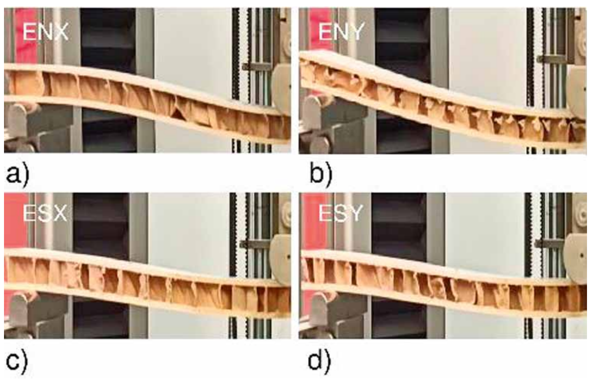



**Figure 5** Method of deformation of beams subjected to three-point bending: a, b) non-impregnated paper; c, d) impregnated paper; a, c) orthotropy direction $x$; b, d) orthotropy direction $y$
**Slika 5.** Načini deformacije ispitnih uzoraka (greda) podvrgnutih savijanju u tri točke: a), b) obično legende idu ispod tablice ( i u engl. tekstu)neimpregnirani papir; c), d) impregnirani papir; a), c) smjer ortotropije $x$; b), d) smjer ortotropije $y$

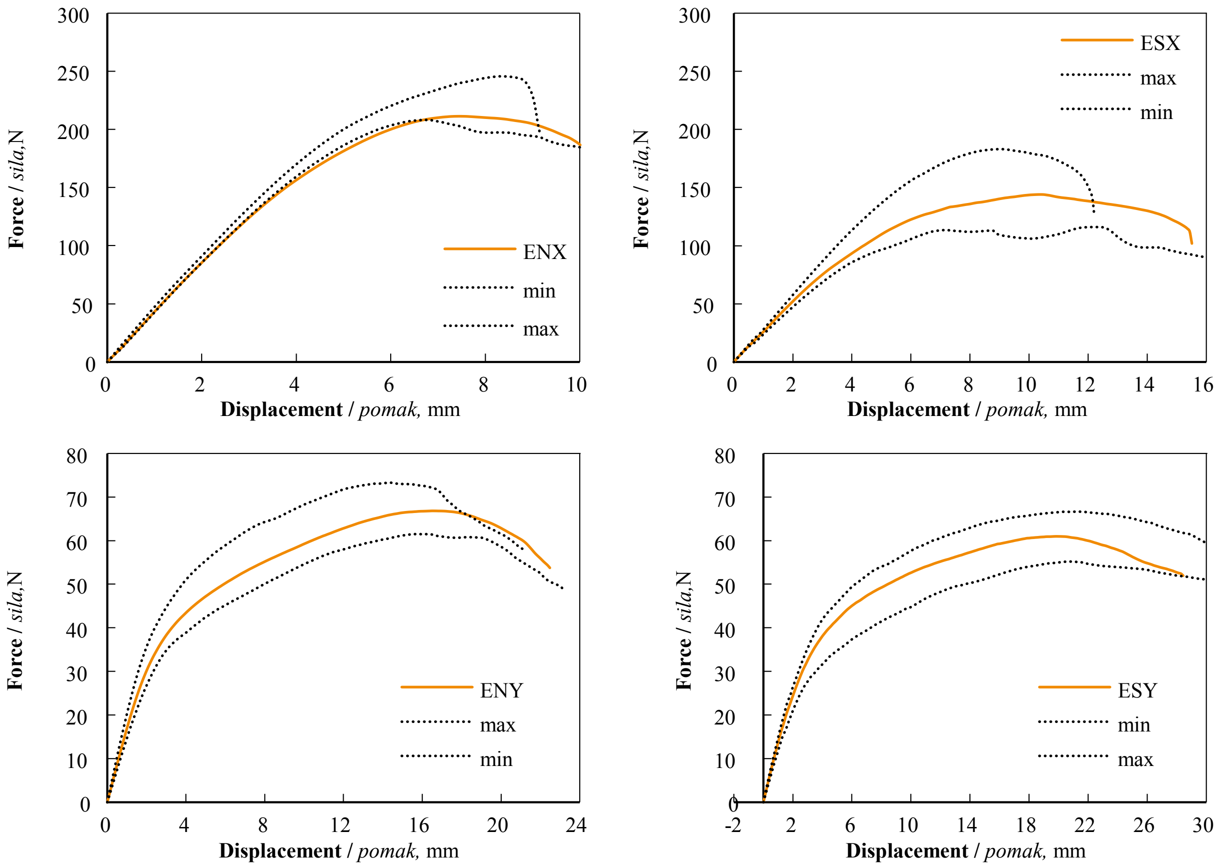



**Figure 6** Dependence of force on a deflection for beams subjected to bending: ENX, ENY – beams with non-impregnated paper and cells oriented in *x* and *y* direction, ESX, ESY – beams with impregnated paper, and cells oriented in *x* and *y* direction; the dotted line marks the smallest and largest force values recorded for each type of sample

**Slika 6.** Ovisnost sile o pomaku za grede podvrgnute savijanju: ENX, ENY – grede od neimpregniranog papira s ćelijama orijentiranima u smjeru *x* i *y*, ESX, ESY – grede od impregniranog papira s ćelijama orijentiranima u smjeru *x* i *y*; isprekidana linija označava najmanju i najveću zabilježenu silu za svaku vrstu uzorka

the force causing bending $F_{max}$=211 N occurs for beams ENX (with non-impregnated cells and for the direction of orthotropy ($x$)). The impregnation of the paper with starch, for the identical arrangement of cells (ESX), causes the value of the maximum destructive force to decrease to 144 N. The values of average destructive forces for the direction of orthotropy ($y$) are in a similar proportion. The maximum value of the force causing bending of ENY beams (with non-impregnated cells and for the orthotropy direction ($y$)) is equal to $F_{max}$=67 N. The starch impregnation of the paper reduces the maximum destructive force to 61 N. It follows that the stiffness of the beams in the ($y$) direction is less sensitive to the impregnation of the paper than in the ($x$) direction. Table 4 shows, however, that the slender cell of the paper core has a significant influence on the orthotropic properties of the honeycomb panel. The modulus of elasticity in the (x) axis is greater than the modulus of elasticity in the ($y$) axis by 61.5 % and 55.5 % for non-impregnated and impregnated cores, respectively. At the same time, the impact of impregnation of Testliner paper with modified starch on the values of these modules for selected directions of orthotropy of the boards was noticeable. For the ($x$) direction, the impregnation of the paper caused a reduction in value $F_{Px}$ of 19.3 % and for direction ($y$) of 6.9 %. It is worth noting that this change was caused only by the change in the value of the linear elasticity modulus of the core cells from $E_x^c$=0.125 MPa to 0.114 MPa, and from $E_y^c$ =0.033 MPa to 0.030 MPa. In this case, the differences are 8.8 % and 9.1 %, respectively, in favor of cells not impregnated with starch. The analytical calculations made with the use of equations 17, 18, 19 do not show, however, such a significant influence of the linear elasticity modulus of the core on the modulus of elasticity of the cellular sheet (Table 4), which is explained by the equation referred to below for Eq. 17,

$$E_{Px} = \frac{2\cdot E_x^f \cdot t^f}{h}\cdot\left(1+\frac{E_x^c}{2\cdot E_x^f}\cdot\frac{t^c}{t^f}\right) \qquad (20)$$

Where, after substituting the appropriate numerical values, we get:

$$\begin{aligned} E_{Px} &= 1122.54\cdot\left(1+1.52\cdot10^{-5}\cdot5.33\right)= \\ &=1122.54\cdot\left(1+8.1\cdot10^{-5}\right) \end{aligned} \qquad (21)$$

It follows that the combined effect of $E_x^c$ and $t^c$ on $E_{Px}$ is equal to 8.1 $\cdot10^{-5}$, therefore negligibly small. Therefore, the solutions proposed by (Bodig and Jayne,

**Table 4** Modulus of elasticity of cellular plates
**Tablica 4.** Modul elastičnosti ploča s jezgrom od papirnog saća heksagonalnih ćelija

| Module | N | | S | |
|---|---|---|---|---|
| | Exp | A | Exp | A |
| $E_{Px}$ | 1874 (104) | 1123 | 1484 (146) | 1123 |
| $E_{Py}$ | 709 (94) | 1123 | 660 (63) | 1123 |
| $G_{Pxy}$ | - | 484 | - | 484 |

exp - experimental results, A - analytical calculations, SD - standard deviation / *exp – eksperimentalni rezultati, A – analitičke kalkulacije, SD – standardna devijacija*

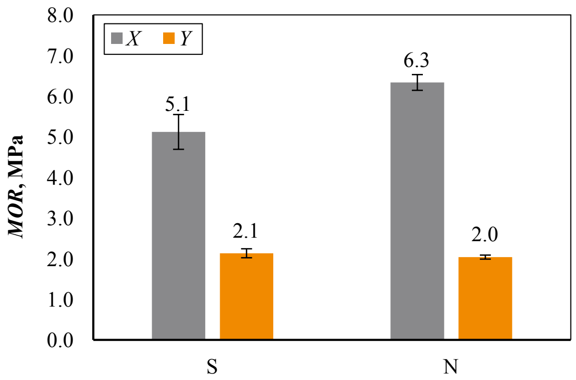



**Figure 7** Bending strength of cellular plates (whiskers indicate standard deviations)
**Slika 7.** Čvrstoća na savijanje ploča sa srednjicom od papirnog saća heksagonalnih ćelija („viskeri" označavaju standardne devijacije)

1982; Chen and Yan, 2012) do not apply to structural cell cores.

The slender core cells also have a marked effect on the strength of the cell plates. Figure 7 shows that the bending strength in the direction of the (*x*) axis is greater than the strength in the direction of the (*y*) axis by 68.3 % and 58.8 %, respectively, for non-impregnated and impregnated cores. The effect of impregnation of Testliner paper with modified starch on the strength of these boards for selected directions of orthotropy was also noticeable. For the (x) direction, the impregnation of the paper caused a reduction in value $MOR_{px}$ of 19.0 %, while for direction (*y*) there was an increase in $MOR_{py}$ of 5 %.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The analysis of the obtained results of experimental and analytical calculations allows for the formulation of several important conclusions.

Slender hexagonal cells significantly differentiate their elastic properties in the main directions of orthotropy. In the (*x*) axis direction, the modulus of elasticity is approximately 3.7 times greater than in the (*y*) axis.

Impregnation of Testliner paper with modified starch reduces the values of the linear elasticity modulus of the cells by about 8.8 %.

The slender core cells differentiate the elastic properties of the cell plates in the main directions of orthotropy. In the (*x*) axis, the modulus of elasticity is about 355 % greater than in the direction of the (*y*) axis.

Impregnation of Testliner paper with modified starch reduces the values of linear elasticity modulus of honeycomb panels by at least 6.9 %.

Analytical solutions that do not include the structural form of the core cannot be used to calculate the modulus of elasticity of sandwich panels with hexagonal core cells.

### Acknowledgements – Zahvala

The author would like to gratefully acknowledge the National Science Centre Poland for financing the present work as part of the research project No. 2016/21/B/ST8/01016.

## 5 REFERENCES
## 5. LITERATURA

1. Beckers, J.; Weekx, S.; Beutels, P.; Verhetsel, A., 2021: COVID-19 and retail: The catalyst for e-commerce in Belgium? Journal of Retailing and Consumer Services, 62: 102645. https://doi.org/10.1016/J.JRETCONSER.2021.102645
2. Bekhta, P.; Ozarkiv, I.; Alavi, S.; Hiziroglu, S., 2006. A theoretical expression for drying time of thin lumber. Bioresource Technology, 97: 1572-1577. https://doi.org/10.1016/j.biortech.2005.06.005
3. Bodig, J.; Jayne, B. A., 1982: Mechanics of wood and wood composites. New York : Van Nostrand Reinhold.
4. Chen, D. H., 2011: Bending deformation of honeycomb consisting of regular hexagonal cells. Composite Structures, 93: 736-746. https://doi.org/10.1016/j.compstruct.2010.08.006
5. Chen, Z.; Yan, N., 2012: Investigation of elastic moduli of kraft paper honeycomb core sandwich panels. Composites Part B: Engineering, 43: 2107-2114. https://doi.org/10.1016/j.compositesb.2012.03.008
6. Chen, Z.; Yan, N.; Deng, J.; Smith, G., 2011: Flexural creep behavior of sandwich panels containing Kraft paper honeycomb core and wood composite skins. Materials Science and Engineering: A, 528: 5621-5626. https://doi.org/10.1016/j.msea.2011.03.092
7. Crupi, V.; Epasto, G.; Guglielmino, E., 2012: Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading. International Journal of Impact Engineering, 43: 6-15. https://doi.org/10.1016/j.ijimpeng.2011.12.002
8. Gibson, L. J., 2005: Biomechanics of cellular solids. Journal of Biomechanics, 38: 377-399. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.09.027
9. Hao, J.; Wu, X.; Oporto, G.; Wang, J.; Dahle, G.; Nan, N., 2018: Deformation and failure behavior of wooden sandwich composites with taiji honeycomb core under a three-point bending test. Materials, 11: 2325. https://doi.org/10.3390/ma11112325

10. Hussain, M.; Khan, R.; Abbas, N., 2019: Experimental and computational studies on honeycomb sandwich structures under static and fatigue bending load. Journal of King Saud University, 31: 222-229. https://doi.org/10.1016/j.jksus.2018.05.012
11. Khojasteh-Khosro, S.; Shalbafan, A.; Thoemen, H., 2020: Preferences of furniture manufacturers for using lightweight wood-based panels as eco-friendly products. European Journal of Wood and Wood Products, 78: 593-603. https://doi.org/10.1007/s00107-020-01519-8
12. Lagus, M., 2019: Hydrophobic Surface Sizing of testliner. Åbo Akademi University, Turku, Finland.
13. Librescu, L.; Hause, T., 2000: Recent developments in the modeling and behavior of advanced sandwich constructions: A survey. Composite Structures, 48: 1-17. https://doi.org/10.1016/S0263-8223(99)00068-9
14. Ma, M.; Yao, W.; Jiang, W.; Jin, W.; Chen, Y.; Li, P., 2021: A multi-area fatigue damage model of composite honeycomb sandwich panels under three-point bending load. Composite Structures, 261: 113603. https://doi.org/10.1016/j.compstruct.2021.113603
15. Maurer, H. W., 2009: Starch in the Paper Industry, in: Starch. Academic Press, MA, USA, pp. 657-713. https://doi.org/10.1016/B978-0-12-746275-2.00018-5
16. Michanickl, A., 2006: Development of a new light wood-based panel. In: Proceeding of the 5th European Wood-Based Panel Symposium. Hannover, Germany.
17. Nilsson, J.; Ormarsson, S.; Johansson, J., 2017: Moisture-related distortion and damage of lightweight wood panels – experimental and numerical study. Journal of the Indian Academy of Wood Science, 14: 99-109. https://doi.org/10.1007/s13196-017-0193-y
18. Ozarska, B.; Harris, G., 2007: Effect of cyclic humidity on creep behaviour of wood-based furniture panels. Electronic Journal of Polish Agricultural Universities, 10: 11.
19. Palomba, G.; Crupi, V.; Epasto, G., 2019: Collapse modes of aluminium honeycomb sandwich structures under fatigue bending loading. Thin-Walled Structures, 145: 106363. https://doi.org/10.1016/j.tws.2019.106363
20. Peliński, K.; Smardzewski, J., 2020: Bending behavior of lightweight wood-based sandwich beams with auxetic cellular core. Polymers, 12: E1723. https://doi.org/doi.org/10.3390/polym12081723
21. Peliński, K.; Wojnowska, M.; Maslej, M.; Słonina, M.; Smardzewski, J., 2017: Modeling of density of periodic structures cores of honeycomb panels. In: Proceedings of 28th International Conference Research for Furniture Industry. Poznan University of Life Sciences, Poznań, Poland, pp. 285.
22. Pohl, A., 2009: Strengthened corrugated paper honeycomb for application in structural elements. ETH, Zurich. https://doi.org/10.3929/ethz-a-005900291
23. Ren, D.; Li, K., 2005: Development of wet strength additives from wheat gluten. Holzforschung, 59: 598-603. https://doi.org/10.1515/HF.2005.097
24. Sam-Brew, S.; Semple, K.; Smith, G. D., 2011: Preliminary experiments on the manufacture of hollow core composite panels. Forest Products Journal, 61: 381-389. https://doi.org/10.13073/0015-7473-61.5.381
25. Shalbafan, A.; Luedtke, J.; Welling, J.; Thoemen, H., 2012: Comparison of foam core materials in innovative lightweight wood-based panels. European Journal of Wood and Wood Products, 70: 287-292. https://doi.org/10.1007/s00107-011-0552-0
26. Słonina, M.; Dziurka, D.; Molińska-Glura, M.; Smardzewski, J., 2022: Influence of Impregnation with Modified Starch of a Paper Core on Bending of Wood-Based Honeycomb Panels in Changing Climatic Conditions. Materials, 15: 395. https://doi.org/10.3390/ma15010395
27. Słonina, M.; Dziurka, D.; Smardzewski, J., 2020: Experimental research and numerical analysis of the elastic properties of paper cell cores before and after impregnation. Materials, 13: 2058. https://doi.org/10.3390/MA13092058
28. Smardzewski, J., 2013: Elastic properties of cellular wood panels with hexagonal and auxetic cores. Holzforschung, 67: 87-92. https://doi.org/10.1515/hf-2012-0055
29. Smardzewski, J.; Jasińska, D., 2016: Mathematical models and experimental data for HDF based sandwich panels with dual corrugated lightweight core. Holzforschung, 71: 265-273. https://doi.org/10.1515/hf-2016-0146
30. Steeves, C. A.; Fleck, N. A., 2004: Collapse mechanisms of sandwich beams with composite faces and a foam core, loaded in three-point bending. Part II: Experimental investigation and numerical modelling. International Journal of Mechanical Sciences, 46: 585-608. https://doi.org/10.1016/j.ijmecsci.2004.04.004
31. Sun, G.; Huo, X.; Chen, D.; Li, Q., 2017: Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. Materials & Design, 133: 154-168. https://doi.org/10.1016/j.matdes.2017.07.057
32. Twede, D.; Selke, S. E. M.; Kamdem, D.-P.; Shires, D. B., 2015: Cartons, crates and corrugated board. In: Handbook of Paper and Wood Packaging Technology. ISBN 1605951358, pp. 574.
33. Wang, Z.; Li, Z.; Xiong, W., 2019: Experimental investigation on bending behavior of honeycomb sandwich panel with ceramic tile face-sheet. Composites Part B: Engineering, 164: 280-286. https://doi.org/https://doi.org/10.1016/j.compositesb.2018.10.077
34. Zeng, H., 2013: Polymer adhesion, Friction, and Lubrication, I. ed. John Wiley & Sons, NJ, USA.
35. ***EN 310, 1993: Wood-based panels – Determination of modulus of elasticity in bending and of bending strength.
36. ***ISO 13061-6, 2014: Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 6: Determination of ultimate tensile stress parallel to grain.
37. ***ISO 1924-2, 2008: Paper and board – Determination of tensile properties. Part 2: Constant rate of elongation method (20 mm/min).



