Contents:

DIMITAR ANGELSKI, VLADIMIR MIHAIOLOV
“The influence of various types of adhesive on the adhesion strength between bonded HPL and furniture boards” 5

ONDREJ BAJZA, ALENA ROHANOVÁ
“In situ density detection method of spruce structural timber” 11

MAREK BARLAK, JACEK WILKOWSKI, PIOTR BORUSZEWSKI, JERZY ZAGÓRSKI, ZBIGNIEW WERNER
“Influence of electron pulses on roughness and wettability of beech wood surface” 16

PIOTR BORYSIUK, RADOSŁAW AURIGA, MAJKOWSKI MARCIN
“Effect of resin surface protection on selected properties of plywood” 20

LADISLAV DZURENDA
“Modification of wood colour of Acer platanoides L. to a brown-red shade caused by thermal treatment ” 26
ZHIVKO GOCHEV, GEORGI VUKOV, PAVLIN VITCHEV, VALENTIN ATANASOV, GEORGI KOVACHEV
“Influence of the cutting mode on the overall vibrations generated by the woodworking milling machine”

CEZARY GOZDECKI, MAREK KOCISZEWSKI, JACEK MIROWSKI, STANISLAW ZAJCHOWSKI
“Screw withdrawal capacity and lateral resistance in wood-PP composites exposed to low temperature”

PAWEŁ KOŁODZIEJCZAK, JACEK WILKOWSKI, MAREK BARLAK, PAWEŁ CZARNIAK, ZBIGNIEW WERNER, JERZY ZAGÓRSKI
“Modification of the surfaces of wood cutting tools using CO$_2$ laser - SEM analysis”

PIOTR KOZŁOWSKI, WOJCIECH KUKULA, KAROL SZYMANOWSKI, GRZEGORZ KOWALUK, PAWEŁ CZARNIAK, RADOSŁAW AURIGA, ŁUKASZ KWAŚNY
“Drilling features of particleboard made of selected fruit trees prunings”

JOZEF KÚDELA
“Accelerated ageing-induced effects on surface properties of wood veneers treated with a modified water-based coating system”

JOZEF KÚDELA, LEOŠ MRENICA, LUBOMÍR JAVOREK
“Influence of milling and sanding on wetting and on thermo-dynamical characteristics of spruce wood surface”

RAFAŁ KUTYŁA, PIOTR PODZIEWSKI, PATRYK KRÓL, KAROL SZYMANOWSKI
“Surface roughness after machining of medium density fiberboards designed for deep milling”

JÁN MATYAŠOVSKÝ, JÁN SEDLIAČIK, MÁRIA ŠMIDRIAKOVÁ, IGOR NOVÁK, PETER JURKOVIČ PETER DUCHOVIČ
“Lowering of formaldehyde emission from wood based panels by modification of polycondensation adhesives with natural fillers, additives and activators”

IGOR NOVÁK, PETER JURKOVIČ, ONDREJ ŽIGO, JOZEF PRACHÁR, JÁN MATYAŠOVSKÝ
“Study of thermal conductivity of polymer composites”

IGOR NOVÁK, JURAJ PAVLINEC, IVAN CHODÁK, JOZEF PREŤO, VLADIMÍR VANKO
„Metalloocene polyolefins grafting designed for hot-melt adhesive compositions”

IGOR NOVÁK, IVAN CHODÁK, JÁN SEDLIAČIK, ONDREJ ŽIGO JÁN MATYAŠOVSKÝ, PETER JURKOVIČ
„Antibacterial modification of polymeric veneers by atmospheric discharge plasma”

TOMASZ ROGOZIŃSKI, CZESŁAW DEMBIŃSKI, ALENA OČKAJOVÁ, ZBIGNIEW POTOK
„A study on properties of wood dust created during windows manufacturing”

2
TOMASZ ROGOZIŃSKI, SERGEI TROFIMOV
“Dust creation during birch plywood production” 99

ALENA ROHANOVÁ, ONDREJ BAJZA
“Interaction between wood density and speed of sound in spruce structural timber” 104

MIROSLAV ROUSEK, JAKUB LISEC, ZDENĚK KOPECKÝ, LUĎKA HLÁSKOVÁ
“Water jet cutting waterproof foliated plywood” 110

MIROSLAV ROUSEK, JAKUB LISEC, LUĎKA HLÁSKOVÁ, ZDENĚK KOPECKÝ
“Abrasive water jet machining of foil waterproof plywood” 118

GABRIELA SLABEJOVÁ, MÁRIA ŠMIDRIaková, MIROSLAV MORINGA
“Surface roughness of water-based finishes on aspen poplar wood” 126

GABRIELA SLABEJOVÁ, MÁRIA ŠMIDRIaková, MIROSLAV MORINGA
“Physical-mechanical properties of surface finish on aspen poplar wood” 132

SERGEI TROFIMOV, TOMASZ ROGOZIŃSKI
“The principles of design and analysis of exhaust and pneumatic transport systems of chipped wood” 137

GRZEGORZ WIELOCH, BOLESŁAW PORANKIEWICZ, JANUSZ CIELOSZYK, BOLESŁAW FABISIAK
“New solutions of ‘sprt’ tool constructions for wood surface equalizing by face milling method” 143

JACEK WILKOWSKI, PAWEŁ KOŁODZIEJCZAK, MAREK BARLAK, PAWEŁ CZARNIAK, ZBIGNIEW WERNER, BOGDAN STASZKIEWICZ
“Effect of laser modification of WC-Co tool-life during particleboards milling” 148
Board of reviewers:
Piotr Beer
Piotr Boruszewski
Piotr Borysiuk
Dorota Dzjurka
Jarosław Górski
Emila Grzegorzewska
Waldemar Jaskółowski
Lubomír Javorek
Grzegorz Kowaluk
Paweł Kozakiewicz
Adam Krajewski
Krzysztof Krajewski
Sławomir Krzosek
Mariusz Mamiński
Andrzej Radomski
Janusz Zawadzki
Tomasz Zielenkiewicz

Scientific council:
Kazimierz Orłowski (Poland)
Ladislav Dzurenda (Slovakia)
Miroslav Rousek (Czech Republic)
Nencho Deliiski (Bulgaria)
Olena Pinchewska (Ukraine)
Włodzimierz Prądzyński (Poland)
The influence of various types of adhesive on the adhesion strength between bonded HPL and furniture boards

DIMITAR ANGELSKI, VLADIMIR MIHAJOLOV

Department of Furniture Production, Faculty of Forest Industry, University of Forestry – Sofia

Abstract: The influence of various types of adhesive on the adhesion strength between bonded HPL and furniture boards. The surfaces of furniture constructive components made of medium density fiberboard or particle board are commonly bonded with laminating materials. In the bonding of furniture panels occurs internal stress in the adhesive joints and its adhesion strength is very important. Internal stress is the main reason for the occurrence of twist and even self-disbonding of the laminating materials in exploitation conditions. In this regard, the objective of this article is to determine the adhesion strength of adhesive joints between furniture boards and high pressure laminates (HPL). The specimen details (medium density fiberboard and particle board) were bonded with 0.6mm thick thermostatic HPL. For the realization of adhesive bonds are used the following four types of adhesives: polyvinyl acetate (PVA), polychloroprene contact aerosol, two component urea-formaldehyde (UF) and polychloroprene liquid glue. The adhesion strength has been determined with peel-off test. The results are presented by graphics and analyzed.