**Corresponding address:**

**JERZY SMARDZEWSKI**

Poznan University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Furniture Design, Wojska Polskiego 28, 60-637 Poznan, POLAND, e-mail: jsmardzewski@up.poznan.pl

Marek Wieruszewski[1], Zbigniew Malinowski[2], Radosław Mirski[3]

# Quality and Dimensional Parameters of Large-Sized Pine Timber in View of Expectations of Polish Sawmill Industry

# Kvaliteta i dimenzijski parametri borove građe velikih dimenzija u svjetlu zahtjeva poljske pilanske industrije

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 4. 3. 2022.
Accepted – prihvaćeno: 25. 3. 2022.
UDK: 674; 674.032.475.4
https://doi.org/10.5552/drvind.2022.0025



**ABSTRACT** • *Changes in the processing directions of round wood require the selection of raw material with appropriate quality and dimensional characteristics. In the case of large-size pine wood, these parameters translate significantly into its value and material indicators. The purpose of the research was to verify the currently applied classification principles with respect to the expectations of the market of wood industry customers. The research was conducted using the direct survey method, taking into account the structure of processing and sorting of production of wood industry representatives. The basic dimensional and quality groups for coniferous wood were separated, with wood defects assigned to them, in accordance with the currently binding principles of the quality and dimensional classification conducted by the State Forests. The respondents pointed out the necessity of changes in the minimum dimensions for wood of higher quality classes and changes in admissibility of selected defects in wood of lower classes.*

**KEYWORDS:** *scots pine; large-size wood; classification; wood defects; market preferences*

**SAŽETAK** • *Promjene u načinu obrade trupaca zahtijevaju odabir sirovine odgovarajuće kvalitete i dimenzija. Kad je riječ o borovoj građi velikih dimenzija, ti parametri znatno utječu na njezinu vrijednost i materijalne pokazatelje. Cilj istraživanja bio je provjeriti trenutačno primjenjive pravilnike o klasifikaciji borove građe s obzirom na očekivanja tržišta drvne industrije. Istraživanje je provedeno metodom izravnoga anketnog ispitivanja predstavnika drvne industrije, pri čemu su uzeti u obzir struktura obrade proizvoda i način proizvodnje. Crnogorično je drvo razvrstano u osnovne dimenzijske i kvalitativne skupine kojima su pridodane greške drva, sukladno trenutačno obvezujućim pravilnicima o klasifikaciji drva prema kvaliteti i dimenzijama što ih provode Državne šume. Ispitanici su upozorili na nužnost promjene minimalnih dimenzija za drvo višeg razreda kvalitete te promjene glede dopuštenih grešaka drva nižeg razreda kvalitete.*

**KLJUČNE RIJEČI:** *borovina; drvo velikih dimenzija; klasifikacija; greške drva; očekivanja tržišta*

[1] Author is a researcher at Poznan University of Life Sciences, Department of Wood Mechanical Technology, Poznan, Poland. https://orcid.org/0000-0002-4867-195X
[2] Author is an employee at Regional Directorate of State Forests in Katowice, Katowic, Poland.
[3] Author is a researcher at Poznan University of Life Sciences, Department of Wood Mechanical Technology, Poznan, Poland. https://orcid.org/0000-0002-4881-579X

## 1 INTRODUCTION
## 1. UVOD

The development of the sawmilling sector is dependent on raw material resources. It is determined by the availability of timber which would ensure the execution of production orders. At present, shortages of timber negatively influence the wood industry both in Poland and worldwide. Despite the considerable increase in timber prices, wood products continue to be in high demand. Although its resources are limited, the great demand for timber on the global market results, among other things, from the environmental directives reducing the carbon footprint, as well as an increased interest in renewable energy sources. Additionally, price fluctuations destabilise the world timber market, influencing the situation of both wood conversion enterprises and manufacturers of wood-based products.

Factors directly influencing production costs include technological and material efficiency. They are crucial for the production profitability in economic entities operating in the wood sectors (Salehirad and Sowlati, 2006; Neykov *et al*., 2020). Both their measurement and improvement are essential for the development and progress in any enterprise (Kovalčík, 2018). Production efficiency is influenced by the current ratio of the product price to the price of the raw material. Thus, each growth in raw material prices, while maintaining product prices at the same level, will result in the reduction of production profitability. In sawmilling conversion processes, the quality of timber and its customisation are major parameters affecting their efficiency (Dzbeński *et al*., 2007; Wieruszewski and Mydlarz, 2021).

The production of round materials is based on standards; they define the principles of sorting and the principles of separation and characteristics of individual grades. When separating timber for production, standards are applied, which should not limit the possibility of their flexible separation, especially by agreement of the parties involved in the commodity trade. In this respect, characteristic is exemplified by, among others, the sawmill production. The rules of sorting raw material adopted in the country provide for differentiation in quality both in domestic and foreign trade.

Market research is a popular method of obtaining empirical data on market needs. Surveys are commonly applied, particularly in marketing research and market analysis (Nowicki, 1993; Ratajczak, 2001, 2003). Opinions of timber buyers are elements of studies on the effect of raw material quality on directions of its application, in line with sustainable development trends both at the level of the wood industry and forest management operations (Marianowska, 2005; Gonzalez *et al*., 2019). Market research makes it possible to identify demand preferences, which characterise investigated groups of processors with specific technological processes (Bell *et al*., 2013; Dammer *et al*., 2016; Daian and Ozarska, 2009). This research consists in the analysis of the target group, limited in terms of their interest and the number of respondents. An advantage of surveys is connected with the fact that they provide research results within a short period of time. However, a drawback of this method, when applied to determine market needs, may result from the low share of data returned by respondents, which is reflected in the lesser accuracy of analyses due to limited representativeness of obtained data. This paper refers to assortment grading of softwood timber on the wood market in Poland. Grading was based on quality requirements for roundwood defined as the Technical Specifications for large-sized softwood timber (Regulation no. 51, Malinowski and Wieruszewski, 2017). The authors applied the survey method to assess the assortment grading of pine timber based on feedback from representative wood conversion operators in Poland.

The aim of the study was to indicate the direction of expected changes in national standardisation adapted to the requirements of coniferous roundwood sorting for sawmill processing.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

The objective of this study was to verify the characteristics of timber specific to softwood and affecting its utilisation, depending on the specific operations of sawmills. The research theses were grouped based on the main thematic sets concerning dimensions and wood defects. The sawmilling market was investigated within the adopted methodology of direct questionnaire surveys (Collective work, 2010; Stupnicki, 2015). Respondents assessed the effect of quality and dimensional characteristics of softwood for sawn timber products described in the Technical Specifications. Presented ranges of wood characteristics are reflected in the principles of their classification. Based on the recorded and synthesised results individual quality factors were adapted to the currently binding classification of large-sized softwood timber. Such collected and systematised data made it possible to evaluate the expectations of the wood industry in relation to the current timber classification. The study was conducted on a set of data, which covered assessment of the principles of roundwood classification. Questions directed to representatives of sawmilling companies addressed principles specifying the criterion of wood quality. To maintain comparability of recorded results, it was assumed that quality elements identified by sawmills for timber (i.e. wood defects) were determined based on

**Table 1** Features and layout of defects for large coniferous raw material included in the survey
**Tablica 1.** Značajke i raspored grešaka crnogoričnog drva velikih dimenzija obuhvaćenih anketnim istraživanjem

| **Feature to be assessed (dimension or scope)** *Značajka koja se procjenjuje (dimenzija ili opseg)* | **Proposed quality class from the highest** *Predložena klasa kvalitete poredana od najviše do najniže* |
|---|---|
| Min. diameter at thinner end, cm / *najmanji promjer na tanjem kraju,* cm | WA0, WB0, WC0, WD, other |
| Min. length, m / *najmanja duljina,* m | |
| Open knuckles, diameter in cm / *neurasle kvrge, promjer,* cm | |
| Tumors, height in cm / *tumori, visina,* cm | |
| Roses, diameter in cm / *sljepice, promjer,* cm | |
| Frontal/lateral cracks, range / *čeone/radijalne pukotine, raspon* | |
| Curvature, cm/m / *zakrivljenost,* cm/m | |
| Twist of fibres, cm/m / *usukanost žice,* cm/m | |
| Rind gal, width in cm / *urasla kora, širina,* cm | |
| Blue and brown stain, range / *plavetnilo i smeđa obojenost, raspon* | |
| Resinosis, range / *lučenje smole, raspon* | |
| Internal or external rot, range / *unutarnja ili vanjska trulež, raspon* | |
| Insect walkways, depth in mm / *rupe od insekata, dubina,* mm | |
| Foreign bodies, YES/NO / *stana tijela, DA/NE* | |
| Other proposed features / *druge predložene značajke* | |

WA0 – first class / *prva klasa*, WB0 – second class / *druga klasa*, WC0 – third class / *treća klasa*, WD – fourth class / *četvrta klasa*

the requirements of the PN-79/D-01011 standards. The numbers of quality and dimension grades were arbitrary. A preliminary identification was conducted for the effect of minimum diameter dimensions and length of timber, the share of major defects such as open knots, knobs, roses, end shakes and edge cracks, curvature, twisting, necrosis, blue stain, brown sap stain, resinosis, inner and surface rot, insect holes, foreign bodies as well as other proposed characteristics of roundwood on suitability for specific conversion types.

Analyses were conducted in the years 2017-2019. The number of questionnaires was selected so that it was equivalent to over 5 % of wood industry plants in Poland based on the data from 2016, when a total of 6084 customers were registered at the Forestry and Timber Portal (Malinowski, 2020). The questionnaires were addressed to 390 plants and 37 were returned (which accounted for 9 % of the total). Most frequently, the questionnaire respondents were entrepreneurs converting from 10 thousand $m^3$ to 50 thousand $m^3$ timber (33 % of respondents). The least numerous group among the returned questionnaires comprised representatives of the wood industry converting less than 500 $m^3$ timber annually (3 % of all respondents).

This study lists grading principles (Technical Specifications - WT) and changes proposed by buyers representing the wood industry (Proposals - Pr). Only the proposals of changes in quality parameters indicated most frequently in the questionnaires were included (Table 1). This list does not include wood defects, in relation to which expectations of customers are consistent with the currently binding technical specifications.

## 3 RESULTS
## 3. REZULTATI

When verifying timber utilisation preferences of sawmills, it needs to be stressed that most respondents accepted the current quality classification system of 4 grades adopted for softwood timber. Only in three cases it was proposed to limit it to three quality classes. No changes in wood grading were proposed in any of the questionnaires, in terms of wood thickness, to the presently applied 3-class thickness classification.

Dimensional parameters indicated as requiring corrections concerned only two elements, i.e. the minimum length of large-sized softwood timber and minimum top diameter (Table 1). Dimensional groups are important in view of the references to these groups in the regulations concerning timber classification in the State Forests (Regulation no. 51 DGLP). The minimum length of timber is the shortest segment of large-sized timber meeting the current regulations related to quality and dimensional parameters during timber conversion. The minimum top diameter is the smallest diameter of the thinner log end measured to 1 mm inside bark. The minimum length of large-sized timber on the whole ranged from 2.7 m and 14 m. For quality grade 1 WA0, the lengths proposed by the representatives of the wood industry plants ranged from 2.7 m and 8 m. In individual classes, the following were the most frequently selected length ranges: WA0 – from 6.0 m (37 % of responses), WB0 – from 6.0 m (38 %), WC0 – from 3.0 m (26 %) and WD – from 2.7 m (27 %). The least frequently proposed top log diameter (i.e. the thinner end) was in the range of 12 cm - 30 cm, where in terms of individual grades the highest number of re-

**Table 2** List of dimensional parameters according to technical conditions and surveys for large-size wood (Malinowski, 2020)
**Tablica 2.** Popis dimenzijskih parametara prema tehničkim uvjetima i prikupljenim anketnim podatcima za drvo velikih dimenzija (Malinowski, 2020.)

| **Dimensions** / *Dimenzije* | | **Class of wood** / *Klasa drva* | | | |
|---|---|---|---|---|---|
| | | WA0 | WB0 | WC0 | WD |
| Min upper diameter, cm / *najmanji gornji promjer,* cm | WT | 22 | 14 | 14 | 14 |
| | Pr | 25 | 20 | | |
| Min length, m / *najmanja duljina,* m | WT | 2.7 | 2.7 | 2.7 | 2.7 |
| | Pr | 6 | 6 | 3 | |

WT – technical conditions / *tehnički uvjeti;* Pr – proposal / *prijedlog*

sponses included the following grades: WA0 – 25 cm (50 % of responses), WB0 – 20 cm (33 %), WC0 – 14 cm (39 %) and WD – 14 cm (52 %). The presented percentage shares indicate a considerable percentage of responses for a given dimension.

In terms of timber quality, the respondents evaluated the weight of considered wood defects (Table 3). The importance of defects proposed for the classification of timber utilisation is almost identical to the currently binding classification. However, respondents indicated an additional wood feature, i.e. resinosis, which should be included in the Polish classification of roundwood.

When comparing the currently binding classification principles and the most frequently presented proposals concerning the range of observed wood defects, it may be stated that their considerable share was analogous. One of the most important proposed changes suggested a rejection of the classification of higher quality grades (WA0 and WB0) based on the first four

**Table 3** List of quality parameters according to defects (Malinowski, 2020)
**Tablica 3.** Popis parametara kvalitete vezanih za greške (Malinowski, 2020.)

| **Knots** / *Kvrge* | | **Class of wood** / *Klasa drva* | | | |
|---|---|---|---|---|---|
| | | WA0 | WB0 | WC0 | WD |
| Open knuckles diameter, cm<br>*promjer neuraslih kvrga,* cm | WT | N | N | D | D |
| | Pr | | | 2 | 2 |
| Tumors, height in cm<br>*tumori, visina,* cm | WT | N | ½ circuit | D | D |
| | Pr | | N | 1 | |
| Roses, diameter in cm<br>*sljepice, promjer,* cm | WT | D | D | D | D |
| | Pr | N | N | N | |
| Rot / *trulež* | | WA0 | WB0 | WC0 | WD |
| Internal decay, ø forehead<br>*unutarnja trulež, udjel u promjeru čela* | WT | N | N | 1/5 ø | 1/3 ø |
| | Pr | | | N | N |
| External rot, perimeter on ø front<br>*vanjska trulež, udjel u opsegu na promjeru čela* | WT | N | N | 1/4 at 1/10 | D |
| | Pr | | | N | N |
| Construction defects / *konstrukcijske greške* | | WA0 | WB0 | WC0 | WD |
| Rind gal, cm<br>*urasla kora*, cm | WT | D | D | D | D |
| | Pr | N | N | N | |
| Resinosis, range<br>*lučenje smole, raspon* | WT | D | D | D | D |
| | Pr | N | N | N | |
| Twist of fibers, cm/m<br>*usukanost vlakanaca,* cm/m | WT | 5/1 | D | D | D |
| | Pr | N | N | N | |
| Stain / *obojenje* | | WA0 | WB0 | WC0 | WD |
| Blue stain<br>*plavetnilo* | WT | N | N | 1/2 | D |
| | Pr | | | N | |
| Brown stain<br>*smeđa obojenost* | WT | N | N | N | D |
| | Pr | | | | N |
| Cracks / *pukotine* | | WA0 | WB0 | WC0 | WD |
| Lateral and frontal/lateral cracks<br>radijalne i čeone/radijalne pukotine | WT | N | N | N | D |
| | Pr | | | | N |
| Mechanical damage / *mehanička oštećenja* | | WA0 | WB0 | WC0 | WD |
| Insect walkways<br>*rupe od insekata* | WT | N | N | N | D |
| | Pr | | | | N |
| Foreign bodies<br>*strana tijela* | WT | N | N | N | D |
| | Pr | | | | N |

N – unacceptable / *neprihvatljvo;* D – acceptable / *prihvatljivo* meters (this proposal concerns the share of open knots and knobs). According to the respondents, the Polish softwood grading system needs to meet the requirements, in which conditions for a given grade have to be met over the entire section of graded timber (while observing the specification for the shortest section). It should be stressed that in Polish forests large-sized softwood timber has been inspected by sections since 1967 and that the requirements of the PN-67/D-95017 standard apply.

## 4 DISCUSSION
## 4. RASPRAVA

The proposed high quality grades (WA0 and WB0) in the Polish softwood timber classification, characterised by increased quality requirements, may be associated with the growing market value of this raw material (Adamczyk, 2002; Adamowicz and Cierniak, 2011; Lis, 2012). Higher quality of large-sized softwood timber indicates the interest of enterprises in enhancing efficiency indexes for performed conversion operations (Ratajczak and Pikul-Bieniek, 2009). Highly accurate dimensioning of produced timber also aims at increasing the quality and improving rational utilisation of the raw material (Przypaśniak, 2015). The analysis of questionnaire survey studies indicates frequent responses confirming the indication of minimum length of higher quality timber (6.0 m), which includes a proposal for timber length standardisation. The marked discrepancy and at the same time the varied range of indicated wood defects for individual quality grades may indicate that the approach of the State Forests is still insufficiently adapted to the needs of their customers (Ratajczak, 2001, 2003). An example of the convergent regulations binding under the current conditions for classification and proposals of the respondents may be provided by the guidelines for the determination of curvature, discolouration and spotting, as well as mechanical damage. Globalisation is now a phenomenon that also affects wood-based industries. The timber trade and market are based on the theory of derived demand, which means that the demand for timber depends on the demand for final products (Paluš *et al.*, 2021). Work on changing wood sorting systems is also underway in other European countries. These activities are aimed at adapting and adjusting the assortment structure within the wood processing lines and the use of products (Brandstetter *et al.*, 2020; Burawska-Kupniewska *et al.*, 2021).