Keywords: adhesion strength, bonding, HPL, MDF, particle board

INTRODUCTION

In furniture made of wood-based materials, the technology of bonding of thin layers of laminating material is most commonly used. High Pressure Laminate (HPL) is one of the most durable laminating materials and is available with special performance properties including chemical, fire and wear resistance. Usual it consists of about 60-70% kraft paper and about 30-40% thermosetting resins. Thermosetting creates strong, irreversible bonds that contribute to its durability. European standard EN 438 classifies HPL into different grades according to its properties and application: Standard (S); postforming (P); suitable for horizontal (H) or vertical (V) applications; flame retardant (F); compact (C) or external (E), pearlescent (A), metal (M) or wood veneer finishes (W), multicolour core (B) and metal reinforced. HPL can withstand up to 180°C without deterioration or discoloration.

HPL sheets are bonded at high pressures and temperatures. Thus the main characteristics of laminates are: impact resistance, scratch resistance lack of vapor and water permeability, heat resistance (occasional, up to 180°C), lack of shrinkage and swelling. These features of the material are a prerequisite for the occurrence of high internal stresses in adhesive compounds between HPL sheets and substrate. Internal stress is the main reason for the occurrence of twist and even self-disbonding of the laminating materials in exploitation conditions. Thus the adhesive material aims to ensure a rigid, irreversible and sufficiently strong fixation of the laminating material to the elaborated surface. High pressure laminate is laminated to a composite panel utilizing a variety of adhesives. The surface of the furniture elements to be laminated should be smooth, homogenous and clean out of dust and other contaminants. Particleboard or medium-density fiberboards (MDF) are the preferred substrate because they provide a stable, durable, consistent and economical foundation. Since the laminates do not absorb water and steam, another important requirement for the panels is to possess even minimal water and steam penetration to render uptake of the glue solvents. In order to achieve minimal shrinkage of the adhesive layer during its hardening, it is recommended the adhesives to have the highest possible dry residue content (Albin et al. 1991).
Adhesion is a complex physic-chemical phenomenon for which, however, there is not a rigorous theoretical definition. Adhesion is difficult to define, and an entirely satisfactory definition has not been found (Kaelblea 1964, Landrock A. 2008, Silva et al. 2011). The adhesion strength is the bond between laminate and substrate, which can be the weakest link of the system. A chain is only as strong as its weakest link and therefore adhesion and cohesion should be in balance for optimum performance. Various test methods for adhesion property or bonding quality are available. One of the most common and accepted techniques for measuring polymer adhesion is the peel test (Zosel 1991). When a properly made adhesion joint is stressed to the point where it fails, the failure normally occurs within the adhesive layer itself. In this relation, the purpose of the current study was to determine the adhesion strength of adhesive joints between furniture boards and HPL.

EXPERIMENTAL SECTION

Samples are made of 18 mm thick furniture boards (by “Kronospan”). The particleboard panels with density 680 kg/m² and medium-density fiberboards (MDF) with 750 kg/m² density have been used in this study. From them were made 80 test pieces to provide a 10-fold repeat of each experimental series for determining the strength of an adhesive bond between the laminate and substrate. The thermoplastic HPL sheets (by “Formica”) was with 1,35g/m² density and a thickness of 0.6 mm. According to the European Standard EN 438 and to ISO 4586 more than 60% of laminate consists of paper and the remaining 30 to 40% consists of cured phenol-formaldehyde resin for core layers and melamine-formaldehyde resin for the surface layer. For bonding we used four adhesive system - D3 polyvinyl acetate (PVAc) glue (103.10 by Jowacoll), polychloroprene glue (by Madan Proma) also known as chloroprene rubber (CR), polychloroprene contact aerosol (CR-aero) contact adhesive (SPRAY-KON B707), two component urea-formaldehyde (UF) glue (by Dynea).

![Fig. 1. a - Test method, b - T-shape steel stamp connected to sample, c - laminated sample before bonding the steel stamps and cutting to separate sample pieces](image)

Fig. 1. a - Test method, b - T-shape steel stamp connected to sample, c - laminated sample before bonding the steel stamps and cutting to separate sample pieces
The rational consumable norms of the adhesive systems were determined by preliminary experiments. During their implementation, adhesive compounds were made with the recommended values for minimal and maximum glue consumption. Their adhesion strength was compared with the normative for the minimum strength of furniture compounds. On the other hand, the economic efficiency was determined by estimating the material consumption to obtain the determined strength of the compounds. In this way were determined the regime values of the one of the main technological parameter - quantity of the applied adhesive (Q).

The test samples were laminated under a standard hydraulic press mode and conditioned for 24 hours at 20 °C and 65% humidity of the air. After that they are laminated the adhesion strength of the glue adhesive is defined by peel-off test. The current study has used a method by which the adhesive compound is applied with a tensile load perpendicularly to the laminating surface (Merdjanov 2016). This method is similar to the pull-off test for coating adhesion and it is presented in Figure 1. The tensile forces are spread via T-shape steel body (stamp), attached to the HPL sheet by a cyanoacrylate adhesive. On both sides of the stamp (3) the HPL sheet is interrupted by a cutting in depth equal to the depth of the coating material and the adhesive. Next to the mobile bar (7) of the testing machine ‘Heckert – FP 100” – Germany are attached “U”-shaped clip (6). The fixed part of the machine is embedded with a chain (1), which second end is gripped to the steel body via a nail (2) that passes through the chain and stamp holes. The clip shoulders are gripped to the sample from the side of the cut HPL sheet. The speed at which the adhesive compound is tensile loaded is 20 mm.min⁻¹. The load applied to the sample is increased gradually until the HPL sheet is separated (peeled off) from the particleboard. The destruction of the adhesive compound can be adhesive (between the substrate and adhesive layer) or cohesive (within the adhesive layer itself). By the reported destruction force we determine the adhesive strength of the compound.

RESULTS
The statistically processed test data are presented in table 1 via the following indicators: average (Y), standard deviation (Sx), standard error (mx), variation coefficient (Vx) and coefficient of accuracy (P). On figures 1 and 2, are presented the arithmetic mean values of the adhesion strength of the adhesive compounds between the furniture boards and the HPL sheets. The predominant destructions of the adhesive compounds are of mixed type - adhesion-cohesion.