The additional specification of such a defect as resinosis and its relatively restrictive treatment may indicate a growing demand for sawn products, where this defect is particularly undesirable. Resinosis reduces the potential for surface refining and bonding of wood. This results from the directions of extensive prefabrication of softwood timber. It is also a major drawback of the softwood timber classification in accordance with the European standards PN-EN 1611-1:2002/A1:2003 Sawn timber – Classification of softwood timber based on visual inspection – Part 1: European spruce, fir, pine, Douglas pine and larch.

By increasing the requirements and technical parameters for roundwood of higher quality classes and attempting to provide dimensional standardisation of timber will promote adaptation of the timber market to European standards PN-EN 1927-2: 2008.

## 5 CONCLUSIONS
## 5. ZAKLJUČAK

The sawmilling sector expects individual dimensional verification of minimum length (from 3 m in class WC0 and from 6m in higher classes) and thickness of softwood for higher quality classes (from 20 cm in class WB0 and 25 cm in class WA0), as well as grading of timber based on the inspection of timber sections of specific, comparable quality.

In the case of the quality classification concerning anatomical structure defects buyers mostly expect higher quality in lower quality grades (especially for knots, rind gal, resinosis, twist of fibres).

Defects related to discolouration or mechanical damage are consistent, to a considerable extent, with the currently binding technical specifications.

Defects, which to date have been disregarded in the classifications, play an increasingly important role and determine the utilisation of obtained sawn materials. Resinosis is an example of such defects.

**Acknowledgements** – Zahvala

This research was funded by the National Centre for Research and Development, BIOSTRATEG3/344303/14/NCBR/2018.

## 6 REFERENCES
## 6. LITERATURA

1. Adamczyk, W., 2002: Tartaki odbiły się od dna (online). http://www.drewno.pl/serwis/archiwum/szerzej/sz021101.html (Accessed Dec. 30, 2021).
2. Adamowicz, K.; Cierniak, N., 2011: Elastyczność cenowa popytu na drewno sosnowe sprzedawane na rynku detalicznym surowca drzewnego na przykładzie RDLP w Zielonej Górze, Leśne Prace Badawcze. Forest Research Papers, 72 (2): 191-196.
3. Bell, J. E.; Mollenkopf, D. A.; Stolze, H. J., 2013: Natural resource scarcity and the closed loop supply chain: a resource advantage view. International Journal of Physical Distribution & Logistics Management, 43 (5/6): 351-379. https://doi.org/10.1108/IJPDLM-03-2012-0092
4. Brandstetter, M.; Zeleniuc, O.; Pei, G.; Campean, M., 2020: Conversion efficiency of fir roundwood into saw-

logs. BioResourses, 15 (2): 5653-5665. (online). https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_15_3_5653_Brandstetter_Conversion_Efficiency_Fir_Roundwood/7776 (Accessed Mar. 23, 2022).
5. Burawska-Kupniewska, I.; Krzosek, S.; Mankowski, P., 2021: Efficiency of visual and machine strength grading of sawn timber with respect to log type. Forests, 12: 1467. https://doi.org/10.3390/f12111467
6. Daian, G.; Ozarska, B., 2009: Wood waste management practices and strategies to increase sustainability standards in the Australian wooden furniture manufacturing sector. Journal of Cleaner Production, 17 (17): 1594-1602. https://doi.org/10.1016/j.jclepro.2009.07.008
7. Dammer, L.; Bowyer, C.; Breitmayer, E.; Eder, A.; Nanni, S.; Allen, B.; Carus, M.; Essel, R., 2016: Mapping study on cascading use of wood products; Technical Report 2016. World Wide Fund For Nature (Formerly World Wildlife Fund) (online). http://awsassets.panda.org/downloads/cascading_use_of_wood_web.pdf. (Accessed Dec. 23, 2021).
8. Dzbeński, W.; Kozakiewicz, P.; Wiktorski, T., 2007: Sortowanie tarcicy ogólnego przeznaczenia. Wyd. SGGW, Warszawa, pp. 7-100.
9. Gonzalez, E. D. R. S.; Koh, L.; Leung, J., 2019: Towards a circular economy production system: trends and challenges for operations management. International Journal of Production Research, 57 (23): 7209-7218. https://doi.org/10.1080/00207543.2019.1656844
10. Kovalčík, M., 2018: Efficiency of the Slovak forestry in comparison to other European countries: An application of Data envelopment Analysis. Central European Forestry Journal, 64: 46-54. https://doi.org/10.1515/forj-2017-0026
11. Lis, W., 2012: Recipients of round wood from the state forests in Poland. Intercathedra 28 (1): 36-41.
12. Malinowski, Z., 2020: Efektywność przerobu wielkowymiarowego drewna sosny w aspekcie normalizacji drewna okrągłego i tarcicy. Praca doktorska, pp. 36-46.
13. Malinowski, Z.; Wieruszewski, M., 2017: Zmiany w normalizacji wielkowymiarowego drewna sosnowego w powojennych dziejach Państwowego Gospodarstwa Leśnego Lasy Państwowe, Sylwan nr 4: 287-294. https://doi.org/10.26202/sylwan.2016117
14. Marianowska, M., 2005: Polskie tartaki poza ligą europejską. Inwestor nr 7: 16.
15. Neykov, N.; Antov, P.; Savov, V., 2020: Circular economy opportunities for economic efficiency improvement in wood-based panel industry. In: Proceedings of 11th International Scientific Conference "Business and Management 2020", Vilnius, Lithuania. https://doi.org/10.3846/bm.2020.493
16. Nowicki, R., 1993: O restrukturyzacji polskiego przemysłu drzewnego w świetle doświadczeń Agencji Rozwoju Przemysłu S. A., Kierunki zmian strukturalnych w przemyśle drzewnym w Polsce na tle tendencji światowych, ITD., Ministerstwo Gospodarki, Agencja Rozwoju Przemysłu, 13-14 maja 1993, Poznań-Puszczykowo.
17. Paluš, H.; Dzian, M.; Parobek, J.; Šupín, M., 2021: Globalisation impacts on timber consumption in Slovakia. SHS Web of Conferences, 129: 08014. https://doi.org/10.1051/shsconf/202112908014
18. Przypaśniak, J., 2015: Lasy Państwowe głównym źródłem surowca drzewnego – stan zasobów i prognoza użytkowania. Praca zbiorowa Sektor leśno-drzewny w zrównoważonej gospodarce. Instytut Technologii Drewna, Stowarzyszenie Producentów Płyt Drewnopochodnych w Polsce, Centrum Informacyjne Lasów Państwowych, pp. 15-24.
19. Ratajczak, E., 2001: Rynek drzewny. Analiza struktur przedmiotowych, Wydawnictwo ITD: 1-283, Poznań.
20. Ratajczak, E., 2003: Wyzwania nowej gospodarki dla drzewnictwa. Prace naukowe. Doniesienia. Komunikaty, 46 (169): 91-113.
21. Ratajczak, E.; Pikul-Bieniek, J., 2009: Zarządzanie i marketing w polskim przemyśle tartacznym. Drewno-Wood, 52 (18): 75-91.
22. Salehirad, N.; Sowlati, T., 2006: Productivity and efficiency assessment of the wood industry: A review with a focus on Canada. Forest Products Journal, 56 (11/12): 25-32.
23. Stupnicki, R., 2015: Analiza i prezentacja danych ankietowych. Wyd. AWF, Warszawa (online). https://platforma.awf.edu.pl/Materials/Details/NTU1YjFkODZlMWY0NjEyY2QyZDU5NzRh (Accessed Dec. 21 2021)
24. Wieruszewski, M.; Mydlarz, K., 2021: The influence of habitat conditions on the properties of pinewood. Forests, 12: 1311. https://doi.org/10.3390/f12101311
25. ***PN-67/D-95017 Drewno tartaczne sosnowe i modrzewiowe.
26. ***PN-79/D-01011 Drewno okrągłe. Wady.
27. ***PN-EN 1611-1:2002/A1:2003 Tarcica – Klasyfikacja drewna iglastego na podstawie wyglądu. Część 1: Europejskie świerki, jodły, sosny, daglezje i modrzewie.
28. ***PN-EN 1927-2:2008 Klasyfikacja jakościowa drewna okrągłego iglastego. Część 2: Sosny.
29. ***Collective work, 2010: Foresight priorytetowych, innowacyjnych technologii na rzecz automatyki, robotyki i techniki pomiarowej. Redaktor Szewczyk R. PIAP. Warszawa.
30. ***Zarządzenie nr 51 Dyrektora Generalnego Lasów Państwowych z dnia 30 września 2019 r. (znak: ZM.800.8.2019) w sprawie wprowadzenia warunków technicznych w obrocie surowcem drzewnym w Państwowym Gospodarstwie Leśnym Lasy Państwowe.

**Corresponding address:**

**MAREK WIERUSZEWSKI**

Bartin University, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznań, POLAND,
e-mail: marek.wieruszewski@up.poznan.pl

Luďka Hanincová, Jiří Procházka, Vít Novák, Zdeněk Kopecký[1]

# Influence of Moisture Content on Cutting Parameters and Fracture Characteristics of Spruce and Oak Wood

# Utjecaj sadržaja vode na parametre piljenja i obilježja loma smrekovine i hrastovine

**ORIGINAL SCIENTIFIC PAPER**

**Izvorni znanstveni rad**

Received – prispjelo: 7. 3. 2022.

Accepted – prihvaćeno: 13. 4. 2022.

UDK: 630*82; 67.017

https://doi.org/10.5552/drvind.2022.0026



**ABSTRACT** • *The objective of this study was to determine the effect of the moisture content on cutting parameters and fracture characteristics of spruce and oak wood. Samples of Norway spruce (Picea abies (L.) H. Karst.) and English oak (Quercus robur L.) were dried to required moisture content and then used for the machinability test on circular sawblade machine. Results indicate that cutting force and feed force increase with increasing moisture content up to the fiber saturation point (FSP). When the moisture content increases above the FSP, the minimum values of cutting and feed force are achieved. Based on performed experiments, the fracture toughness and shear yield strength were derived. Fracture toughness decreases with increasing moisture content. The minimum values of fracture toughness are achieved at the moisture content level above the FSP. Shear yield strength decreases linearly with increasing moisture content: the decrease is up to 17 % compared to samples with moisture content at the FSP. Based on calculated results, the influence of moisture content and wood species on cutting and fracture characteristics was discussed.*

**KEYWORDS:** *cutting force; feed force; fracture toughness; shear yield strength; moisture content*

**SAŽETAK** • *Cilj ovog istraživanja bio je utvrditi utjecaj sadržaja vode na parametre piljenja i obilježja loma smrekovine i hrastovine. Uzorci smrekovine (Picea abies (L.) H. Karst.) i hrastovine (Quercus robur L.) sušeni su do sadržaja vode potrebnoga za ispitivanje obradivosti na kružnoj pili. Rezultati pokazuju da se sila rezanja i posmična sila povećavaju s povećanjem sadržaja vode do točke zasićenosti vlakanaca (TZV). Kada se sadržaj vode poveća iznad TZV-a, postižu se najmanje vrijednosti sile rezanja i posmaka. Lomna žilavost i granica tečenja pri smicanju izvedene su na temelju provedenih istraživanja. S povećanjem sadržaja vode lomna se žilavost smanjuje. Najmanje vrijednosti lomne žilavosti zabilježene su pri sadržaju vode iznad TZV-a. Granica tečenja se pri smicanju linearno smanjuje s povećanjem sadržaja vode: smanjenje je do 17 % u usporedbi s uzorcima sa sadržajem vode pri TZV-u. Na temelju dobivenih rezultata razmatran je utjecaj sadržaja vode i vrste drva na obilježja piljenja i loma.*

**KLJUČNE RIJEČI:** *sila rezanja; posmična sila; lomna žilavost; granica tečenja pri smicanju; sadržaj vode*

[1] Authors are researchers at Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Wood Science and Technology, Brno, Czech Republic.

# 1 INTRODUCTION
# 1. UVOD

Wood is the world's most widely available material for a variety of applications in furniture production or timber construction (Moore, 2015). Its advantage over other materials, such as metals or ceramics, is the seemingly easy machinability with both manual tools and industrial machines (Czarniak *et al.*, 2019). Wood is composed of cellulose fibers, hemicellulose and lignin, which all contain a significant amount of free hydroxyl groups (Hartley and Hamza, 2016). Free hydroxyl groups and their amount in wood have an important effect on the fixation of water (Månsson, 1983; Rautkari *et al.*, 2013) and also on the movement of water in wood (Burr and Stamm, 2002; Sperry, 2003). Water in wood has a number of effects, from changes in shape due to swelling and shrinking (Stamm and Tarkow, 1947) to changes in the vast majority of mechanical and physical properties (Kretschmann, 2010). These properties also influence the behaviour of the material during machining, which has been the subject of much research in the past (Naylor and Hackney, 2013), however with inconsistent results in the effect of moisture on cutting conditions. In practice, the theory has long been established that higher humidity results in the fibres moving away from each other, and therefore the cutting force required to break wood with bound water content is smaller (Moradpour *et al.*, 2013a; Lucic *et al.*, 2004), because the mechanical properties of wood also decrease (Kollmann and Côté, 1984). However, this theory failed in many experiments and the measured main (parallel) cutting force was significantly higher with increasing humidity to the limit of fibre saturation (Porankiewicz *et al.*, 2011), which in turn supports the theory, which also takes into account the increasing plasticity of wet wood leading to greater friction during machining (Varkocek *et al.*, 2004), which has already been described in earlier works (McKenzee, 1961). However, the increase in the main cutting force can also be influenced by the higher weight of the evacuated chip, which follows from the work of (Porankiewicz *et al.*, 2011) and also has been taken into account in calculations of (Ratnasingam *et al.*, 1999). Recent research is also more inclined to this theory, but it is not very conclusive and there is not much research directly focused on measuring cutting conditions as a function of humidity by modern methods (Nasir and Cool, 2020). Earlier measurement methods prove to be insufficient for this issue, and therefore this work focuses on the application of a newer calculation method (Orlowski and Ochrymiuk, 2017), which is based on the system of fracture mechanics and was taken from metalworking (Atkins, 2003). The method works with shear strength and fracture toughness in order to determine the cutting force, similarly as in Hlásková *et al.* (2015), where it was applied to saw blade cutting. This method was also successfully applied in wood-based materials processing (Kowaluk *et al.*, 2007). Based on previous experiments, it can also be assumed that the effects of moisture and fibre direction will be different depending on the species and its density (Axelsson *et al.*, 1993a). For example, in Moradpour *et al.* (2013a), woody plants with similar densities, which might affect some variables, were investigated. Therefore, in this work, the effect of moisture content on cutting force was investigated on two species with very different densities, i.e., Norway spruce (*Picea abies* (L.) H. Karst.) and English oak (*Quercus robur* L.).

# 2 MATERIALS AND METHODS
# 2. MATERIJALI I METODE

## 2.1 Machinability test
## 2.1. Test obradivosti

The experiments were performed on a research device used for cutting with circular sawblades (Kopecký and Rousek, 2012). The research device simulates the conditions of circular sawing machine in actual operation. The parameters of the cutting process were recorded using sensors installed on the research device. More detailed characteristics are described in the paper of Hlásková *et al.* (2021).

The cutting process was performed with the circular sawblade for longitudinal wood cutting (Flury Systems AG, Arch, Switzerland), with carbide-tipped straight teeth. The construction parameters of the blade are shown in Table 1.

The machine settings were as follows: the optimum operating rotational speed n = 3800 $min^{-1}$ i.e., cutting velocity $v_c = 69$ $m \cdot s^{-1}$. The feed rate varied within the range of $v_f = 2–22$ $m \cdot min^{-1}$ with measuring steps presented in Table 2. This corresponds to the changing feed per tooth $f_z$ and the mean uncut chip thickness $h_m$. A series of ten measurements were performed for each

**Table 1** Parameters of saw blade
**Tablica 1.** Parametri lista kružne pile

| | |
|---|---|
| Saw blade diameter *D*, mm<br>*Promjer lista pile D*, mm | 350 |
| Teeth number *z* / *Broj zubi z* | 28 |
| Saw blade thickness *s*, mm<br>*Debljina lista pile s*, mm | 2.5 |
| Kerf width *b*, mm / *Širina propiljka b*, mm | 3.6 |
| Tooth height *h*, mm / *Visina zuba h*, mm | 10.5 |
| Tooth pitch $t_p$, mm / *Korak zuba* $t_p$, mm | 39.27 |
| Clearance angle $\alpha_f$, ° / *Leđni kut* $\alpha_f$, ° | 15 |
| Rake angle $\gamma_f$, ° / *Prsni kut* $\gamma_f$, ° | 20 |
| Cutting edge radius $\rho_0$, μm<br>*Radijus rezne oštrice* $\rho_0$, μm | 8 |

**Table 2** Kinematic parameters
**Tablica 2.** Kinematički parametri

| | | | | | | |
|---|---|---|---|---|---|---|
| Feed rate $v_f$, m/min<br>*Posmična brzina* $v_f$, m/min | $v_f = f_z \cdot n \cdot z$ | 2 | 6 | 10 | 16 | 22 |
| Mean uncut chip thickness $h_m$, mm<br>*Srednja debljina odvojene strugotine* $h_m$, mm | $h_m = f_z \cdot \sin \varphi_{2m}$ | 0.011 | 0.033 | 0.055 | 0.089 | 0.123 |
| Feed per tooth $f_z$, mm<br>*Pomak po zubu* $f_z$, mm | $f_z = \frac{v_f}{n\ .\ z}$ | 0.019 | 0.056 | 0.094 | 0.15 | 0.207 |
| Cutting speed $v_c$, m/s<br>*Brzina rezanja* $v_c$, m/s | $v_c = \pi \cdot D \cdot n$ | 69.6 | | | | |
| Entry angle $\psi_1$, °<br>*Ulazni kut* $\psi_1$, ° | $\psi_1 = arccos\left(\frac{a_e + e}{D/2}\right)$ | 31.0 | | | | |
| Exit angle $\psi_2$, °<br>*Izlazni kut* $\psi_2$, ° | $\psi_2 = arccos\left(\frac{a_e}{D/2}\right)$ | 42.0 | | | | |
| Mean fiber cutting angle $\varphi_{2m}$, °<br>*Srednji kut zahvata,* $\varphi_{2m}$, ° | $\varphi_{2m} = \frac{\psi_1 + \psi_2}{2}$ | 36.5 | | | | |

feed rate and each type of machined material. Statistical analysis of variance ANOVA was used to assess the effect of the different MC of wood on the cutting parameters when cutting spruce and oak samples for each feed rate used in the experiment. Subsequently, a Scheffé test was performed at each feed rate (StatSoft, Hamburg, Germany). Statistical analyses were performed for a significance level $\alpha = 0.05$.

The rotary movement of the cutting tool and the constant feed rate result in a change of the uncut chip thickness. The model of the cutting is determined based on the technology used by characterizing the individual angles between the wood fiber grain, the tool planes, and the motion vectors. In the case of the longitudinal cutting of wood with a circular saw blade, it is the axial-perpendicular cutting model ($\varphi_1$ =90, $\varphi_2$ =0–90, $\varphi_3$ =0–90). The kinematic parameters are calculated according to the relations given in Table 2.

## 2.2 Materials
## 2.2. Materijali

Samples of Norway spruce (*Picea abies*) and English oak (*Quercus robur)* were dried to required moisture content (MC) and then used for the machinability test. The dimensions of the samples, the moisture content levels and densities for given moisture content are presented in Table 3.

The first level of MC (Sample 1) was approximately 5 % and was achieved by leaving the samples under normal room conditions at a temperature of approximately 18 to 20 °C and a humidity of 40 to 60 %. The second, third and fourth levels of MC were achieved by conditioning the samples in the climate chamber Memmert CTC 256 (Memmert GmbH, Schwabach, Germany), the condition setting was to 20 °C and 60 % humidity for the second level of MC (Sample 2); the condition setting was 20 °C and 80 % humidity for the third level of MC (Sample 3); and last temperature was 20 °C and humidity 90 % for the fourth level of MC (Sample 4). These conditions correspond to an approximate wood moisture content of 12 %, 20 % and FSP i.e., approximately 30 % MC. The fifth level of MC (50 %) was achieved by soaking samples in distilled water (Sample 5). The MC was measured after conditioning with the wood moisture meter (HMB-WS25, Merlin Technology GmbH, Ried im Innkreis, Austria), which is used for rapid non-destructive measurements of MC.

**Table 3** Specification of machined material
**Tablica 3.** Specifikacija obrađenog materijala

| **Wood species**<br>*Vrste drva* | **Samples**<br>*Uzorci* | **Dimension L × w × e, mm**<br>*Dimenzije L × w × e,* mm | **Moisture content, %**<br>*Sadržaj vode,* % | **Density, kg·m$^{-3}$**<br>*Gustoća,* kg·m$^{-3}$ |
|---|---|---|---|---|
| Spruce<br>*smrekovina* | 1 | 700 x 250 x 20 | 5.5 | 534 |
| | 2 | | 11.9 | 542 |
| | 3 | | 21.6 | 558 |
| | 4 | | 32.1 | 571 |
| | 5 | | 52.3 | 666 |
| Oak<br>*hrastovina* | 1 | 700 x 250 x 20 | 4.7 | 698 |
| | 2 | | 11.3 | 709 |
| | 3 | | 20.2 | 732 |
| | 4 | | 29.6 | 774 |
| | 5 | | 49.3 | 873 |

### 2.3 Methodology for determining fracture parameters
### 2.3. Metodologija određivanja parametara loma

Using the measured moment of force $M_c$, and the feed force $F_f$, other components of the resulting active force (shear force, friction force, thrust force) were calculated based on the Ernst–Merchant circle force diagram (Hlásková *et al.*, 2019).

By cutting with a circular saw blade, the average total cutting power $P_{c\_T}$ can be calculated using the cutting forces model published by Atkins (2003, 2005). This model considers the elements of fracture mechanics: shear yield strength $\tau_\gamma$ and fracture toughness $R$. This methodology was developed for various woodworking technologies by the authors Orlowski, Ochrymiuk and Atkins (2014), Chuchala *et al.* (2020, 2021), Hlásková, Kopecký and Novák (2020) and Sinn *et al.* (2020). The model is expressed in the form of Eq. (1):

$$P_{c\_T} = z_a \cdot \frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}} \cdot h_m \cdot v_c + z_a \cdot \frac{R \cdot b}{Q_{shear}} \cdot v_c + P_{ac} + P_{dull} \quad (1)$$

Where $z_a$ is the number of simultaneously cutting teeth; $b$ is the kerf width; $\gamma$ is the shear strain along the shear plane; and $Q_{shear}$ is the coefficient of friction correction.

Total power consists of four components. The first component expresses the internal work of plasticity along the shear plane. The shear strain along the shear plane γ is described as:

$$\gamma = \frac{\cos \gamma_f}{\cos(\Phi - \gamma_f) \cdot \sin \Phi} \quad (2)$$

Where $\gamma_f$ is the rake angle, and ϕ is the shear plane angle, which expresses the orientation of the shear plane.

The second component expresses the internal work required to separate/form a new surface, where the fracture toughness $R$ corresponds to the specific work of separating the material.

The coefficient of friction correction $Q_{shear}$ depends basically on the orientation of the shear plane to the workpiece and represents the effect of the friction between the rake face and the chips. $Q_{shear}$ is expressed in a following form:

$$Q_{shear} = \left[1 - \left(\sin \beta_\mu \cdot \sin \Phi / \cos(\beta - \gamma_f) \cos(\Phi - \gamma_f)\right)\right] \quad (3)$$

Where $\beta_\mu = \tan^{-1}\mu$ is the friction angle, and $\mu$ is the coefficient of friction.

The third component expresses the kinetic energy for chip acceleration and its sweep out by the circular sawblade out of point of cutting. The third component does not affect the value of cutting resistance (Kopecký *et al.*, 2014):

$$P_{ac} = \dot{m} \cdot v_c^2 \quad (4)$$

$$\dot{m} = \frac{b \cdot l \cdot v_f \cdot \rho_w}{2} \quad (5)$$

Where $l$ is the cut length, and $\rho_w$ is the wood density.

The effect of chip acceleration power, $P_{ac}$, on the overall cutting power is negligible. Therefore, $P_{ac}$ was omitted from the analyses performed in this research (Hlásková *et al.*, 2021).

The fourth component, $P_{dull}$, is the power that considers the dulling of cutting edges. It is important to note that this model assumes perfect cutting-edge sharpness; therefore, the component $P_{dull}$ can be omitted.

The cutting force per single tooth is expressed by the slope of the line in the form:

$$F_c^{1z} = (k) \cdot h_m + q \quad (6)$$

$$F_c^{1z} = \left(\frac{\tau_\gamma \cdot b \cdot \gamma}{Q_{shear}}\right) \cdot h_m + \left(\frac{R \cdot b}{Q_{shear}}\right) \quad (7)$$

Where $k$ corresponds to the slope and $q$ to the intercept of the linear regression line with the $y$ axis. The regression variable is the mean uncut chip thickness $h_m$. By comparing the regression equation with the experimental data obtained from the machinability tests, it is possible to determine the values of the fracture parameters (fracture toughness $R_{\parallel\perp}$, and shear yield strength $\tau_{\gamma\parallel\perp}$).

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Cutting force
### 3.1. Sila rezanja

Figure 1 shows an almost linear increase in the cutting force per one tooth occurred along with an increasing uncut chip thickness, which confirms the theoretical assumptions (Eq. 6). In addition, Figure 1 shows the coefficients of determination $r^2$, and the regression equations of the cutting force per one tooth as a function of the uncut chip thickness.

All tests showed statistically significant differences in the mean values of the cutting forces for each feed rate. Therefore, we were able to statistically prove the effect of MC of wood on the value of the cutting force when cutting spruce wood and oak wood with a circular sawblade.

Figure 1 presents the well-known fact that higher cutting force is required when cutting hardwood. When machining spruce samples compared to oak samples, the cutting force is reduced by up to 20 %. When cutting oak samples, the direction of the linear line of regression increases steeper compared to spruce samples. The observed trend is in line with the research of Willinston (1988) and Aguilera and Martin (2001). In the past, many experiments have been focused on the issue of machining softwood and hardwood (Kivimaa, 1950; McKenzie, 1960; Koch, 1964; Goli *et al.*, 2009; Wy-

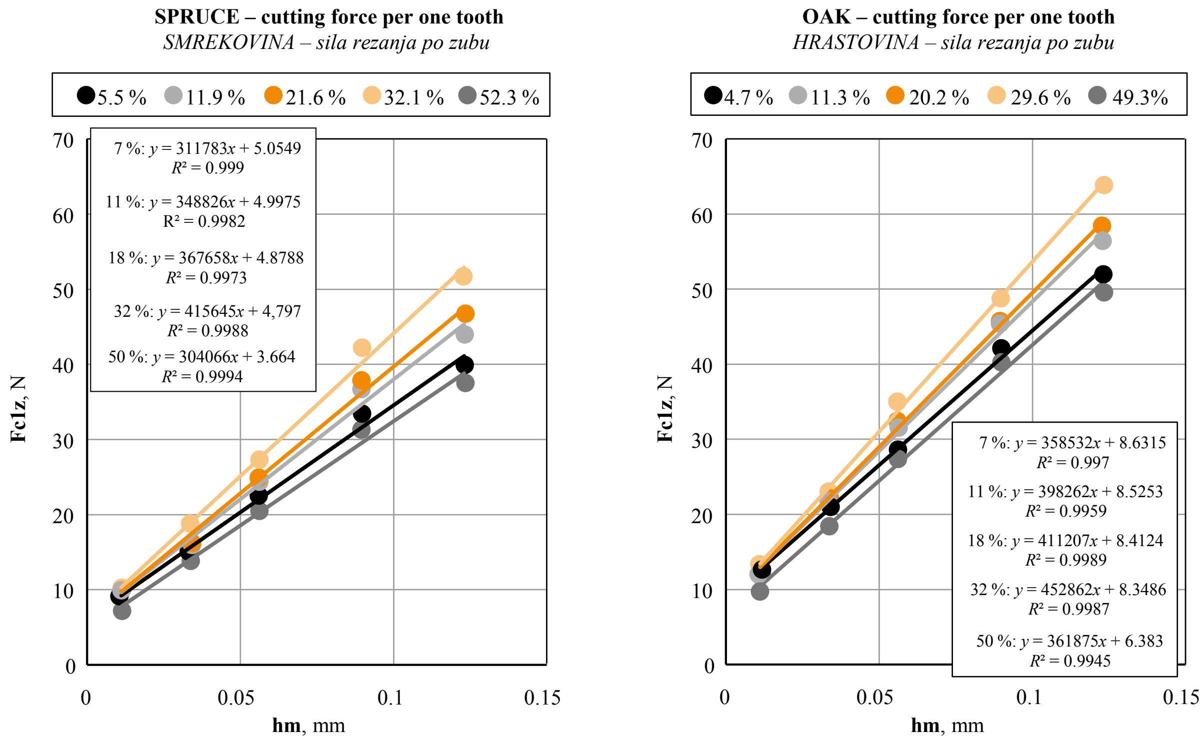



**Figure 1** Dependence of average value of measured cutting force per one tooth as a function of mean uncut chip thickness
**Slika 1.** Ovisnost prosječne vrijednosti sile rezanja po jednom zubu kao funkcije srednje debljine neodvojene strugotine

eth, Goli and Atkins, 2009; Cristóvão *et al.*, 2011; Moradpour *et al.*, 2013b). The results of our experiment confirm their claim that the cutting force depends on the wood species.

Moreover, Figure 1 indicates the effect of the MC on the value of the cutting force. The values of cutting force increase with increasing wood moisture content up to the FSP. If the wood cell lumens are filled with free water, the values of the cutting force decrease significantly - by 22 % compared to the samples with MC at the FSP for oak, and by 27 % for spruce. The highest value of cutting force was observed when machining oak and spruce samples at FSP. Wood saturated with free water had the lowest cutting force values. Cristóvão *et al.* (2011), Moradpour *et al.* (2013b) and Lucic *et al.* (2004) state in their publications that the increasing MC up to the FSP results in a deterioration of the mechanical properties of the wood and thus causes a reduction in the cutting force. Our results are contrary to the assumption of the above authors, but they are in accordance with the following researchers: Increasing the MC of wood to FSP results in an increase in the distance between the cellulose chains (Kollmann and Côté, 1984) and thus the wood swells, resulting in increased friction between the tool and workpiece kerf sides and greater gripping at the cutting point. In the range of bound water, we must also consider the degree of elastic deformation, which increases with higher moisture content. As a result of these deformations, the cutting tool is gripped in the cut (Varkocek *et al.*, 2004), which leads to an increase in the value of the cutting force. Postnikov (1965) and Mikolašik (1981) stated that cutting force and power requirements increase with increasing MC of wood, despite the decrease in mechanical properties of wood. They explained this effect by saying that, for a workpiece with a higher moisture content, the friction between the tool, the chips and both workpiece kerf sides increase the cutting force more than the decreasing mechanical properties of the wood. The effect of MC on the value of the cutting force may vary depending on the observed wood species (Cristóvão *et al.*, 2011; Moradpour *et al.*, 2013b). Axelsson *et al.*, 1993a claim that the MC can affect the cutting force positively or negatively depending on the cutting direction and wood temperature. Porankiewicz *et al.* (2011) argued that the parallel cutting force increases with the MC from 8 % to 30 % and then, decreases slightly with a further increase in MC up to 133 %.

The MC above the FSP contains free water, which helps to reduce the friction at the tool rake, acts as a lubricant in the cut, and consequently reduces the cutting force (Siklienka *et al.*, 2017).

### 3.2 Feed force
### 3.2. Posmična sila

Figure 2 shows that the force required to feed the workpiece in the sawblade at a speed of 2–22 m/min ranges from 10 N to 35 N for oak samples and from 8 to 31 N for spruce samples. The higher feed force is needed for machining hardwood than softwood; when machining oak samples, the increase in the feed force is up to 15

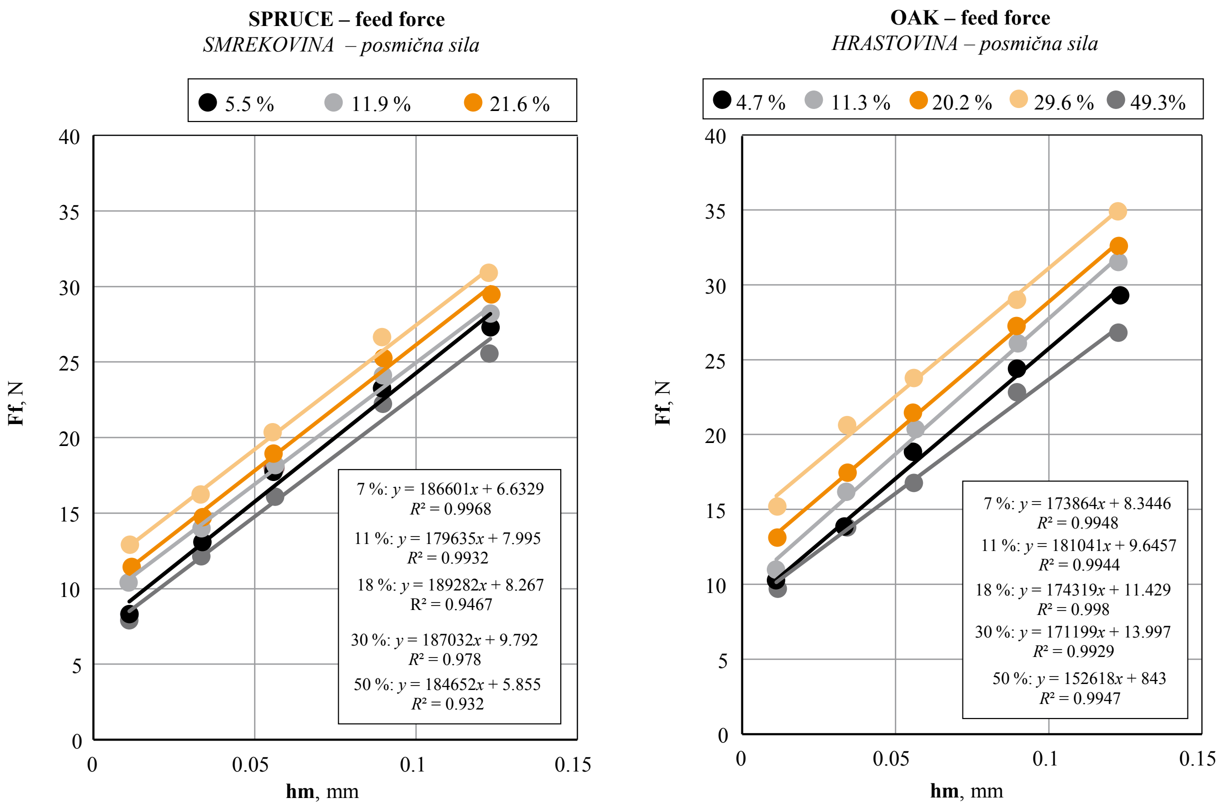



**Figure 2** Dependence of average value of feed force as a function of mean uncut chip thickness
**Slika 2.** Ovisnost prosječne vrijednosti posmične sile kao funkcije srednje debljine neodvojene čestice

% compared to spruce samples. The dependence is linear with a high coefficient of determination. Koch (1964), Moradpour *et al.* (2013b), Kminiak and Kubs (2016) found that cutting force increases with feed speed. Increasing the feed speed (connected with increasing uncut chip thickness) is generally associated with higher cutting force and power (Axelsson *et al*., 1993b; Cristóvão *et al.*, 2011; Aguilera and Martin, 2001) (Axelsson *et al.,* 1993, Vazquez-Cooz and Meyer, 2006; Aguilera, 2011a; Cristóvão *et al*., 2012).

We have also found that, as the MC increases, the feed force increases in the range of bond water. Significant elastic deformations occur in the saw kerf and in gripping the cutting tool at the cutting point by sides of saw kerf, thus increasing the feed force. At MC above the FSP, the feed force decreases. At this MC level, the values of the feed force are the lowest during machining with the circular saw blade. The decrease in feed force of oak samples compared to sample no. 4 (at the FSP) was 25 % and up to 20 % for spruce samples. Due to the presence of free water, which acts as a lubricant, the feed mechanisms do not require such a large feed force, as is the case with dry wood.