<table>
<thead>
<tr>
<th>Type of glue joint</th>
<th>Aver. Y N/mm²</th>
<th>Sx N/mm²</th>
<th>mx N/mm²</th>
<th>Vx %</th>
<th>Px %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl acetate glue (103.10 by Jowacoll) and MDF</td>
<td>6,9</td>
<td>0,5</td>
<td>0,19</td>
<td>5,8</td>
<td>2,05</td>
</tr>
<tr>
<td>Polychloroprene contact aerosol (SPRAY-KON B707) and MDF</td>
<td>3,4</td>
<td>6,83</td>
<td>2,42</td>
<td>7,18</td>
<td>2,54</td>
</tr>
<tr>
<td>Polychloroprene glue and MDF</td>
<td>5,4</td>
<td>0,92</td>
<td>0,31</td>
<td>9,3</td>
<td>3,09</td>
</tr>
<tr>
<td>Urea-formaldehyde glue and MDF</td>
<td>6,8</td>
<td>0,59</td>
<td>0,21</td>
<td>6,3</td>
<td>2,24</td>
</tr>
<tr>
<td>Polyvinyl acetate glue (103.10 by Jowacoll) and particle board</td>
<td>3,6</td>
<td>0,44</td>
<td>0,11</td>
<td>10,57</td>
<td>2,64</td>
</tr>
<tr>
<td>Polychloroprene contact aerosol and particle board</td>
<td>2,3</td>
<td>1,36</td>
<td>0,45</td>
<td>13,3</td>
<td>4,22</td>
</tr>
<tr>
<td>Polychloroprene glue and particle board</td>
<td>3,8</td>
<td>1,92</td>
<td>0,64</td>
<td>6,1</td>
<td>2,01</td>
</tr>
<tr>
<td>Urea-formaldehyde glue and particle board</td>
<td>3,3</td>
<td>0,75</td>
<td>0,19</td>
<td>11,72</td>
<td>2,93</td>
</tr>
</tbody>
</table>
As it’s known, the recommended minimum tensile strength for furniture components is 2.5 N/mm\(^2\). Only the adhesive compound between particle board and HPL made with polychloroprene contact aerosol glue has a lower value (2.3 N/mm\(^2\)). For a similar consumption and adhesive joint (see Figure 2), but with a MDF base, a relatively high adhesion strength (3.4 N/mm\(^2\)) was obtained. This means that for particle board surfaces it is necessary to apply a quantity of contact adhesive greater than 60 g/m\(^2\) to compensate for the significant porosity of the material. The smoother surface and the lower porosity of the MDF samples is a major cause of the higher strengths of their HPL adhesive joints than those made with a particle board base.

![Fig. 2. The adhesion strength of glue joints between particle board and HPL.](image)

From the preliminary experiments it was found that the compounds made with polyvinyl acetate glue and polychloroprene liquid glue has very high adhesion strength. It can be seen from Figures 2 and 3 that even when using low cost norms, the adhesive compounds have very good adhesion strength. From the point of view of compliance with environmental standards, PVAc adhesives are more suitable than polychloroprene glue. Polychloroprene glue, on the other hand, is more technological as its adhesive compounds quickly achieve minimal technological strength without the need for continuous clamping of the bonded materials to one another.

Compounds made with Urea-formaldehyde glue also have very good adhesion strength. To achieve a high-quality bonding between the particle board and the HPL sheet, it is necessary to use a relatively high consumption rate of urea-formaldehyde glue (Q = 150 g/m\(^2\)). On the other hand when laminating MDF with HPL, it is possible to work with a relatively low consumption rate of urea-formaldehyde glue (Q = 80 g/m\(^2\)). Urea-formaldehyde adhesives are thermo-reactive and when they are cured, are being converted into a solid insoluble state characterized by a spatially cross-linked structure, high heat resistance and medium water resistance. This leads to an increase in the durability of the furniture components of an aggressive environment. However, as a disadvantage of the adhesive seams formed by urea-formaldehyde glue is considered their high stiffness and brittleness. On the one hand, this leads to quick dulling of the cutting tools and, on the other hand, to internal
stresses and cracking. Another feature of urea-formaldehyde glue is that the free formaldehyde released in the form of gas is toxic to humans.

CONCLUSIONS

Based on the research, the following conclusions could be made:

1. The adhesion strength of the tested adhesive compounds between the particle board and HPL sheets is relatively low. However, the adhesion strength of the joints responds to the required minimum technological tensile strength for the laminating of furniture components. On the basis of the obtained results, the consumption rate of the chosen adhesives can be considered for rationally chosen. For the polychloroprene contact aerosol glue only, it is recommended that the amount of glue is not less than 60 g/m².

2. The adhesion strength of the tested adhesive compounds between MDF and HPL sheets is relatively high. This means that all used adhesives are suitable for making quality joints and MDF is a suitable material for making laminated with HPL furniture components. The compounds with polyvinyl acetate and urea-formaldehyde glue have a very high strength adhesion. Especially from an environmental point of view it is recommended to use polyvinyl acetate glue. If urea-formaldehyde glue is required for heat and water resistance of the adhesive compound, it is appropriate to use the urea-formaldehyde glue.

ACKNOWLEDGEMENT

This work has been supported by the Scientific Sector in the University of Forestry (project No 55 /2017).

REFERENCES


**Streszczenie:** Wpływ różnych rodzajów kleju na adhezję pomiędzy przyklejonym HPL a płytami meblowymi. Celem badań było określenie wytrzymałości spoiny pomiędzy płytami meblowymi a laminatem wysokociśnieniowym. Próbki (MDF i płyty wiórowe) były sklejone z HPL o grubości 0,6 mm przy użyciu następujących klejów: polioctanowinylowego, kleju kontaktowego chloroprenowego w aerozolu, dwukomponentowego mocznikowo-formaldehydowego oraz polichloroprenowego ciekłego. Siła adhezji została określona poprzez test odrywania.

Author’s address:

Dimitar Angelski,
10 Kliment Ohridsky Blvd.
1797, Sofia, Bulgaria
email: d.angelski@ltu.bg
phone: +359 887567168
In situ density detection method of spruce structural timber

ONDREJ BAJZA, ALENA ROHANOVÁ

Faculty of Wood Sciences and Technology, Technical University in Zvolen

Abstract: In Situ Density Detection Method of Spruce Structural Timber. Density of wood is a significant parameter determining the quality. We can use PILODYN 6J device to detect the density of wood in situ. Depth of steel pin penetration is measured on any side of the board. For evaluation of the results dependencies between wood density and depth of penetration measured in vitro are applied. Spruce wood with a thickness of 40mm has been made by prism log-sawing patterns. Side of a board (inner and outer – closer to pith) has been taken into account when shooting the pin. Various correlations were found between density of wood and the depth of penetration (outer: \( r = -0.30 \), inner: \( r = -0.51 \)). More significant result has been identified on the inner side of boards. The knowledge allows increasing the reliable identification of wood density by PILODYN 6J device in situ based on the consideration of the board side.

Keywords: density wood, spruce structural timber, pin penetration, board, outer side, inner side

INTRODUCTION

Wood is one of the elementary building materials. It can be used in a wide range of applications, historically and of course actually as construction or supplementary material. Wood is anisotropic material, and therefore the detection of its properties is difficult from the methodical and experimental point of view.

Bending strength, modulus of elasticity and wood density are considered significant parameters influencing the wood quality in wooden constructions. Wood density can be tested using various methods. The dynamical hardness can be used to detect the approximate values of wood density. The device PILODYN 6J uses this principle, as well. Steel pin is shot into wood by constant force and the depth of penetration is measured. This non-destructive or semi-destructive method can be used to predict the indicative wood density in constructions elements or standing tree in situ. Authors Hansen 2000, Mäkipää & Linkosalo 2011 describe the universal use of the PILODYN 6J device.