### 3.3 Fracture parameters
### 3.3. Parametri loma

Based on the experiments performed, the input parameters ($\phi$, $\mu$, $\beta_\mu$, $\gamma$, $Q_{shear}$) for the axial-perpendicular model were calculated for cutting with the circular sawblade ($b$ = 3.5 mm, $\varphi_{2m}$ = 36.5°). The characteristic data were estimated according to Atkins (2005). The main parameters of the model were determined based on regression analysis; the fracture toughness, $R_{\|\perp}$ from the intercept; the shear yield strength, $\tau_{\gamma\|\perp}$ from its slope. The shear yield strength values $\tau_{\gamma\|\perp}$ were calculated for the uncut chip thickness, $h_m$ > 0.12 mm, when the cutting resistance was practically constant (Orlowski and Palubicki, 2009). The values of the fracture parameters are given in Table 4. Fracture toughness and shear yield strength are given in the literature for the individual directions of loading and for the main directions of crack propagation. However, our results represent a combination of these basic directions because the machining was performed in the axial-perpendicular direction of cutting. The values of the fracture parameters are relevant only for a given cutting edge, and therefore cannot be considered as the material constants (Hlásková *et al*., 2020).

Figure 3 summarizes the fracture toughness and shear yield strength in boxplots to illustrate the influence of the wood species and MC on fracture parameters.

Fracture toughness of spruce samples is up to 42 % lower compared to oak samples. Ashby *et al*. (1985) claim that the fracture toughness of dry wood depends on the density. The statement is justified by the fact that higher density samples provide greater resistance to crack propagation due to higher wood mass concentra-

**Table 4** Fracture parameters
**Tablica 4.** Parametri loma

| **Wood species** *Vrsta drva* | ***w*, %** | μ | $\beta_\mu$, ° | ϕ, ° | γ | $Q_{shear}$ | $\tau_{\gamma\|\|\perp}$, MPa Mean Score ± SD | $R_{\gamma\|\|\perp}$, J/m² Mean Score ± SD |
|---|---|---|---|---|---|---|---|---|
| **Spruce** *smrekovina* | 5.5 | 0.46 | 25.23 | 42.63 | 1.468 | 0.797 | 50.23 ± 0.891 | 1404.14 ± 86.835 |
| | 11.9 | 0.33 | 23.72 | 45.63 | 1.457 | 0.745 | 46.48 ± 0.959 | 1388.19 ± 100.646 |
| | 21.6 | 0.41 | 22.51 | 43.75 | 1.484 | 0.711 | 45.11 ± 0.939 | 1355.22 ± 105.631 |
| | 32.1 | 0.40 | 21.88 | 44.06 | 1.479 | 0.716 | 43.43 ± 1.206 | 1332.5 ± 90.396 |
| | 52.3 | 0.43 | 23.06 | 43.47 | 1.489 | 0.705 | 42.21 ± 1.846 | 1017.77 ± 133.523 |
| **Oak** *hrastovina* | 4.7 | 0.68 | 34.26 | 37.866 | 1.608 | 0.625 | 61.11 ± 1.179 | 2397.64 ± 90.454 |
| | 11.3 | 0.56 | 29.29 | 40.31 | 1.549 | 0.656 | 57.02 ± 1.204 | 2368.14 ± 91.315 |
| | 20.2 | 0.53 | 28.19 | 40.91 | 1.536 | 0.665 | 55.32 ± 1.436 | 2336.77 ± 121.679 |
| | 29.6 | 0.54 | 28.75 | 40.62 | 1.542 | 0.661 | 51.397 ± 1.251 | 2319.06 ± 79.739 |
| | 49.3 | 0.64 | 32.59 | 38.71 | 1.586 | 0.636 | 50.62 ± 1.969 | 1773.06 ± 119.767 |

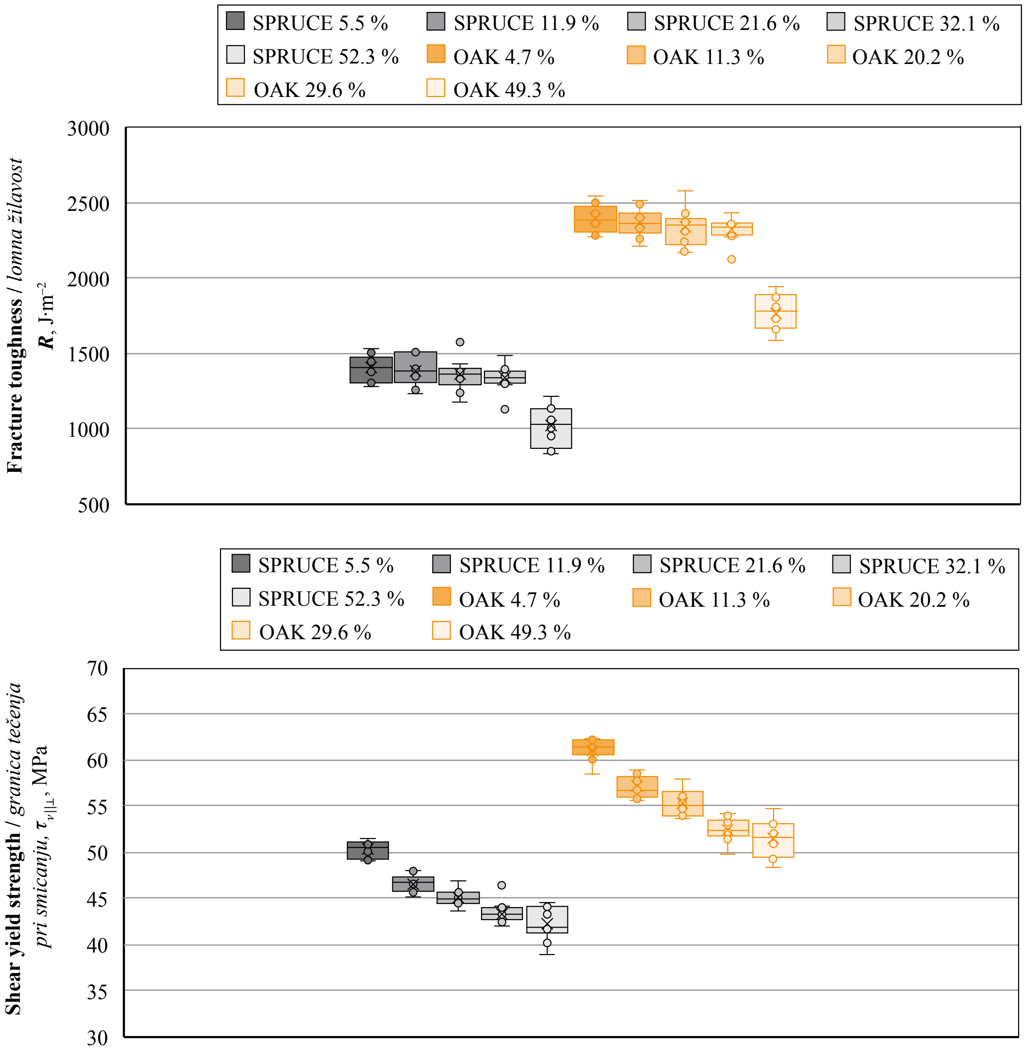



**Figure 3** Fracture toughness and shear yield strength for all moisture content levels
**Slika 3.** Lomna žilavost i granica tečenja pri smicanju za pojedine sadržaje vode

tion (Petterson and Bodig, 1983). The same conclusion was published by Leicester (1974), Kretschmann *et al.* (1990) and Gibson and Ashby (1997).

Few previous investigations have considered the dependency of fracture behavior on moisture content (Majano-Majano *et al.*, 2012). Kretschmann (2010) states that there is only limited information on the effect of MC on fracture toughness. This information suggests that fracture toughness is either insensitive to MC or increases with decreasing wood MC. Petterson and Bodig (1983) report that fracture toughness decreases with increasing MC for various wood samples. Our results agree with the literature and confirm that higher MC level negatively affects the mechanical properties of wood. Fracture toughness decreases with increasing moisture content: the decrease for oak samples is up to

28 % and for spruce samples up to 26 %. The minimum values of fracture toughness are achieved at the MC level above FSP for spruce ($R_{\gamma\|\perp}$ = 1018 J·m$^{-2}$) and oak samples ($R_{\gamma\|\perp}$ = 1773 J·m$^{-2}$). Nikitin (1966) explains this claim by the penetration of water into the crystal structure of cellulose microfibrils. This leads to a reduction in crystallinity and a consequent reduction in fracture toughness. The maximum values are reached at MC of approximately w = 5 %, for spruce ($R_{\gamma\|\perp}$ = 1404 J·m$^{-2}$) and oak samples ($R_{\gamma\|\perp}$ = 2398 J·m$^{-2}$). According to Conrad *et al*. (2003), the fracture toughness of solid wood reaches a maximum between 6 to 8 % MC.

Due to the fibrous structure, wood has different shear yield strengths in three perpendicular directions. Our method of breaking the workpiece is most closely approached by shear in the transverse plane, where the forces act perpendicular to the fibers in the radial or tangential direction. This type of failure is often called “cutting fibers” or “shear strength” (Pozgaj, 1993). Shear yield strength for oak samples is up to 23 % higher compared to spruce samples. Values of the shear yield strength are higher for oak samples than for spruce samples at all moisture content levels. Shear yield strength decreases linearly with increasing moisture content: the decrease for oak samples is up to 17 % and for spruce samples up to 16 %. The minimum values of shear yield strength are achieved at the moisture content level above FSP: for spruce samples ($\tau_{\gamma\|\perp}$ = 42 MPa) and for oak samples ($\tau_{\gamma\|\perp}$ = 51 MPa). The maximum values are reached at moisture content of approximately w = 5 %, for spruce ($\tau_{\gamma\|\perp}$ = 50 MPa) and oak samples ($\tau_{\gamma\|\perp}$ = 61 MPa). Naylor *et al.* (2012) claim that a linear decrease in shear strength was observed with an increase in moisture content in the range 6.5–35 %. The three hardwoods studied showed the highest values, and they were approximately 45 % higher than those of softwoods.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

Contrary to the opinion of some authors, the results have shown that, during circular sawing, the cutting force and feed force increased with increasing MC up to the FSP. As the MC increases above the FSP, the cutting and feed forces significantly decrease (reaching the minimum values). For a workpiece with a higher moisture content, the tool is gripped in the saw kerf and the friction between the tool, the chips and both workpiece kerf sides increase the cutting force more than the decreasing mechanical properties of the wood. If the wood contains free water, the cutting and feed force are reduced because the free water acts as a lubricant in the cut and helps to reduce friction at the tool rake.

On the basis of the measurements, the basic relationships for calculating fracture toughness and shear yield strength of spruce and oak samples were derived without the need to perform complex fracture tests. The values of fracture parameters are only suitable for the axial-perpendicular cutting model and cannot be considered as material constants. It can be concluded that the moisture content of wood affects the fracture toughness $R_{\|\perp}$, and shear yield strength $\tau_{\gamma\|\perp}$. As the moisture content increases, the values of these parameters decrease. The minimum values of fracture parameters are achieved at the moisture content level above FSP.

## 5 REFERENCES
## 5. LITERATURA


1. Ahmet, K.; Dai, G.; Jazayeri, S.; Tomlin, R., 1999: Experimental procedures for determining the equilibrium moisture content of twenty timber species. Forest Products Journal, 49: 88-93.
2. Barkas, W. W., 1936: Wood-water relationships, 2: The fibre saturation point of beech wood. Proceedings of the Physical Society, 48: 576-588. https://doi.org/10.1088/0959-5309/48/4/305
3. Böhner, G., 1996: Überlegungen und Ergänzungen zum „Keylwerth-Diagramm”. Holz als Roh-und Werkstoff, 54: 73-79. https://doi.org/10.1007/s001070050139
4. Box, G. E. P.; Draper, N. R., 2007: Response surfaces, mixtures, and ridge analyses, 2nd ed. Wiley Series in Probability and Statistics. Wiley, Hoboken, NJ, USA.
5. Browning, B. L., 1966: The chemistry of wood. Interscience Publishers Inc., New York, USA.
6. Brunner, R., 1987: Die Schnittholztrocknung, 5th ed. Brunner-Hildebrand GmbH, Hannover, Germany.
7. Chatterjee, S.; Hadi, A. S., 2013: Regression analysis by example, 5th ed. Wiley, Somerset, UK.
8. Côté, W. A., 1964: Anatomy and ultrastructure of reaction wood. In: Cellular Ultrastructure of Woody Plants. Presented at the Advanced Science Seminar, Syracuse University Press, Upper Saranac Lake, New York.
9. Côté, W. A.; Day, A. C.; Timell, T. E., 1969: A contribution to the ultrastructure of tension wood fibers. Wood Science and Technology, 3: 257-271. https://doi.org/10.1007/BF00352301
10. Felten, J.; Sundberg, B., 2013: Biology, chemistry and structure of tension wood. In: Cellular Aspects of Wood Formation, Plant Cell Monographs. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 203-224. https://doi.org/10.1007/978-3-642-36491-4_8
11. Fengel, D.; Wegener, G., 1983: Wood: Chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin. https://doi.org/10.1515/9783110839654
12. Glass, S. V.; Zelinka, S. L.; Johnson, J. A., 2014: Investigation of historic equilibrium moisture content data from the Forest Products Laboratory (No. FPL-GTR-229). Forest Products Laboratory, Madison, WI, USA.
13. Groover, A., 2016: Gravitropisms and reaction woods of forest trees – evolution, functions and mechanisms. New Phytol, 211: 790-802. https://doi.org/10.1111/nph.13968
14. Hailwood, A. J.; Horrobin, S., 1946: Absorption of water by polymers: analysis in terms of a simple model. Transactions of the Faraday Society, 42: B084. https://doi.org/10.1039/tf946420b084
15. Hernández, R. E., 2007: Moisture sorption properties of hardwoods as affected by their extraneous substances,

wood density and interlocked grain. Wood and Fiber Science, 39: 132-145.
16. Jankowska, A., 2018: Assessment of sorptive properties of selected tropical wood species. Drvna industrija, 69: 35-42. https://doi.org/10.5552/drind.2018.1733
17. Jankowska, A.; Drożdżek, M.; Sarnowski, P.; Horodeński, J., 2016: Effect of extractives on the equilibrium moisture content and shrinkage of selected tropical wood species. BioResources, 12: 597-607. https://doi.org/10.15376/biores.12.1.597-607
18. Jannot, Y.; Kanmogne, A.; Talla, A.; Monkam, L., 2006: Experimental determination and modelling of water desorption isotherms of tropical woods: afzelia, ebony, iroko, moabi and obeche. Holz als Roh- und Werkstoff, 64: 121-124. https://doi.org/10.1007/s00107-005-0051-2
19. Klement, I.; Vilkovská, T.; Uhrín, M.; Barański, J.; Konopka, A., 2019: Impact of high temperature drying process on beech wood containing tension wood. Open Engineering, 9: 428-433. https://doi.org/10.1515/eng-2019-0047
20. Klement, I.; Vilkovská, T.; Vilkovský, P.; Hýsek, Š., 2020: Structural differences between reaction wood and opposite wood with different drying temperatures. BioResources, 15: 4407-4416. https://doi.org/10.15376/biores.15.2.4407-4416
21. Kojs, P.; Malik, I.; Wistuba, M.; Stopka, R.; Trabka, K., 2012: Mechanizmy wzrostu ekscentrycznego i formowania się drewna reakcyjnego w kontekście badań dendrogeomorfologicznych – wprowadzenie do nowej hipotezy / Model of eccentric growth and reactive wood formation in the context of dendrogeomorphological research – introduction to a new hypothesis. Studia i Materiały Centrum Edukacji Przyrodniczo-Leśnej, 14: 147-156.
22. Kollmann, F., 1936: Technologie des Holzes, 1st ed. Springer, Berlin.
23. Kúdela, J.; Čunderlík, I., 2012: Bukové drevo, štruktúra, vlastnosti, použitie / Beech wood, structure, properties, use. Technická univerzita vo Zvolene, Zvolen.
24. Langrish, T. A. G.; Walker, J. C. F., 1993: Transport processes in wood. In: Primary Wood Processing: Principles and Practice. Springer Netherlands, Dordrecht, pp. 121-152. https://doi.org/10.1007/978-94-015-8110-3_5
25. Majka, J.; Olek, W., 2013: The influence of equilibrium moisture content data on accurate control of timber kiln drying intensity. In: Procedings of 4th European Drying Conference (EuroDrying'2013), European Federation of Chemical Engineering, Paris, France.
26. Popper, R.; Niemz, P., 2009: Wasserdampfsorptionsverhalten ausgewählter heimischer und überseeischer Holzarten. Bauphysik, 31: 117-121. https://doi.org/10.1002/bapi.200910017
27. Popper, R.; Niemz, P.; Croptier, S., 2009: Adsorption and desorption measurements on selected exotic wood species: Analysis with the Hailwood-Horrobin model to describe the sorption hysteresis. Wood Research, 54: 43-56. https://doi.org/10.3929/ethz-a-006104740
28. Redman, A. L.; Bailleres, H.; Turner, I.; Perré, P., 2016: Characterisation of wood-water relationships and transverse anatomy and their relationship to drying degrade. Wood Science and Technology, 50: 739-757. https://doi.org/10.1007/s00226-016-0818-0
29. Salin, J.-G., 2011: Inclusion of the sorption hysteresis phenomenon in future drying models. Some basic considerations. Maderas: Ciencia y Tecnologia, 13: 173-182. https://doi.org/10.4067/S0718-221X2011000200005
30. Scurfield, G., 1973: Reaction wood: Its structure and function. Science, 179: 647-655. https://doi.org/10.1126/science.179.4074.647
31. Scurfield, G.; Wardrop, A., 1962: The nature of reaction wood. VI. The reaction anatomy of seedlings of woody perennials. Australian Journal of Botany, 10: 93. https://doi.org/10.1071/BT9620093
32. Simón, C.; Esteban, L. G.; de Palacios, P.; Fernández, F. G.; Martín-Sampedro, R.; Eugenio, M. E., 2015: Thermodynamic analysis of water vapour sorption behaviour of juvenile and mature wood of *Abies alba* Mill. Journal of Materials Science, 50: 7282-7292. https://doi.org/10.1007/s10853-015-9283-7
33. Simpson, W. T., 1973. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber Science, 5: 41-49.
34. Skaar, C., 1988: Wood-water relations. Springer-Verlag, Berlin; New York.
35. Spalt, H., 1958: Water vapor sorption by wood. Forest Products Journal, 8: 288-295.
36. Tarmian, A.; Perré, P., 2009: Air permeability in longitudinal and radial directions of compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Holzforschung, 63: 352-356. https://doi.org/10.1515/HF.2009.048
37. Tarmian, A.; Remond, R.; Dashti, H.; Perré, P., 2012: Moisture diffusion coefficient of reaction woods: compression wood of *Picea abies* L. and tension wood of *Fagus sylvatica* L. Wood Science and Technology, 46: 405-417. https://doi.org/10.1007/s00226-011-0413-3
38. Tarmian, A.; Remond, R.; Faezipour, M.; Karimi, A.; Perré, P., 2009: Reaction wood drying kinetics: tension wood in *Fagus sylvatica* and compression wood in *Picea abies*. Wood Science and Technology, 43: 113-130. https://doi.org/10.1007/s00226-008-0230-5
39. Tulik, M.; Jura-Morawiec, J., 2011: Drewno reakcyjne a architektura korony drzewa / Reaction wood and tree crown architecture. Sylwan, 155: 808-815.
40. Wardrop, A.; Davies, G., 1964: The nature of reaction wood. VIII. The structure and differentiation of compression wood. Australian Journal of Botany, 12: 24. https://doi.org/10.1071/BT9640024
41. Weichert, L., 1963: Untersuchungen über das Sorption- und Quellungsverhalten von Fichte, Buche und Buchen-Preßvollholz bei Temperaturen zwischen 20 ° und 100 °C. Holz als Roh-und Werkstoff, 21: 290-300. https://doi.org/10.1007/BF02610962
42. Wengert, E. M., 1976: Predicting average moisture content of wood in a changing environment. Wood and Fiber Science, 7: 264-273.
43. ***Wood Handbook, 2010: Wood as an Engineering Material. General Technical Report No. FPL-GTR-190, Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, USA.