Depth of penetration depends on the wood structure (summer wood and spring wood), wood quality (fresh wood, old wood, reaction wood, degraded wood) (Reinprecht 2009, Reinprecht and Hrivnák 2010). Moisture content also affects the depth of penetration. This knowledge was described by the following authors Görlacher (1987), Hansen (2000), Rohanová (2008), Rohanová (2013). Authors Görlacher 1987, Hansen 2000 describe the interaction between penetration depth and the angle of shooting; however, significant influence was not confirmed.

MATERIAL AND METHODS

Board timber (Picea abies Karst. L.) selected randomly were used for the experimental testing. Board dimensions: 40 x 200 x 2500 mm – 5 pcs.

Model of pin penetration was designed in order to represent following points:
- Distribution of wood density along the board (across segments and test specimens),
- Impact of penetration side (inner, outer) on the depth of penetration.

Board side marking:
- outer (A), inner (B) closer to pith (Fig.1).

Mäkipää - Linkosalo (2011) present a similar procedure for dry and wet wood.
The test specimens were conditioned at standard conditions, i.e. at the temperature 20 ± 2 °C, relative air humidity 65 ± 5 %, and the equilibrium moisture content of 12 % (reference humidity).

Place for pin penetration was chosen as a place with an angle $\alpha = 90^\circ$ on the inner and outer side of board (it is necessary to determine the place for testing as the most accurate for perpendicular penetration of pin to growth rings), Fig.1.

![Fig. 1 Measuring of the angle between the penetration pin and the growth ring](image)

On the test specimens wood density was tested by gravimetric method (2 measurements) according to EN 408 standard.

**RESEARCH OBJECTIVE**

The results of the experiments are summarized in Tab. 1, which provides basic statistical characteristics. There are the average values of all the boards.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Statistical characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>$\bar{x}$</td>
</tr>
<tr>
<td>Wood density $\rho_{12}$ (kg.m$^{-3}$)</td>
<td>90</td>
</tr>
<tr>
<td>Depth of penetration (mm)</td>
<td></td>
</tr>
<tr>
<td>$h_{\text{together}}$</td>
<td>170</td>
</tr>
<tr>
<td>$h_{\text{outer}}$</td>
<td>85</td>
</tr>
<tr>
<td>$h_{\text{inner}}$</td>
<td>85</td>
</tr>
</tbody>
</table>

$n$ – number of specimens, $\bar{x}$ - mean, $x_{\text{max}}$ - maximum value, $x_{\text{min}}$ – minimum value, V% - coefficient of variation

**Depth of penetration** (Fig. 2) – following the tests we found out that there were different average values in individual boards. Regardless the board side (together) the highest value was detected on board no.1, which has the smallest density $\rho_{12} = 363$ kg.m$^{-3}$. In the case of other boards, the values were balanced ($h_{\text{together}}, h_{\text{outer}}, h_{\text{inner}}$).

When considering the board side the following findings in all boards were determined:
- outer side – values houter are 10-15% lower than htogether,
- inner side – values hinner are 10-15 % higher than htogether.

Depth of penetration is an indicator for measuring the approximate wood density. It is supposed that higher values of the penetration depth can predict the assessed characteristics more reliably.
Dependence consider measuring of penetration depth on the both side of board (together). Dependence of wood density on the penetration depth is only 12%, $P = 0.000$. When comparing these findings with literature (GÖRLACHER 1987, HANSEN 2000) where the selection of test specimens was ideal regarding the radial growth rings, the correlation coefficient determined in our study is significantly lower. Side of the board was not taken into account during the experimental pin penetration. It can be assumed that our result – lower correlation – was caused by e.g. random selection of boards, different wood structure of the boards, inaccuracy of perpendicularity of shooting, different density of spring wood in pith parts of board, the position of the board in prism.

Differentiation of the outer and inner sides of the pin penetration demonstrated that a higher correlation is on the inner side of board (Fig. 3). The density of the wood on the inner side depends to 26% on the depth of penetration, $P = 0.000$. On the other hand, on the outer side the dependence is only 9%, $P = 0.006$, i.e., reliability is 99.4%.

Density of wood is a significant parameter for timber quality grading. The device PILODYN 6J can be used for predicting the approximate wood density in situ. Device measures the depth of steel pin penetration. Correlation between the depth of penetration and wood density has been identified.

In the first part of the experiment the depth of penetration and density of wood along the boards were measured. The course of wood density variability along the board was balanced or increasing. Different densities of wood among the individual boards were measured. In group of 5 boards the relationship between depth of penetration and wood density of the wood was studied with correlation $r = 0.34$. Dependence was decreasing slightly. Boards with higher densities featured the penetration depth from 10 to 17 mm; with lower densities this is quite a wide range. Experiment results of spruce timber were in conformity with authors GÖRLACHER (1987), HANSEN (2000). Furthermore, experiments reflected the impact of side of the board (inner, outer) on the depth of penetration.
CONCLUSION
Conclusions of the results are as follows:
- penetration depths on the inner side are 10-20% deeper than on the outer side, in every specimen,
- dependence of penetration depth on wood density is 26% higher on inner side than on the outer side, correlation factor \( r = -0.51 \), \( P = 0.000 \),
- dependence of penetration depth on the growth rings width low correlation factor on sides \( r = -0.33 \sim -0.44 \). It can be assumed that wood structure (spring and summer wood - growth rings) has significant impact in these experiments. The results show the expected impact on the position regarding the pith side.

Experiment results show the possibility of using equipment PILODYN 6J in identifying wood density in situ. The method should be applied mainly to the inner side of the board, which reflects more significant interaction between penetration depth and wood density.

AKNOWLEDGMENTS
This study was supported by project under the contract VEGA under contract No. 1/0395/16.

REFERENCES
2. HANSEN, CH. P., 2000: Application of the pilodyn in forest tree improvement. (Replaces Technical Note No. 2) Forest Seed Centre, Humlebaek, Denmark.

Author’s address:

Ing. Ondrej Bajza  
Doc. Ing. Alena Rohanová, PhD.  
Technická univerzita vo Zvolene, Drevárska fakulta  
T. G. Masaryka 24, 960 53 Zvolen, Slovakia  
bajza.ondrej@gmail.com, rohanova@tuzvo.sk,
Influence of electron pulses on roughness and wettability of beech wood surface

MAREK BARLAK¹, JACEK WILKOWSKI², PIOTR BORUSZEWSKI³, JERZY ZAGÓRSKI¹, ZBIGNIEW WERNER¹

¹ Plasma and Ion Technology Division (FM2), National Centre for Nuclear Research Świerk - NCBJ
² Department of Mechanical Processing of Wood, Warsaw University of Life Sciences - SGGW
³ Department of Technology and Entrepreneurship in Wood Industry, Warsaw University of Life Sciences - SGGW

Abstract: Influence of electron pulses on roughness and wettability of beech wood surface. The paper presents the preliminary results of the investigations of electron irradiated beech wood. It is shown that a change of roughness and wettability by water depends on the number and energy density of electron pulses. This information can be useful e.g. in the production of the furniture boards.

Keywords: electron irradiation, beech veneer, roughness, wettability, wood industry

INTRODUCTION

Cellulose is the most popular natural polymer and the main structural component of wood. As a polymer with a high degree of polymerization, it is characterized by excellent strength properties. Properties of lignocellulosic materials can be improved by modifying the basic component of wood, i.e. cellulose. The existing methods of wood modification consist in the use of chemical (saturation by liquids) [Fowkes 1964] and physical (the effect of temperature, pressure) methods [Gerardin et al. 2007]. As a part of the material research, it is proposed to study surface modification of lignocellulosic particles (chips), especially by electron beam irradiation of the surface. Based on literature reports, the proposed idea has not been used thus far in forest sciences in the field of wood technology. Implementation of the proposed methods of wood particles modification, aims at improving the surface properties owing to a significant increase of free surface energy. This approach allows one to develop methods of producing wood particles with minimum adhesive binders. Adopting the proposed methods in the manufacturing of wood materials leads to a development of ecological, low-carbon, formaldehyde-free materials used for furniture production [Wolkenhauer et al. 2009; Żenkiewicz 2007]. We propose the investigations of electron irradiated beech wood, as an introduction of the irradiation of the mentioned above chips.

Any modified or newly developed material should be characterized in terms of surface properties determining further behaviour in an aggressive environment (e.g. water or organic solvents) and - as a consequence - susceptibility to degradation including hydrophilicity of lignocellulosic materials, which makes bioattacks more likely. Moreover, surface properties of a material strongly affect gluing, finishing or impregnation. Water contact angle is a quantity allowing for characterization of surface properties. A single measurement provides few important parameters: surface free energy, contact angle, wetting coefficient or work of adhesion [Gindl et al. 2001]. Characterization of surface properties allows for prediction of interactions with wetting materials (lacquers or adhesives). Our investigations, described here, include the measurements of the surface roughness and surface wettability by water.
EXPERIMENTAL

The samples of beech veneer with the dimension of $700 \times 200 \times 1.5 \text{ mm}^3$ were used in the investigations. Samples were prepared in pairs (modified sample and reference sample) from the same piece of wood, to make the results independent of the microstructure of wood.

The samples were irradiated with pulsed electron beams using a “RITM-2M” device, developed and manufactured by MICROSPALV OOO company and presented in Fig. 1. RITM is a source of low-energy high current electron beams of microsecond duration, which generates a fairly homogeneous wide-aperture electron beam up to 10 cm in diameter [8].

![Fig. 1. Pulse electron beam device](image)

The sample irradiation processes were performed in vacuum chamber, where the base pressure was about $1.1 \times 10^{-1} \text{ Pa}$. 5N purity argon was used for adjusting the pressure. The electron energy was in the range from 14 to 30 keV. The pulse energy density was about 1, 3 and 7 J/cm$^2$. The pulse duration was about 2 µs. The number of pulses was 1, 5, 10 and 15.

The measurement of surface roughness was conducted using a Mitutoyo SJ-201 contact profilometer with stylus of a radius of 0.01 mm at a press force of 4 mN. The measurement distance was 12.5 mm (5 elementary sections with a length of 2.5 mm each). The roughness parameter $R_a$ (mean deviation of profile) was calculated according to PN-84/D-01005 [4].

Water wettability of electron irradiated samples were investigated in sessile drop tests. The tests were determined using Phoenix 300 contact angle analyzer.

RESULTS AND DISCUSSION

Figs 2 and 3 show statistically insignificant influence of the number of pulses on surface roughness and statistically significant influence of the energy density of pulses, respectively.

In the first case, we can see, that the average value of $R_a$ is the highest for 5 pulses and the lowest for 1 pulse. The difference between minimum and maximum values is about 25%.

In the second case, an increase in the energy density of pulses leads to a significant increase in surface roughness parameter $R_a$ of beech wood. This result is consistent with investigation of Wilkowski et al. [2012] who studied oak and ash wood after thermal modification.
The sessile drop results are shown in Fig. 4. They demonstrate scattered relations as regards the effect of pulse energy and the number of pulses. We may conclude that the effects of the number and the energy of pulses are too weak to grant applicability.

CONCLUSIONS

Based on our investigations it can be stated that the value of the roughness of wood surface is dependent on the number of the electron pulses and their energy density. We can see that the influence energy density of pulses is the higher.

It can be deduced that an increase of the number of pulses and electron energy leads generally to a reduction of the values of wetting angles, which may indicate an improvement of the surface wettability.

To verify the effect of the proposed modification on the surface wettability, the research should be continued within the range of process parameters with a final goal to develop an innovating process of better joining wood with other materials.

REFERENCES

3) GINDL M., SINF G., GINDL W., REITERER A., TSCHIDGE S., 2001: A comparison of different methods to calculate the surface free energy of wood using contact angle
4) PN-84/D-01005 - Chropowatość powierzchni drewna i materiałów drewnopochodnych - terminologia i parametry

**Streszczenie: Wpływ impulsów elektronowych na chropowatość i zwilżalność powierzchni drewna bukowego.** W artykule przedstawiono pierwsze wyniki badań powierzchni drewna bukowego, poddanego działaniu elektronów. Przedstawiono zmiany chropowatości i zwilżalności wodą w zależności od liczby i gęstości energii impulsów elektronowych. Taka informacja może być użyteczna np. w produkcji płyt meblowych.

Author's address:

Marek Barlak
e-mail: marek.barlak@ncbj.gov.pl
Jerzy Zagórski
e-mail: jerzy.zagorski@ncbj.gov.pl
Zbigniew Werner
e-mail: zbigniew.werner@ncbj.gov.pl
National Centre for Nuclear Research Świerk - NCBJ
Plasma and Ion Technology Division (FM2)
7 Andrzeja Sołtana St.
05-400 Otwock
Poland

Jacek Wilkowski
e-mail: jacek_wilkowski@sggw.pl
Piotr Boruszewski
e-mail: piotr_boruszewski@sggw.pl
Warsaw University of Life Sciences - SGGW
Faculty of Wood Technology
159 Nowoursynowska St.
02-776 Warsaw, Poland
Effect of resin surface protection on selected properties of plywood

PIOTR BORYSIUK, RADOSŁAW AURIGA, MAJKOWSKI MARCIN

Faculty of Wood Technology, Warsaw University of Life Sciences, Poland

Abstract: Effect of resin surface protection on selected properties of plywood. Within the framework of the research a finished with urea-formaldehyde resin (resin) and phenolic-formaldehyde resin (bakelized) under industrial conditions plywood were studied. The obtained samples were tested onto resistance to moisture in the form of water vapour, surface absorption and abrasion resistance. The results of the study were shown as the reference to unprotected plywood. In general, it was found that all coated plywood indicated reduced absorption of water vapour and water in comparison with unprotected plywood. Better protection provides coating of PF resin. Plywood coated with resin showed a greater resistance to abrasion (50%) than unprotected plywood. Better protection, in this case, provides an UF resin coating.