**Corresponding address:**

**LUĎKA HANINCOVÁ**

Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Wood Science and Technology, Zemědělská 3, Brno, 613 00, CZECH REPUBLIC, e-mail: ludka.hanincova@mendelu.cz

# HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

Osnovana je na temelju Zakona o Hrvatskoj komori inženjera šumarstva i drvne tehnologije.

Komora je samostalna i neovisna strukovna organizacija koja obavlja povjerene joj javne ovlasti, čuva ugled, čast i prava svojih članova, skrbi da ovlašteni inženjeri obavljaju svoje poslove savjesno i u skladu sa zakonom, promiče, zastupa i usklađuje njihove interese pred državnim i drugim tijelima u zemlji i inozemstvu.

## Članovi komore:

inženjeri šumarstva i drvne tehnologije koji obavljaju stručne poslove iz područja šumarstva, lovstva i drvne tehnologije.

## Stručni poslovi:

projektiranje, izrada, procjena, izvođenje i nadzor radova iz područja uzgajanja, uređivanja, iskorištavanja i otvaranja šuma, lovstva, zaštite šuma, hortikulture, rasadničarske proizvodnje, savjetovanja, ispitivanja kvalitete proizvoda, sudskoga vještačenja, izrade i revizije stručnih studija i planova, kontrola projekata i stručne dokumentacije, izgradnja uređaja, izbor opreme, objekata, procesa i sustava, stručno osposobljavanje i licenciranje radova u šumarstvu, lovstvu i preradi drva.

## Zadaci Komore:

- promicanje razvoja struke i skrb o stručnom usavršavanju članova,
- poticanje donošenja propisa kojima se utvrđuju javne ovlasti Komore,
- reagiranje struke na pripremu propisa iz područja šumarstva, lovstva i drvne tehnologije,
- suradnja s nadležnim institucijama i zastupanje struke u odnosu prema njima,
- organizacija stručnoga usavršavanja,
- zastupanje interesa svojih članova,
- izdavanje pečata i iskaznice ovlaštenim inženjerima,
- briga i nadzor poštivanja kodeksa strukovne etike,
- osiguravanje članova Komore za štetu koja bi mogla nastati investitorima i trećim osobama i sl.

Članovima Komore izdaje se rješenje, pečat i iskaznica ovlaštenoga inženjera.
Za uspješno obavljanje zadataka te za postizanje ciljeva ravnopravnoga i jednakovrijednoga zastupanja struka udruženih u Komoru, članovi Komore organizirani su u razrede:

- Razred inženjera šumarstva
- Razred inženjera drvne tehnologije

HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE
Prilaz Gjure Deželića 63
10000 ZAGREB

telefon:
++ 385 1 376-5501
e-mail:
info@hkisdt.hr

www.hkisdt.hr

Marta Pędzik[1,2], Zdzisław Kwidziński[2,3], Tomasz Rogoziński[2]

# Particles from Residue Wood-Based Materials from Door Production as an Alternative Raw Material for Production of Particleboard

# Iverje nastalo obradom drvnih materijala pri proizvodnji vrata kao alternativna sirovina za proizvodnju ploča iverica

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 10. 3. 2022.
Accepted – prihvaćeno: 13. 4. 2022.
UDK: 674.8
https://doi.org/10.5552/drvind.2022.0027



**ABSTRACT** • *Problems with the availability of particleboards are a challenge for constructors and production companies that use this material in the technology of their products. During the production process of technical door leaves, a significant amount of wood-based panel residues is created, which is a large base of potential raw material on an annual basis. Given the conceptual link between circular economy (CE) activities, resources, and waste management, efforts should be made to process and reuse them to produce new particleboards. The aim of the study was to determine the physical and hygienic properties of particles obtained from the grinding of lignocellulosic composites used in production. It was found that in terms of dimensions, density as well as formaldehyde content, they have the potential to be an alternative source of raw material for the production of particleboards. However, selecting the type of materials should be carried out, and in the future, the hygienic properties of the manufactured particleboards should be controlled.*

**KEYWORDS:** *door frame industry; particle properties; environmentally friendly; reuse; circular economy*

**SAŽETAK** • *Problemi s dostupnošću ploča iverica izazov su za građevinare i tvrtke koje se tim materijalom koriste u svojim proizvodnim tehnologijama. Tijekom proizvodnje vratnih krila stvara se znatna količina ostatka od obrade drvnih ploča, koji na godišnjoj razini čini potencijalno veliku sirovinsku bazu. S obzirom na konceptualnu vezu između aktivnosti kružne ekonomije (CE), resursa i gospodarenja otpadom, potrebno je uložiti napore kako bi se taj drvni ostatak obradio i ponovo iskoristio za proizvodnju ploča iverica. Cilj ovog istraživanja bio je utvrditi fizikalna svojstva i ekološku prihvatljivost iverja dobivenog u procesu obrade (glodanja) lignoceluloznih kompozitnih materijala. Utvrđeno je da po dimenzijama, gustoći i sadržaju formaldehida takvo iverje može biti alternativni izvor sirovine za proizvodnju ploča iverica. Međutim, potrebno je odabrati odgovarajuću vrstu materijala, ali i kontrolirati ekološka (higijenska) svojstva izrađenih ploča iverica.*

**KLJUČNE RIJEČI:** *proizvodnja vrata; svojstva iverja; ekološka prihvatljivost; ponovna uporaba; kružna ekonomija*

[1] Author is researcher at Poznań Institute of Technology, Łukasiewicz Research Network, Wood Technology Centre, Poznan, Poland. https://orcid.org/0000-0003-3607-8128
[2] Authors are researchers at University of Life Sciences, Faculty of Forestry and Wood Technology, Department of Furniture Design, Poznan, Poland. https://orcid.org/0000-0003-4957-1042
[3] Author is researcher at Porta KMI Poland S. A., Bolszewo, Poland. https://orcid.org.pl/0000-000208522-9650

## 1 INTRODUCTION
## 1. UVOD

Due to the numerous uses of wood in construction materials, packaging, transport, furniture and energy, rational use of wood has become an essential aspect of environmental protection. The amount of resources present in the environment is limited. In some industries, it is possible to wholly or partially replace wood with another raw material (Mohd Ali *et al*., 2020). An example of an adequate substitution of wood with alternative raw materials is the industry of wood-based panels, more specifically particleboards (Nurhazwani *et al*., 2016; Pędzik *et al.*, 2022).

Problems with the availability of particleboards are a challenge for constructors and production companies that use this material in the technology of their products. The annual global production of chipboard in 2020 amounted to over 96 million $m^3$, of which 40.5 million $m^3$ was European production (FAO, 2022). These data show that particleboard is an important material. The production volume of particleboard in 2020 was lower by approx. 9 % compared to 2015, and by approx. 5 % compared to 2018. Nevertheless, the decline in production is not due to the lack of interest and demand on the part of enterprises but is related to the raw material deficit. Therefore, research has been carried out for a long time to expand the raw material base for the particleboard industry. Due to the trend of the circular economy (CE) and recycling of materials, materials containing wood or other lignocellulosic particles, previously unused in industrial production, seem to be a large base of the raw material (Foti *et al*., 2022). Various sources have already been considered, i.e., wood residues and low-value woody species, plantations of fast-growing trees, or urban waste. Raw materials alternatives to wood are often by-products and residues from the agricultural and food industries, i.e., cereal straws, agricultural crops, food and agricultural wastes, hulls and husks of seeds and seaweeds (Pędzik *et al*., 2021). The undoubted advantage of using these raw materials is their renewable nature, ease of obtaining, and low price. They are not the main target of cultivation, so competition is much less.

Managing by-products is an important aspect when planning and designing production and using products (Azambuja *et al*., 2018). In many cases, from such raw materials, it is possible to produce good-quality boards that meet the requirements of technical standards, so it is necessary to look for other, new sources of raw materials. Therefore, using waste as a raw material for particleboard production can reduce the burden on producers with increasing production costs (Lee *et al*., 2018). What is a waste for one industry, for another maybe a valuable source of full-value raw material and at the same time contribute to the improvement of the condition and protection of the environment. Sustainable resource management means not only prudent sourcing of resources but also rational use of them. They are recycled in the form of waste and finished products (Foti *et al*., 2022). Due to the development and technological progress, guided by the idea of reusing raw materials, factories producing particleboards use a significant addition of post-consumer and recycled wood. The research proves that particleboards made, in the core layer, with 50 % content of particles from recycling boards glued with UF resin and laminated particleboards do not significantly deteriorate the properties of the panels (Czarnecki *et al*., 2003).

The amount of pure softwood particles in particleboards is already much less than a few years ago. Following trends and responding to market needs, more and more attention is paid to the use of waste and by-products. Particleboards are available to produce wood from forest thinning, saw waste, and recycled wood, including recycled wood for furniture, pallets, wooden packaging, and construction and demolition components (Azambuja *et al*., 2018).

One of the industries where a significant amount of particleboard is used is the production of joinery products. In the production plants of doors and door frames, a considerable amount of wood-based panel residues is generated during the production process. It is estimated that in a large production plant from the technical door leaf, there is an average of about 2.3 kg of waste, which generates about 10 tons during a two-shift production. On an annual basis, such an amount of waste is an expensive and considerable challenge to manage. At the same time, it is a good basis for valuable raw material. This waste is generated from materials used in the production of door leaves. These are wood composite materials composed of softwood, plywood, particleboard, HDF boards, MDF boards, and light filling boards containing HDF and paper honeycomb. These residues constitute a waste material from processing at various stages of production, i.e., formatting, drilling holes, milling, etc. Their dimensions depend on the type of technological operation and the specific shapes or patterns of milling the door leaves. Such amounts and composition cause problems with utilizing and managing these residues in production plants. They are subject to thermal conversion. Given the conceptual link between CE-compliant activities, resources, and waste management, steps should be taken to process and reuse panel waste from the production of technical door leaves. Producers of wood-based panels must use careful sorting methods to produce the uncontaminated wood raw material. There is also a visible development of research in managing construction and demolition waste, including waste plywood, particleboard, wood, and MDF boards (Yuan and Shen, 2011). When assessing the re-use of these materials, their mechanical and hygienic properties should be considered. This is necessary because of the formaldehyde-based adhesive resins, plastics, laminates, and films they contain.

Considering the above aspects, the aim of this study was to determine the physical and hygienic properties of particles obtained from the grinding of residues from the production of technical door leaves as a potential raw material for the production of three-layer particleboards.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Preparation of raw material
### 2.1. Priprema sirovine

Elements of wood-based panels, which are the residues from the production of technical door leaves of the PORTA KMI Poland S.A. company, were used for the tests. These materials are a waste product resulting from milling openings in various types of door leaves in the TechnoPORTA line - an intelligent, customized technological line for the automated production of technical doors (Figure 1).

The obtained waste of wood composite materials included: particleboard, HDF with CPL (Continuous Pressed Laminates) and finish foil, MDF, glued wood, and paper. The waste was divided into two groups. The first includes softwood, hardwood, particleboard, tubular particleboard and HDF, and the second includes insulation fiberboard, MDF, and paper honeycomb boards (Figure 2).

The materials were shredded in a cutting mill by Condux (Mankato, United States). The obtained particles were divided into fractions on a vibrating sorter by Allgaier (Uhingen, Germany) equipped with four sieves with the mesh size: 8.0, 2.0, 1.0 and 0.5 mm. The fractions from group 1 from 2.0 mm sieves - particles for the core layers (PCL) and 1.0 mm - microparticles (MP) were considered usable based on a preliminary optical assessment of their shape and dimensions. They were subjected to further tests (Figure 3).

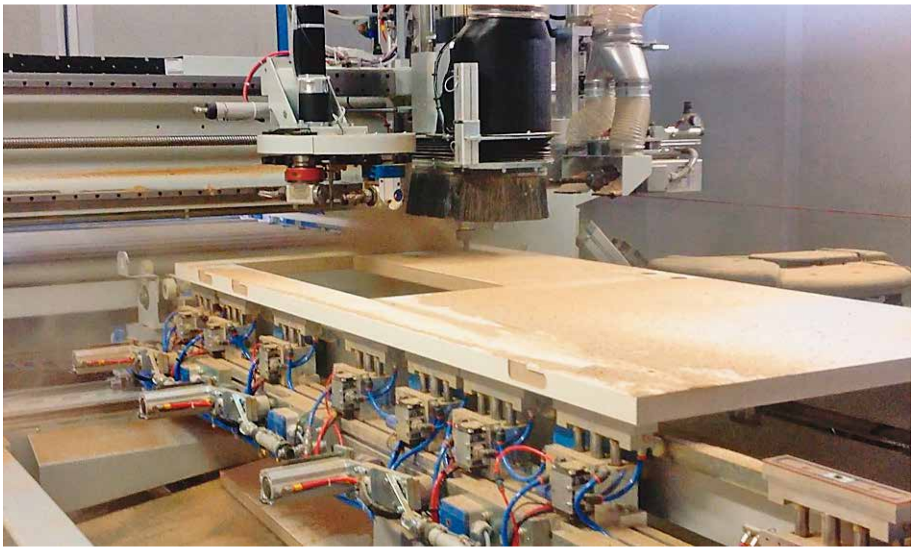


**Figure 1** Milling holes in door leaves on TechnoPORTA line
**Slika 1.** Izrada otvora u vratnim krilima na TechnoPORTA obradnoj liniji

a) b)

**Figure 2** Waste groups a) group 1, b) group 2
**Slika 2.** Skupine otpadnog materijala: a) skupina 1, b) skupina 2


a) b)

**Figure 3** A particle fraction considered as useful a) particles for core layers (PCL) from 2 mm sieve, b) microparticles (MP) from 1 mm sieve

**Slika 3.** Frakcije iverja procijenjene kao odgovarajuće: a) iverje za središnje slojeve iverica (PCL), zadržano na situ otvora oka od 2 mm, b) mikroiverje (MP), zaostalo na situ približnog otvora 1 mm

### 2.2 Determination of poured bulk density and dimensional analysis
### 2.2. Određivanje nasipne gustoće i analiza dimenzija iverja

For the fraction from the 2.0 mm sieve, the fractional composition of the grain mixture was determined. Tests were carried out on a Fritsch AS 200 tap laboratory vibrating screen (Germany) with the following sets of square mesh flat screens with perforation: 4.0, 2.0, 1.0, 0.50, 0.25, and <0.25 mm. Subsequently, a detailed dimensional analysis was also carried out, in which approximately 200 particles were used, corresponding to twice the percentage of each sieve. The length, width, and thickness of the particles were determined, based on which the essential shape factors were determined, i.e., degree of slenderness (**λ**), degree of flatness (**ψ**), width factor (m), according to the following Eqs:

$$\lambda = \frac{l}{h} \quad (1)$$

$$\psi = \frac{w}{h} \quad (2)$$

$$m = \frac{l}{w} \quad (3)$$

Where:

$l$ – mean length of particles (mm), $h$ – mean thickness of particles (mm), $w$ – mean width of particles (mm)

For these fractions, the poured bulk density (**$\rho$**) was also determined in Eq. 4:

$$\rho = \frac{m_c - m_n}{V} \quad (4)$$

Where:

$m_c$ –weight of measuring vessel with raw material (kg), $m_n$ –weight of measuring vessel (kg), $V$ – capacity of measuring vessel ($m^3$)

### 2.3 Determination of formaldehyde content
### 2.3. Određivanje sadržaja formaldehida

The formaldehyde content in the particles of production residues and softwood was determined by the perforator method according to EN ISO 12460-5: 2016-02. The formaldehyde content was expressed in mg formaldehyde/100 g of oven-dry sample and was calculated according to the following Eq:

$$\text{perforator value} = \frac{(A_s - A_b) \cdot f \cdot (100 + H) \cdot V}{m_H} \quad (5)$$

Where:

$A_S$ – absorbance of analyzed extraction solution, $A_b$ - absorbance of analysis with distilled or demineralized water, $f$ – slope of standard curve (mg/ml), $H$ – moisture content of particles as a mass fraction (%), $m_H$ – mass of test pieces (g), $V$ – volume of volumetric flask (ml).

The perforator value was calculated based on a moisture content of 6.5 %.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Characteristics of raw material
### 3.1. Svojstva sirovine

About 170 kg of waste from the production of technical door leaves were used for the tests, of which about 30 kg of wood was obtained as a result of cutting on a cutting mill about 153 kg of particles of all fractions of 8.0, 2.0, 1.0 and 0.5 mm (Table 1).

From group 1 of raw materials, it was possible to obtain approx. 13.6 kg of particles remaining on the 2 mm sieve, classified as particles for the core layers (PCL) and 14.2 kg of fine chips, i.e., from the 1 mm sieve - micropar-

**Table 1** Amounts of particles by fraction obtained by cutting
**Tablica 1.** Količine iverja prema frakcijama određene prosijavanjem iz smjese dobivene glodanjem

| **Screen sieves, mm**<br>*Otvor oka sita*, mm | **Weight, kg**<br>*Masa*, kg | **Fraction content in total mixture of particles, %**<br>*Udio frakcije u ukupnoj smjesi iverja*, % |
|---|---|---|
| 8.0 | 20.1 | 13.1 |
| 2.0 | 53.2 | 34.7 |
| | in it 13.6 | 8.9 |
| 1.0 | 26.1 | 17.0 |
| | in it 14.2 | 9.3 |
| 0.5 | 20.7 | 13.5 |
| <0.5 | 33.0 | 21.6 |

ticles (MP). This means that out of approx. 170 kg of randomly collected production waste, characterized by a high level of differentiation, approx. 18 % of particles can be used to produce particleboards in appropriate proportions to the core layer and surfaces layers.

### 3.2 Poured bulk density and dimensional analysis
### 3.2. Nasipna gustoća i analiza dimenzija iverja

The efficiency of particleboards depends on the density of the raw material; therefore, the amount of particles required to achieve the assumed density of particleboards decreases with the increase in the density of the particles themselves (Abdul Halip *et al.*, 2022; Eisenbies *et al.*, 2019). The bulk density of particles was determined for the fractions recognized as usable. The bulk density of particles constituting a heterogeneous mixture of particles is subject to a considerable error. It largely depends on the shape and size of the particles and how they are formed in the mass and 8 % moisture. The industrial waste chips used for the tests had a moisture content of approx. 8 %. At this humidity, the bulk density of PCL is 110 kg/m$^3$, and the MP is 170 kg/m$^3$. For comparison, the bulk density of standard pine shavings is 120 kg/m$^3$, while industrial shavings are approx. 135 kg/m$^3$. Dukarska *et al.* (2021) obtained similar results in their work, proving at the same time the influence of humidity on the density of MP intended for outer layers of particleboards and PCL. On the other hand, higher values of MP were obtained for particles from construction waste and demolition wood(Azambuja *et al.*, 2018). In the case of a material such as lignocellulosic particles, the bulk density value depends primarily on the absolute density of the raw material itself. The bulk density of grain species is significantly lower than that of tree species. For triticale straw, it is approx. 30 kg/m$^3$, and for rapeseed straw approx. 45 kg/m$^3$ (Dukarska *et al.*, 2021).

Then, for PCL, the determination of the fractional composition was performed (Figure 4), and the essential shape factors were determined (Table 2).

The analysis shows that the most significant mass share is constituted by the particles retained on the

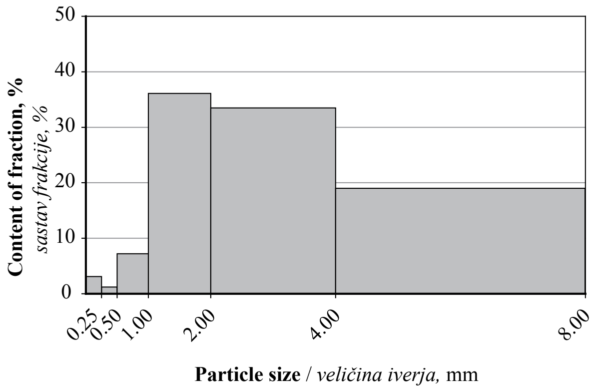



**Figure 4** Fractional composition of production waste particles
**Slika 4.** Frakcijski sastav smjese iverja iz otpadnog materijala nastalog u proizvodnji vrata

sieves with a 2.0 and 1.0 mm mesh size. Their share is respectively 33.5 and 36.1 % of the total mixture of particles. The proportion of particles from the sieve with the largest mesh size of 4.0 mm is 19 %. A small share, less than 10 %, was observed for the fraction on the 0.5 mm sieve, while smaller particles totaled 4.3 %, which is a small share positively influencing the sizing of particles. The share of individual fractions presented in this way proves the homogeneity of the material.

The dimensional analysis is carried out for mixtures with different particle sizes, which differ in shape despite being in the same screen fraction. Knowledge of particle geometry is an important aspect to use for the production of panels, and it gives information about the homogeneity of the material, which affects the quality of the manufactured products (Dukarska *et al.*, 2021). It is also essential because of the possibility of planning and adjusting the production process. Longer particles can provide greater bending strength of the boards. The analysis of average values shows that most particles are much longer than more comprehensive. However, as confirmed by statistical analysis, in the case of particles of the 4.0 mm fraction, they do not resemble standard wood particles due to the low value of the width factor. It is a mixture in which there are many particles of considerable width but not of a small thickness. They are essentially the remains of HDF boards with CPL and

**Table 2** Linear PCL dimensions and their characteristic shape factors
**Tablica 2.** Dimenzije iverja za središnje slojeve iverica (PCL) i njihovi karakteristični faktori oblika

| **Fraction, mm** *Frakcija*, mm | **Average dimensions, mm** *Prosječne dimenzije*, mm | | | **Shape factors** *Faktori oblika* | | |
|---|---|---|---|---|---|---|
| | *l* | *w* | *h* | *λ* | *ψ* | *m* |
| 4.0 | 17.20±7.56 | 6.81±2.35 | 0.76±0.24 | 22.63 | 8.96 | 2.53 |
| 2.0 | 12.01±7.96 | 3.22±1.04 | 0.51±0.23 | 23.55 | 6.31 | 3.73 |
| 1.0 | 11.29±5.17 | 1.64±0.41 | 0.60±0.29 | 18.82 | 2.73 | 6.88 |
| 0.5 | 7.23±3.11 | 0.99±0.46 | 0.45±0.15 | 16.07 | 2.20 | 7.30 |

finish foil. Coefficients characterizing the particles on the sieves of 1.0 and 0.5 mm indicate slender and coarser particles. The presence of residual glue on the surface of the particles can affect the width and thickness of the particles and thus the degree of flatness. Considering the standard deviation, the particles obtained from particleboards, and timber from wood waste from construction and demolition, have similar average dimensions (Azambuja *et al*., 2018). Moreover, the dimensions of particles from recycled pallets selected for the core layer of particleboard were from 0.25 to 4.0 mm, and for the surface layers from 0.125 to 1.0 mm (Iždinský *et al*., 2021). In terms of the production of particleboards, the use of both long and smaller particles is useful because of the excellent compression of the particles and possibility of filling the gaps between them, and consequently obtaining boards of a quality that meets the requirements of the standards.

### 3.3 Formaldehyde content
### 3.3. Sadržaj formaldehida

For the production of particleboards, urea-formaldehyde and melamine-urea-formaldehyde resins are the primary source of formaldehyde (Cao *et al*., 2022; Osman *et al*., 2020). Although formaldehyde is a component of many products used daily, it is tolerated by the human body in small amounts. Due to its harmfulness, it is a carcinogenic compound, and its allowed quantity must be controlled (Pizzi *et al*., 2020).

For particle boards, the permissible formaldehyde content in boards, according to the EN 312: 2010 standard concerning the technical requirements of particle boards for the E1 hygiene class, is ≤8 mg/100 g oven-dry board. The methods for testing the emission and formaldehyde content are standardized according to EN 717-1 and EN ISO 12460-5: 2015. Due to the correlation between the emission and formaldehyde content, producers who want to expand their sales markets to buyers from outside Europe are often obliged to meet more restrictive internal requirements of individual institutions. When determining the suitability of particles derived from the processing of wood-based panel residues, the formaldehyde content of the particles should be defined, bearing in mind that the use of amino resins may increase the formaldehyde content of the panels made of them. PCL and MP were analyzed (Table 3).

There was no significant difference between the formaldehyde content in either of the tested fractions. This value is respectively 3.3 and 3.1 mg/100 g oven-dry samples. At the actual humidity of the samples at the time of testing, the expanded uncertainty of the results was at the confidence level of 0.95 is ± 0.35 for PCL and ± 0.32 for MP. For comparison, the formaldehyde content in the softwood particles is 0.8mg / 100 g oven-dry sample. The lower hygiene of waste particles is understandable. It results from the fact that these particles come from wood-based materials, for the production of which formaldehyde resins have already been used. Nevertheless, in terms of hygiene, particles from production residues can be used as a raw material for particleboard production. However, the selection and amount of binder should be considered, and the level of formaldehyde content and emission from the finished product should be controlled.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

A significant amount of production waste from the production of technical door leaves causes an expensive problem with its management. Composite ma-

**Table 3** Formaldehyde content (perforator value)
**Tablica 3.** Sadržaj formaldehida (perforatorska vrijednost)

| **Tested material** *Ispitivani materijal* | **Perforator value (mg/100g oven-dry sample) (calculated perforator value at a moisture content of 6.5 %)** *Perforatorska vrijednost* (mg/*100* g *apsolutno suhog drva*) (*vrijednost izračunana za sadržaj vode od 6,5 %*) |
|---|---|
| Particles for core layers (PCL) *iverje za središnje slojeve ploča iverica (PCL)* | 3.3 |
| Microparticles (MP) / *mikroiverje (MP)* | 3.1 |

terials used in the production plant consist of wood materials, which can be an alternative source of raw material for wood to produce particleboards. In order to determine this suitability, the physical and hygienic properties of particles obtained from the comminution of the lignocellulosic composites used were determined. Based on the conducted research, it was found that the particles obtained from fragmented materials containing softwood, hardwood, particleboard, tubular particleboard with HDF are in terms of dimensions similar to the particles used in the production of boards. The formaldehyde content turned out to be higher than that of wood particles, but with an appropriate selection of the amount and type of binder, they can be reused. Separated from many fractions and materials, PCL and MP represent a potential for use as a raw material for producing three-layer particleboards.

## 5 REFERENCES
## 5. LITERATURA


1. Abdul Halip, J.; SaifulAzry Osman Al-Edrus, S.; Hua Lee, S.; Md Tahir, P.; Yuziah Mohd Yunus, N.; Sapuan Salit, M.; Ilyas Rushdan, A., 2022: Effects of planting density of rubber tree clone (RRIM 2020 Clone and RRIM 2025 Clone) wood to particleboard properties. Journal of Renewable Materials, 10: 1951-1960. https://doi.org/10.32604/jrm.2022.016025
2. Azambuja, R. da R.; Castro, V. G. de, Trianoski, R.; Iwakiri, S., 2018: Recycling wood waste from construction and demolition to produce particleboards. Maderas. Ciencia y tecnología, 20: 681-690. https://doi.org/10.4067/S0718-221X2018005041401
3. Cao, L.; Pizzi, A.; Zhang, Q.; Tian, H.; Lei, H.; Xi, X.; Du, G., 2022: Preparation and characterization of a novel environment-friendly urea-glyoxal resin of improved bonding performance. European Polymer Journal, 162: 110915. https://doi.org/10.1016/j.eurpolymj.2021.110915
4. Czarnecki, R.; Dziurka, D.; Łęcka, J., 2003: The use of recycled boards as the substitute for particles in the centre layer of particleboards. Electronic Journal of Polish Agricultural Universities, 6 (2): 01.
5. Dukarska, D.; Pędzik, M.; Rogozińska, W.; Rogoziński, T.; Czarnecki, R., 2021: Characteristics of straw particles of selected grain species purposed for the production of lignocellulose particleboards. Particulate Science and Technology, 39: 213-222. https://doi.org/10.1080/02726351.2019.1686096
6. Dukarska, D.; Rogoziński, T.; Antov, P.; Kristak, L.; Kmieciak, J., 2021: Characterisation of wood particles used in the particleboard production as a function of their moisture content. Materials, 15: 48. https://doi.org/10.3390/ma15010048
7. Eisenbies, M. H.; Volk, T. A.; Therasme, O.; Hallen, K., 2019: Three bulk density measurement methods provide different results for commercial scale harvests of willow biomass chips. Biomass and Bioenergy, 124: 64-73. https://doi.org/10.1016/j.biombioe.2019.03.015
8. Foti, D.; Voulgaridou, E. E.; Karastergiou, S.; Taghiyari, H. R.; Papadopoulos, A. N., 2022: Physical and mechanical properties of eco-friendly composites made from wood dust and recycled polystyrene. Journal of Renewable Materials, 10: 75-88. https://doi.org/10.32604/jrm.2022.017759
9. Iždinský, J.; Reinprecht, L.; Vidholdová, Z., 2021: Particleboards from recycled pallets. Forests, 12: 1597. https://doi.org/10.3390/f12111597
10. Kabirifar, K.; Mojtahedi, M.; Wang, C.; Tam, V. W. Y., 2020: Construction and demolition waste management contributing factors coupled with reduce, reuse, and recycle strategies for effective waste management: A review. Journal of Cleaner Production, 263: 121265. https://doi.org/10.1016/j.jclepro.2020.121265
11. Lee, S. H.; Ashaari, Z.; Ang, A. F.; Abdul Halip, J.; Lum, W. C.; Dahali, R.; Halis, R., 2018: Effects of two-step post heat-treatment in palm oil on the properties of oil palm trunk particleboard. Industrial Crops and Products, 116: 249-258. https://doi.org/10.1016/j.indcrop.2018.02.050
12. Mohd Ali, R. A.; Ashaari, Z.; Lee, S. H.; Anwar Uyup, M. K.; Bakar, E. S.; Farah Azmi, N. I., 2020: Low viscosity melamine urea formaldehyde resin as a bulking agent in reducing formaldehyde emission of treated wood. BioResources, 15: 2195-2211. https://doi.org/10.15376/biores.15.2.2195-2211
13. Nurhazwani, O.; Jawaid, M.; Paridah, M. T.; Abdul, J. H.; Hamid, S. A., 2016: Hybrid particleboard made from bamboo (*Dendrocalamus asper*) veneer waste and rubberwood (*Hevea brasilienses*). BioResources, 11: 306-323. https://doi.org/10.15376/biores.11.1.306-323
14. Osman, N. F.; Bawon, P.; Lee, S. H.; Zaki, P. H.; Osman Al-Eldrus, S. S.; Abdul Halip, J.; Mohd Atkhar, M. S., 2020: Characterization of particleboard made from oil heat-treated rubberwood particles at different mixing ratios. BioResources, 15: 6795-6810. https://doi.org/10.15376/biores.15.3.6795-6810
15. Pędzik, M.; Auriga, R.; Kristak, L.; Antov, P.; Rogoziński, T., 2022: Physical and mechanical properties of particleboard produced with addition of walnut (*Juglans regia* L.) wood residues. Materials, 15: 1280. https://doi.org/10.3390/ma15041280
16. Pędzik, M.; Janiszewska, D.; Rogoziński, T., 2021: Alternative lignocellulosic raw materials in particleboard production: A review. Industrial Crops and Products, 174: 114162. https://doi.org/10.1016/j.indcrop.2021.114162
17. Pizzi, A.; Papadopoulos, A. N.; Policardi, F., 2020: Wood composites and their polymer binders. Polymers, 12: 1115. https://doi.org/10.3390/polym12051115
18. Yuan, H.; Shen, L., 2011: Trend of the research on construction and demolition waste management. Waste Management 31, 670-679. https://doi.org/10.1016/j.wasman.2010.10.030
19. ***FAO, 2022. Food and Agriculture Organisation of the United Nations [WWW Document]. Forestry Production and Trade. URL https://www.fao.org/faostat/en/#data/FO (Accessed Oct. 3, 2022).



**Corresponding address:**

**MARTA PĘDZIK**
Łukasiewicz Research Network – Poznań Institute of Technology, Centre of Wood Technology, Winiarska St. 1, 60-654 Poznań, POLAND, e-mail: marta.pedzik@pit.lukasiewicz.gov.pl

spinvalis

*Kvaliteta s potpisom Slavonije.*

Industrijska 24, 34000 Požega | Avenija Dubrovnik 14, 10 000 Zagreb
+385 34 311 150 | spinvalis@spinvalis.hr

**www.spinvalis.hr**

# Upute autorima

## Opće odredbe

Časopis *Drvna industrija* objavljuje znanstvene radove (izvorne znanstvene radove, pregledne radove, prethodna priopćenja), stručne radove, izlaganja sa savjetovanja, stručne obavijesti, bibliografske radove, preglede te ostale priloge s područja biologije, kemije, fizike i tehnologije drva, pulpe i papira te drvnih proizvoda, uključujući i proizvodnu, upravljačku i tržišnu problematiku u drvnoj industriji.
Predaja rukopisa podrazumijeva uvjet da rad nije već predan negdje drugdje radi objavljivanja ili da nije već objavljen (osim sažetka, dijelova objavljenih predavanja ili magistarskih radova odnosno disertacija, što mora biti navedeno u napomeni) te da su objavljivanje odobrili svi suautori (ako rad ima više autora) i ovlaštene osobe ustanove u kojoj je istraživanje provedeno. Cjelokupni sadržaj Drvne industrije dostupan je za skidanje s interneta, tiskanje, daljnju distribuciju, čitanje i ponovno korištenje bez ograničenja sve dok se naznače autor(i) i originalni izvor prema Creative Commons Attribution 4.0 International License (CC BY). Autor(i) zadržavaju izdavačka prava bez ograničenja.
Znanstveni i stručni radovi objavljuju se na engleskom jeziku, uz sažetak na hrvatskome. Također, naslov, podnaslovi i svi važni rezultati trebaju biti napisani dvojezično. Uredništvo osigurava inozemnim autorima prijevod na hrvatski. Ostali se članci uglavnom objavljuju na hrvatskome. Znanstveni i stručni radovi podliježu temeljitoj recenziji najmanje dvaju recenzenata. Izbor recenzenata i odluku o klasifikaciji i prihvaćanju članka (prema preporukama recenzenata) donosi Urednički odbor.
Svi prilozi podvrgavaju se jezičnoj obradi. Urednici će od autora zahtijevati da tekst prilagode preporukama recenzenata i lektora, te zadržavaju i pravo da predlože skraćivanje ili poboljšanje teksta. Autori su potpuno odgovorni za svoje priloge. Podrazumijeva se da je autor pribavio dozvolu za objavljivanje dijelova teksta što su već negdje objavljeni te da objavljivanje članka ne ugrožava prava pojedinca ili pravne osobe. Radovi moraju izvještavati o istinitim znanstvenim ili tehničkim postignućima. Autori su odgovorni za terminološku i metrološku usklađenost svojih priloga. Radovi se šalju elektronički putem poveznice http://journal.sdewes.org/drvind