Key words: plywood, surface protection, surface finish, phenol-formaldehyde resin, urea-formaldehyde resin

INTRODUCTION

Plywood, despite the appearance on the market of new wood-based materials, is still a valuable material for versatile use. This is due to its favorable strength parameters what is a result, inter alia, of the layered structure and cross-fiber in adjacent veneers (Baldwin 1995, Curry and Hearmon 1967, Okuma 1976, Parczewski et al. 1969, Sellers 1985, Starecki 1991, Niemz 1993). However, a limitation in the application of plywood may be an insufficient surface resistance to external factors during its use. These factors include effect of moisture, UV radiation as well as abrasion. The plywood resistance can be improved by the use of appropriate surface finishes or chemicals (Tyszka 1987, Borysiuk et al. 2005, Borysiuk et al. 2006, Borysiuk and Jabłoński 2003, Borysiuk and Nowak 2006). The industrial production involves a phenolic films or polypropylene coatings, especially with regard to the building plywood (Kurowska and Borysiuk 2010). These coatings provide good resistance to atmospheric agents with the initial strength properties of the plywood remained. However, the use of this type of coating requires a development of technological process with additional equipment and materials. A simplest method of plywood protection is the use of resins applied to the surface in liquid form and then cured. In this way, a protective coating is formed on the plywood surface, however there is no conclusive information about the quality of obtained protection depending on the applied adhesive resin.

The objective of the present study was to determine the resistance of coatings based on standard adhesive resins produced on plywood in industrial conditions.

MATERIAL AND METHODS

The study included birch plywood with thickness of 20 mm, finished in industrial condition with coatings prepared on the basis of phenol-formaldehyde and urea-formaldehyde resins. Characteristics of surface finishing of the different plywood variants are shown in table 1. All tests were performed on samples of 100 x 100 mm^2. For each of the tested plywood variants was made 10 repetitions of individual determinations.
Table 1. Characteristics of methods of finishing the surface of the tested plywood.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Surface finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Plywood without coating (unprotected)</td>
</tr>
<tr>
<td>B</td>
<td>Plywood with phenol-formaldehyde resin coating (application ok. 150 g/m², pressing parameters: temperature 150°C, time 5 min., pressure unit ok. 1.7 MPa)</td>
</tr>
<tr>
<td>C</td>
<td>Plywood with urea-formaldehyde resin coating (application ok. 150 g/m², pressing parameters: temperature 100°C, time 5 min., pressure unit ok. 1.5 MPa)</td>
</tr>
</tbody>
</table>

The samples tested to:
- resistance to moisture in the form of water vapor – designated as absorbency and swelling of plywood in conditioned air with a relative humidity of 100% and temperature 20 °C. Before the test, narrow surfaces of the samples were protected with a moisture-proofing agent so the penetration into the material could only occur through the wide surface. Samples were weighed and measured and then placed in a climatic chamber. The first four measurements were carried out every hour and the next one every 24 hours. Total test time was 1008 hours.
- surface absorption – study was carried out based on the guidelines of PN-EN 382-2:2001. Absorption was determined after 2 and 24 hours of assay.
- abrasion resistance – study was carried out based on the guidelines of PN-EN 438-2:2016-04. Determinations were performed on the device's ERICHSEN 352/C. Grinding wheels H10 and a load of 1000 g were used. During the test specimen weight loss was determined after a set number of cycles (600 cycles), the control measurements being performed every 100 cycles. At the same time, the surface of the plywood surfaces was observed to capture the traces of abrasion.

RESEARCH RESULTS

The results of the tests are shown in tab. 2, 3, 4 and Figure 1. Considering the impact of the tested coatings on the absorbability of plywood as a percentage of humidity increase, it can be generally found that all variants with coverings indicated a significant decrease in relation to unprotected plywood. It ranged between 38 ÷ 72 % in dependence on the type of coverage after 5 hours of air conditioning and 12 ÷ 19 % after 1008 hours of air conditioning. For the non-protected plywood in same conditions the gain of moisture reached 11.92 %, and for plywood covered with 9.62 ÷ 10.50 %. It is worth mentioning that regardless of the type of coating, especially in the second half of the air-conditioning, covered plywood reached similar levels of the humidity increase. The maximum differences between the variants (A, B and C) did not exceed 2.4 % (1008 h). Among the examined plywood, the lowest moisture content (lowest water vapor absorption) was found in plywood coated with phenol-formaldehyde resin - 9.62 %. Higher moisture content of plywood coated with phenol-formaldehyde resin relative to the plywood coated with the UF resin in the interval 24 - 360 h can be associated with the fact that the alkaline phenol-formaldehyde resin is hygroscopic (Thoemen et al. 2010).

Regardless of the variant, all plywood characterized by a similar upward trend in terms of moisture increase. This clearly demonstrates that, despite a long period of air conditioning (1008 h - 42 days), they have not yet reached the level of equilibrium moisture. On this basis, it can also be stated that the cover being made is only a delay rather than a permanent obstacle to the penetrating moisture. It should also be noted, that the long-term effect of moisture on the cured urea-formaldehyde resin leads to the hydrolysis of bonding between the carbon and nitrogen atoms in the cured binder molecule (especially at elevated temperatures), resulting in a decrease in its strength and resistance (Dunky 2004).
Analyzing the effect of the tested coatings on the swelling of plywood (Table 3) it can be stated that for all variants of the coatings was observed reduced swelling compared to the plywood unprotected. Depending on the type of coatings, this fall was $20 \div 50\%$ after 5 h air conditioning and $11 \div 23\%$ after 1008 h air conditioning. After this period the swelling for unprotected plywood reached $5.02\%$, and for coated plywood (variant B, C) $3.87 \div 4.49\%$. It is worth mentioning that regardless of the type of coating, plywood reached similar levels of growth expansion. The maximum differences between the different variants (A, B and C) does not exceed in this case $1.2\%$ (after 1008 h). Among the examined plywood, plywood with coating of phenol-formaldehyde resin showed the smallest increase in swelling - $3.87\%$. It should also be noted that the increase in swelling of plywood received a similar character and speed, regardless of the type of surface finish. Niemz (1993) reports that as the moisture content of plywood increases by 1%, the swelling increases by about $0.30\%$. In the present studies, during 1008 h of air-conditioning a similar increase in the swelling of plywood was observed. It carried, regardless of the type of coating $0.40 \div 0.43\%$ per 1% increase in moisture.

Table 2. Percentage increase in moisture during air conditioning.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Absorbance as percentage increase of moisture after a specified time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>0.28</td>
</tr>
<tr>
<td>B</td>
<td>0.12</td>
</tr>
<tr>
<td>C</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 3. Percentage swelling of plywood during air conditioning.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Swelling after a specified time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>0.10</td>
</tr>
<tr>
<td>B</td>
<td>0.05</td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table 4. Surface absorption value after 2 h and 24 h testing for plywood according to the surface finish.

<table>
<thead>
<tr>
<th>Time [h]</th>
<th>Surface absorption depending on the type of plywood coverage [g/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>376</td>
</tr>
<tr>
<td>24</td>
<td>834</td>
</tr>
</tbody>
</table>

All the applied coatings resulted in lower surface absorption plywood (Table 4). The best effects of the reduction of water absorption was noted in case of plywood coated with phenol-formaldehyde resin - variant B. With respect to unsecured plywood (variant A) reduction of adsorption was completed after 2 h – 90% and after 24 h – 76%. A slightly lower absorption decrease was noted for coatings made from urea-formaldehyde resin (variant C). With respect to unsecured plywood the decrease was respectively 2 h – 88% and after 24 h – 74%. It should be emphasized here that all the coatings produced under industrial conditions showed the same tendency to change surface adsorption - uniform increase over time. In the case of unprotected plywood the maximum increase in water absorption was recorded in the first 2 hours of study - over 45% of the maximum value recorded after 24 h.
Fig. 1. The percentage weight loss of coated plywood relative to the control plywood - unprotected (100 %) determined after successive measurement series (100 cycles).