## Upute

Predani radovi smiju sadržavati najviše 15 jednostrano pisanih A4 listova s dvostrukim proredom (30 redaka na stranici), uključujući i tablice, slike te popis literature, dodatke i ostale priloge. Dulje je članke preporučljivo podijeliti na dva ili više nastavaka. Tekst treba biti u *doc formatu*, u potpunosti napisan fontom *Times New Roman* (tekst, grafikoni i slike), normalnim stilom, bez dodatnog uređenja teksta.
Prva stranica poslanog rada treba sadržavati puni naslov, ime(na) i prezime(na) autora, podatke o zaposlenju autora (ustanova, grad i država) te sažetak s ključnim riječima (duljina sažetka približno 1/2 stranice A4).
Posljednja stranica treba sadržavati titule, zanimanje, zvanje i adresu (svakog) autora, s naznakom osobe s kojom će Uredništvo biti u vezi.
Znanstveni i stručni radovi moraju biti sažeti i precizni. Osnovna poglavlja trebaju biti označena odgovarajućim podnaslovima. Napomene se ispisuju na dnu pripadajuće stranice, a obrojčavaju se susljedno. One koje se odnose na naslov označuju se zvjezdicom, a ostale uzdignutim arapskim brojkama. Napomene koje se odnose na tablice pišu se ispod tablica, a označavaju se uzdignutim malim pisanim slovima, abecednim redom.
Latinska imena trebaju biti pisana kosim slovima (italicom), a ako je cijeli tekst pisan kosim slovima, latinska imena trebaju biti podcrtana.
U uvodu treba definirati problem i, koliko je moguće, predočiti granice postojećih spoznaja, tako da se čitateljima koji se ne bave područjem o kojemu je riječ omogući razumijevanje ciljeva rada.
Materijal i metode trebaju biti što preciznije opisane da omoguće drugim znanstvenicima ponavljanje pokusa. Glavni eksperimentalni podaci trebaju biti dvojezično navedeni.
Rezultati trebaju obuhvatiti samo materijal koji se izravno odnosi na predmet. Obvezatna je primjena metričkog sustava. Preporučuje se upotreba SI jedinica. Rjeđe rabljene fizikalne vrijednosti, simboli i jedinice trebaju biti objašnjeni pri njihovu prvom spominjanju u tekstu. Za pisanje formula valja se koristiti Equation Editorom (programom za pisanje formula u MS Wordu). Jedinice se pišu normalnim (uspravnim) slovima, a fizikalni simboli i faktori kosima (italicom).
Formule se susljedno obrojčavaju arapskim brojkama u zagradama, npr. (1) na kraju retka.
Broj slika mora biti ograničen samo na one koje su prijeko potrebne za objašnjenje teksta. Isti podaci ne smiju biti navedeni i u tablici i na slici. Slike i tablice trebaju biti zasebno obrojčane, arapskim brojkama, a u tekstu se na njih upućuje jasnim naznakama ("tablica 1" ili "slika 1"). Naslovi, zaglavlja, legende i sav ostali tekst u slikama i tablicama treba biti napisan hrvatskim i engleskim jezikom.
Slike je potrebno rasporediti na odgovarajuća mjesta u tekstu, trebaju biti izrađene u rezoluciji 600 dpi, crno-bijele (objavljivanje slika u koloru moguće je na zahtjev autora), formata jpg ili tiff, potpune i jasno razumljive bez pozivanja na tekst priloga.
Svi grafikoni i tablice izrađuju se kao crno-bijeli prilozi (osim na zahtjev). Tablice i grafikoni trebaju biti na svojim mjestima u tekstu te originalnog formata u kojemu su izrađeni radi naknadnog ubacivanja hrvatskog prijevoda. Ako ne postoji mogućnost za to, potrebno je poslati originalne dokumente u formatu u kojemu su napravljeni (*excel* ili *statistica* format).
Naslovi slika i crteža ne pišu se velikim tiskanim slovima. Crteži i grafikoni trebaju odgovarati stilu časopisa (fontovima i izgledu). Slova i brojke moraju biti dovoljno veliki da budu lako čitljivi nakon smanjenja širine slike ili tablice. Fotomikrografije moraju imati naznaku uvećanja, poželjno u mikrometrima. Uvećanje može biti dodatno naznačeno na kraju naslova slike, npr. "uvećanje 7500 : l".
Diskusija i zaključak mogu, ako autori žele, biti spojeni u jedan odjeljak. U tom tekstu treba objasniti rezultate s obzirom na problem postavljen u uvodu i u odnosu prema odgovarajućim zapažanjima autora ili drugih istraživača. Valja izbjegavati ponavljanje podataka već iznesenih u odjeljku *Rezultati*. Mogu se razmotriti naznake za daljnja istraživanja ili primjenu. Ako su rezultati i diskusija spojeni u isti odjeljak, zaključke je nužno napisati izdvojeno. Zahvale se navode na kraju rukopisa. Odgovarajuću literaturu treba citirati u tekstu, i to prema harvardskom sustavu (*ime – godina*), npr. (Bađun, 1965). Nadalje, bibliografija mora biti navedena na kraju teksta, i to abecednim redom prezimena autora, s naslovima i potpunim navodima bibliografskih referenci. Popis literature mora biti selektivan, a svaka referenca na kraju mora imati naveden DOI broj, ako ga posjeduje (http://www.doi.org) (provjeriti na http://www.crossref.org).

## Primjeri navođenja literature

Članci u časopisima: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. Naziv časopisa, godište (ev. broj): stranice (od – do). Doi broj.

Primjer

Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. http://dx.doi.org/10.1007/s001070050479.

Knjige: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. (ev. izdavač/editor): izdanje (ev. svezak). Mjesto izdanja, izdavač (ev. stranice od – do).

Primjeri

Krpan, J., 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb, Tehnička knjiga.
Wilson, J. W.; Wellwood, R. W., 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551- 559.
Ostale publikacije (brošure, studije itd.)
Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Web stranice
***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node 00.html. First published 1997 (pristupljeno 27. siječnja 2010).

Autoru se prije konačnog tiska šalje pdf rada. Rad je potrebno pažljivo pročitati, ispraviti te vratiti Uredništvu s listom ispravaka. Autori znanstvenih i stručnih radova besplatno dobivaju po jedan primjerak časopisa. Autoru svakog priloga također se dostavlja besplatan primjerak časopisa.

Dodatne informacije o načinu pisanja znanstvenih radova mogu se naći na web adresi:
**www.ease.org.uk/publications/author-guidelines**

# Instructions for authors

## General terms

The "Drvna industrija" ("Wood Industry") journal publishes scientific papers (original scientific papers, review papers, previous notes), professional papers, conference papers, professional information, bibliographical and survey articles and other contributions related to biology, chemistry, physics and technology of wood, pulp and paper and wood products, including production, management and marketing issues in the wood industry.

Submission of a paper implies that the work has not been submitted for publication elsewhere or published before (except in the form of an abstract or as part of a published lecture, review or thesis, in which case it must be stated in a footnote); that the publication is approved by all co-authors (if any) and by the authorities of the institution where the research has been carried out. The complete content of the journal *Drvna industrija* (Wood Industry) is available on the Internet permitting any users to download, print, further distribute, read and reuse it with no limits provided that the author(s) and the original source are identified in accordance with the Creative Commons Attribution 4.0 International License (CC BY). The authors retain their copyrights.

The scientific and professional papers shall be published in English with summary in Croatian. The titles, headings and all the relevant results shall be also presented bilingually. The Editor's Office shall provide the translation into Croatian for foreign authors. Other articles are generally published in Croatian. The scientific and professional papers will be subject to a thorough review by at least two selected referees. The Editorial Board shall make the choice of reviewers, as well as the decision about the classification of the paper and its acceptance (based on reviewers' recommendations).

All contributions are subject to proofreading. The editors will require authors to modify the text in the light of the recommendations made by reviewers and language advisers, and they reserve the right to suggest abbreviations and text improvements. Authors are fully responsible for the contents of their contributions. It shall be assumed that the author has obtained the permission for the reproduction of portions of text published elsewhere, and that the publication of the paper in question does not infringe upon any individual or corporate rights. Papers shall report on true scientific or technical achievement. Authors are responsible for the terminological and metrological consistency of their contributions. The contributions are to be submitted by the link http://journal.sdewes.org/drvind

## Details

Papers submitted shall consist of no more than 15 single-sided DIN A-4 sheets of 30 double-spaced lines, including tables, figures and references, appendices and other supplements. Longer papers should be divided into two or more continuing series. The text should be written in doc format, fully written using Times New Roman font (text, graphs and figures), in normal style without additional text editing.

The first page of the paper submitted should contain full title, name(s) of author(s) with professional affiliation (institution, city and state), abstract with keywords (approx. 1/2 sheet DIN A4).

The last page should provide the full titles, posts and address(es) of each author with indication of the contact person for the Editor's Office.

Scientific and professional papers shall be precise and concise. The main chapters should be characterized by appropriate headings. Footnotes shall be placed at the bottom of the same page and consecutively numbered. Those relating to the title should be marked by an asterix, others by superscript Arabic numerals. Footnotes relating to the tables shall be printed under the table and marked by small letters in alphabetical order.

Latin names shall be printed in italics and underlined.

Introduction should define the problem and if possible the framework of existing knowledge, to ensure that readers not working in that particular field are able to understand author's intentions.

Materials and methods should be as precise as possible to enable other scientists to repeat the experiment. The main experimental data should be presented bilingually.

The results should involve only material pertinent to the subject. The metric system shall be used. SI units are recommended. Rarely used physical values, symbols and units should be explained at their first appearance in the text. Formulas should be written by using Equation Editor (program for writing formulas in MS Word). Units shall be written in normal (upright) letters, physical symbols and factors in italics. Formulas shall be consecutively numbered with Arabic numerals in parenthesis (e.g. (1)) at the end of the line.

The number of figures shall be limited to those absolutely necessary for clarification of the text. The same information must not be presented in both a table and a figure. Figures and tables should be numbered separately with Arabic numerals, and should be referred to in the text with clear remarks ("Table 1" or "Figure 1"). Titles, headings, legends and all the other text in figures and tables should be written in both Croatian and English.

Figures should be inserted into the text. They should be of 600 dpi resolution, black and white (color photographs only on request), in jpg or tiff format, completely clear and understandable without reference to the text of the contribution.

All graphs and tables shall be black and white (unless requested otherwise). Tables and graphs should be inserted into the text in their original format in order to insert them subsequently into the Croatian version. If this is not possible, original document should be sent in the format in which it was made (excel or statistica format).

The captions to figures and drawings shall not be written in block letters. Line drawings and graphs should conform to the style of the journal (font size and appearance). Letters and numbers shall be sufficiently large to be readily legible after reduction of the width of a figure or table. Photomicrographs should have a mark indicating magnification, preferably in micrometers. Magnification can be additionally indicated at the end of the figure title, e.g. "Mag. 7500:1".

Discussion and conclusion may, if desired by authors, be combined into one chapter. This text should interpret the results relating to the problem outlined in the introduction and to related observations by the author(s) or other researchers. Repeating the data already presented in the "Results" chapter should be avoided. Implications for further studies or application may be discussed. A conclusion shall be expressed separately if results and discussion are combined in the same chapter. Acknowledgements are presented at the end of the paper. Relevant literature shall be cited in the text according to the Harvard system ("name – year"), e.g. (Bađun, 1965). In addition, the bibliography shall be listed at the end of the text in alphabetical order of the author's names, together with the title and full quotation of the bibliographical reference. The list of references shall be selective, and each reference shall have its DOI number (http://www.doi.org) (check at http://www.crossref.org).:

## Example of references

Journal articles: Author's second name, initial(s) of the first name, year: Title. Journal name, volume (ev. issue): pages (from - to). DOI number.

Example:
Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. http://dx.doi.org/10.1007/s001070050479.

Books:
Author's second name, initial(s) of the first name, year: Title. (ev. Publisher/editor): edition, (ev. volume). Place of publishing, publisher (ev. pages from - to).

Examples:
Krpan, J. 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb: Tehnička knjiga.
Wilson, J.W.; Wellwood, R.W. 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551-559.

Other publications (brochures, studies, etc.):
Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanslalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Websites:
***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node00.html. First published 1997 (Accessed Jan. 27, 2010).

The paper will be sent to the author in pdf format before printing. The paper should be carefully corrected and sent back to the Editor's Office with the list of corrections made. Each contributor will receive 1 copy of the journal.

Further information on the way of writing scientific papers can be found on the following website:

**www.ease.org.uk/publications/author-guidelines**

HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

Hrvatski savez udruga privatnih šumovlasnika

## Projekt *Šume u rukama žena* - Fem4Forest

Projekt "Šume u rukama žena" („*Fem4Forest*") želi ojačati sektor baziran na šumama na lokalnoj, regionalnoj i međuregionalnoj razini kroz povećanu uključenost i jačanje sposobnosti žena, podržavajući njihovu jednaku prisutnost i kompetencije na tržištu.

Projekt se provodi od 01.07.2020 - 21.12.2022. godine u sklopu *Interreg Danube* transnacionalnog programa te je sufinanciran iz fondova EU ( ERDF, IPA, ENI) i Vlade RH (Ured za udruge).

Na projektu sudjeluje 14 partnera iz 10 država Dunavske regije. Hrvatski partneri su Hrvatska komora inženjera šumarstva i drvne tehnologije i Hrvatski savez udruga privatnih šumovlasnika.

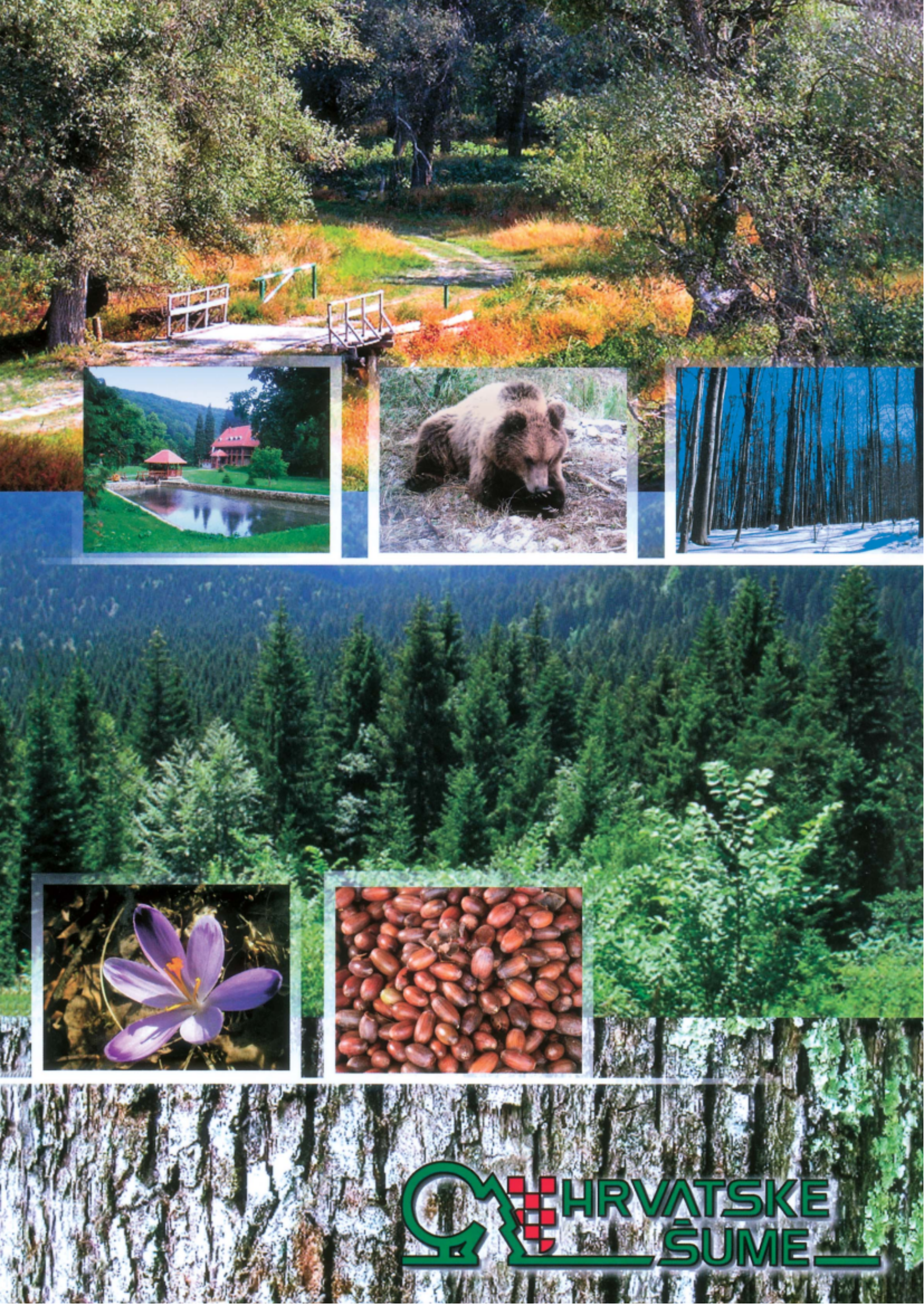
Na temelju provedenih upitnika i intervjua, zaključeno je kako su osobni razvoj i cjeloživotno učenje put za uspješnu karijeru svake žene u svim sektorima, pa tako i šumarskom, a na tom putu potrebno je:

- unaprijediti organizaciju poslovanja,
- učiti o tehnikama upravljanja kolektivom,
- vježbati komunikacijske vještine te
- identificirati uzore u sektoru i njihova iskustva.

Provedeni su razgovori sa ženama uzorima u sektoru, čija dugogodišnja i raznolika karijera, bogato iskustvo te pozitivan stav prema radu mogu poslužiti kao primjer mladim ženama na njihovu putu i profesionalnom razvoju.

U sklopu projekta uskoro počinje provedba trening radionica koje će se fokusirati na vještine vođenja, prezentacijske i komunikacijske vještine te osobne vještine za podizanje motivacije i samopouzdanja.

Za više informacija pratite web stranice projektnih partnera (www.hkisdt.hr, www.hsups.hr).


HRVATSKE
ŠUME


povežite se s prirodom
drvodjelac
Drvodjelac d.o.o.
Petra Preradovića 14, Ivanec, Hrvatska
+385 (0)42 781 922 | www.drvodjelac.hr