Considering the resistance of the examined plywood to abrasion (Figure 1) it can be stated that plywood with urea-formaldehyde resin coating is characterized by the greatest resistance in this range. Characterized by over 50 % less abrasion loss of material during relative to unprotected plywood. Plywood with a phenol-formaldehyde resin coating showed about 16% less abrasion resistance than urea-formaldehyde resin plywood. However, both plywood did not show signs of coating after 600 cycles. The higher abrasion resistance of UF resin-coated plywood results from the fact that the resin has a higher hardness after hardening (Zenkteler 1996).

CONCLUSIONS

Based on the research conducted, the following conclusions can be drawn:

1. The coating of urea-formaldehyde resin or phenol-formaldehyde resin reduces the penetration of moisture into the plywood, but does not constitute a permanent barrier to it. Better protection in this respect is a PF resin coating.
2. The coating of plywood with urea-formaldehyde resin or phenol-formaldehyde resin significantly limits its surface adsorption.
3. Unprotected plywood exhibits increased surface adsorption (about 45 % of the total value) in the first 2 h of humidification.
4. The plywood with urea-formaldehyde resin or phenol-formaldehyde resin significantly increases the resistance of the surface to abrasion. Better protection in this case indicates a UF resin coating.

REFERENCES

2. BORYSIUK P., DZIURKA D., JABŁOŃSKI M., SOSIŃSKA K., 2006: Wpływ sposobu wykończenia powierzchni sklejki na jej właściwości hydrofobowe. VIth International
9. NIEMZ P., 1993: Physik des Holzes und der Holzwerkstoffe. DRW-Verlag
10. OKUMA M., 1976: Plywood properties influenced by the glue line. Wood Science and Technology, 10; 57-68.
13. PN-EN 438-2:2016-04 Wysokociśnieniowe laminaty dekoracyjne (HPL) - Płyty z żywic termoutwardzalnych (zwyczajowo nazywane laminatami) - Część 2: Oznaczanie właściwości

Streszczenie: Wpływ zabezpieczenia powierzchni sklejek żywicami na wybrane ich właściwości. W ramach pracy badaniami poddano sklejki wykończone w warunkach przemysłowych żywicą mocznikowo-formaldehydową (żywicowane) oraz żywicą fenolowo-formaldehydową (bakelizowane). Dla pozyskanych sklejek zbadano: odporność na działanie wilgoci w postaci pary wodnej, absorbicję powierzchniową, odporność na ścieranie. Wyniki badań przedstawiono w odniesieniu do sklejek niezabezpieczonych. Ogólnie stwierdzono, że wszystkie badane sklejki z powłokami charakteryzowały się zmniejszoną chłonnością pary wodnej i wody w stosunku do sklejek niezabezpieczonych. Lepsze zabezpieczenie w tym zakresie stanowi powłoka z żywicą PF. Sklejki pokryte żywicą wykazały się większą
odpornością na ścieranie (o 50 %) w stosunku do sklejek niezabezpieczonych. Lepsze zabezpieczenie w tym zakresie stanowi powłoka z żywicy UF.

Author’s address:

Piotr Borysiuk, Radosław Auriga, Majkowski Marcin
Warsaw University of Life Sciences
Faculty of Wood Technology
159/34 Nowoursynowska Str.
02-787 Warsaw
Poland
e-mail: piotr_borysiuk@sggw.pl
e-mail: radoslaw_auriga@sggw.pl
Modification of wood colour of *Acer platanoides* L. to a brown-red shade caused by thermal treatment

LADISLAV DZURENDA

Faculty of wood sciences and technology, Technical university in Zvolen, 960 53 Zvolen, Slovakia

**Abstract:** The goal of this paper is to determine the colour of wood species *Acer platanoides* L. in CIE-L*a*b* colour space after thermal treatment – to modify the color of the wood by steam at a temperature of $t = 125 – 130^\circ C$ for the duration of $\tau = 7.5$ h. The maple wood in the thermal process of color homogenization changes from a light brown-white color to a brown-red color shade. The color maple of the maple wood in the CIE-L* color space and *b* is described by the coordinates: $L^* = 63.31 \pm 1.96$; $a^* = 11.12 \pm 0.47$; $b^* = 19.22 \pm 0.55$. The irreversible change in the color of maple wood achieved through the process of heat treatment with water steam, increases the possibilities of wider use of maplewood in construction, art and design.

**Keywords:** colour, CIE-L*a*b* colour space, maple wood, thermal treatment, saturated water steam.

**INTRODUCTION**

The colour of wood is a basic physical property and a typical feature of sapwood and heartwood of wood species. The colour range of native wood of industrially important wood species used as construction material in cabinetmaking and furniture industry covers a wide range: From light white-grey-yellow shades of wood species *Picea excelsa*, *Abies alba*, *Tilia cordata*, *Carpinus betulus* through red-brown shades of heartwood of wood species *Quercus robur*, *Fraxinus excelsior*, *Juglans regia* as stated by Drapela (1980), Klement – Réh – Detvaj (2010), Makoviny (2010).

Thermal treatment of wood, in addition to targeted physico-mechanical and chemical changes of wood Kollmann-Gote (1968), Nikolov-Rajčev-Deliiski (1980), Sergovsky-Rasev (1987), Trebula (1986), Lawnniczak (1995), Dzurenda - Orloswki (2011), are accompanied by a change in wood color. Whilst in the past, colour changes expressed as darkening of thermally modified wood were used for removing unwanted colour differences between light sap and a dark core, or for removing unwanted colour stains caused by scalding, browning or moulding, recent research and development has focused upon a targeted change in the colour of wood of individual wood species to more or less pronounced colour shades or imitations of domestic wood species to look like exotic wood species Tolvaj-Molnar-Nemet-Varga (2010), Dzurenda (2014), Barcik-Gašparik-Razumov (2015).

One of the methods to objectively quantify this optical property of wood is to express it in form of coordinates in CIE-L*a*b* colour space. A colour coordination system (according to CIE – Commision Internationale de l’Eclairage) in terms of ISO 7724 (1984) is based on the measurement of three parameters: Lightness L from 100 for white to 0 for black, chromatic coordinate $a^*$ for determination of shade between red and green colour and chromatic coordinate $b^*$ determining the shade between yellow and blue colour.

The goal of this paper is to determine the colour of wood species *Acer platanoides* L. in CIE-L*a*b* colour space after thermal treatment with steam at temperature of $t = 125 – 130^\circ C$ for the duration of $\tau = 7.5$ h.
MATERIALS AND METHODS

Maple wood in the form of blanks with dimensions 30 x 55 x 500 mm and humidity \( W_p = 58.2 \pm 3.5\% \) was thermally treated with steam in a pressure autoclave: APDZ 240 (LIGNOTHERM Ltd) at Sundermann s.r.o. Banská Štiavnica. The regime of color modification of maple wood is given in Fig. 1.

![Regime of thermal treatment of maple wood using saturated water steam](image1)

Fig. 1 Regime of thermal treatment of maple wood using saturated water steam

These maple blanks were subsequently seasoned to moisture content \( W_p = 12 \pm 0.5\% \) in a conventional wood drying kiln KAD 1x6 by KATRES s.r.o. Seasoned blanks were milled on horizontal planing milling machine FS 200.

The wood colour of maple blanks in CIE-L*a*b* colour space was determined by a colorimeter Color Reader CR-10 (Konica Minolta, Japan). The light source used was D65 and the diameter of collecting area was 8 mm, fig 2.

![Overview of a colorimeter Colour Reader CR-10](image2)

Fig. 2 Overview of a colorimeter Colour Reader CR-10
The coordinates $L^*$, $a^*$ and $b^*$ of CIE-$L^*a^*b^*$ colour space were measured on $n = 35$ maple blank without heat treatment and measured $n = 45$ maple blanks after the thermal treatment. The measurement of colour coordinates on samples of heat-treated maple wood was performed on the marked side at the center of the width of the blank at a distance of 250 mm from the front after the mechanical treatment on the horizontal planer mill FS 200. Colored coordinate values are represented by writing: $x = \bar{x} \pm s_x$, i.e. average measured value and standard deviation. The extent of variance of the set values in the CIE-$L^* a^* b^*$ color space of the thermally unadjusted and treated wood of the maple is judged by the coefficient of variation.

From the difference in the values of the color coordinates $\Delta L^*$, $\Delta a^*$, $\Delta b^*$ determined on the basis of wood surface measurements of the thermally treated and untreated maple cuttings, the total color difference $\Delta E$ is determined according to the following equation ISO 11 664-4:

$$\Delta E^* = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2}$$  \hspace{1cm} (1)

where: $L^*_1, a^*_1, b^*_1$ colour coordinates of maple wood before thermal treatment of wood, $L^*_2, a^*_2, b^*_2$ colour coordinates of thermally treated of maple wood.

**RESULTS AND DISCUSSION**

The color of wood of *Acer platanoides* L. has, according to the authors of Makoviny (2010), Klement – Réh – Detvaj (2010), a pale brownish color. In the color space CIE-$L^*a^*b^*$, according to the work: Babiak – Kubovský – Mamoňová (2004), the color of maple wood is given by coordinates: $L^* = 80.99; A^* = 5.20; B^* = 16.36$.

The color of the wood changes during the thermal treatment to a brown-red shade, as shown in Fig. 3.

![Fig. 3 View of maple wood before thermal treatment and after thermal treatment](image-url)
The color coordinates of maple wood in the CIE-L* a* b* color space before the heat treatment and after the heat treatment are given in tab. 1.

Table 1 Colour range coordinates of maple wood before and after the heat treatment using saturated water steam

<table>
<thead>
<tr>
<th>Norway maple</th>
<th>Colour coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L*</td>
</tr>
<tr>
<td>native wood - thermally unmodified</td>
<td>Number of measurements [-]</td>
</tr>
<tr>
<td></td>
<td>Average value of coordinates [-]</td>
</tr>
<tr>
<td></td>
<td>Standard deviation [-]</td>
</tr>
<tr>
<td></td>
<td>Variation coefficient [%]</td>
</tr>
<tr>
<td>wood after thermal treatment</td>
<td>Number of measurements [-]</td>
</tr>
<tr>
<td></td>
<td>Average value of coordinates [-]</td>
</tr>
<tr>
<td></td>
<td>Standard deviation [-]</td>
</tr>
<tr>
<td></td>
<td>Variation coefficient [%]</td>
</tr>
</tbody>
</table>

Color coordinates of maple wood without heat treatment and after heat treatment in the CIE-L*a*b* color space are:

**Color coordinates of native maple wood:**

\[ L^* = 80.62 \pm 2.42; \quad a^* = 6.37 \pm 1.12; \quad b^* = 16.59 \pm 1.09. \]

**Color coordinates of maple wood after thermal treatment:**

\[ L^* = 16.31 \pm 1.06; \quad a^* = 11.12 \pm 0.47; \quad b^* = 19.22 \pm 0.55. \]

The magnitude of changes in the individual color coordinates of the thermally modified maple wood and the overall color change induced by the heat treatment using saturated water steam with temperature \( t = 125-130 ^\circ C \) for a time \( \tau = 7.5 \) h are shown in form of a column diagram in Fig. 4.

![Fig. 4. Changes of colour coordinates of maple wood caused by the thermal treatment saturated water steam](image-url)
The measured values of color coordinates of the maple wood before thermal treatment are similar to values stated in the work: Babiak - Kubovský - Mamoňová (2004). Due to the thermal treatment, the lightness of maple wood decreased by ΔL* = -17.31 and the color shifts on the chromatic coordinates in the direction of increase of the red color by Δa* = +4.75 and the yellow color values by Δb* = +2.63. Darkening and reddening of maple wood in the process of thermal modification creates original brownish-red color maple blanks.

Total deviation of colour changes of maple wood caused by the thermal treatment calculated via formula (1) equals \( \Delta E^* = 18.14 \). Since this value exceeds the limit of \( \Delta E^* > 12 \) (Cividini 2007), the colour change of maple wood caused by steaming is classified as a significant colour change.

In terms of categorisation of changes of physical and chemical properties of wood, according to Kollmann and Cote (1968), Trebula (1996), this change of colour of maple wood belongs into the group of irreversible changes. It is caused by a partial hydrolysis of hemicelluloses in lignin-saccharidic matrix of wood and the extraction of water-soluble accessory compounds, as stated in works: Bučko (1995), Kačík (2001). These authors have demonstrated the presence of monosaccharides, organic acids and basic lignin building blocks with guaiacyl and syringyl structure in the condensate after the thermal treatment using saturated water steam.

The new color of maple wood (brown-red colour shade), achieved of heat treatment of wood with water vapor, increases the possibilities of wider use of maplewood in building-building, construction, art and design.

CONCLUSION

The colour of maple wood changes during thermal process from light brown-white to a brown-red colour shade. Thermally treated maple wood is declared in CIE-L*a*b* colour space by coordinates \( L^* = 63.31 \pm 1.96; \ a^* = 11.12 \pm 0.47; \ b^* = 19.22 \pm 0.55 \).

Due to the thermal treatment, the lightness of maple wood has decreased by \( \Delta L^* = -17.31 \) and colour coordinates in CIE-L*a*b* colour space shifted by \( \Delta a^* = +4.75 \) for red colour and \( \Delta b^* = +2.63 \) for yellow colour. Darkening and reddening of maple wood in the process of thermal modification creates original brownish-red color maple blanks.

The new color of maple wood, achieved through the process of heat treatment of wood with water steam, increases the possibilities of wider use of maple wood in construction, art and design.

REFERENCES:


ACKNOWLEDGEMENT:
This experimental research was undertaken with the financial support based on the grant agreement VEGA–SR No: 1/0563/16, of the agency VEGA–SR.

Streszczenie: Modyfikacja koloru drewna klonu (Acer platanoides L.) w kierunku barwy czerwono-brązowej w efekcie obróbki termicznej. W ramach pracy oznaczano kolor drewna klonu (Acer platanoides L.) przy wykorzystaniu przestrzeni barw CIELab, poddanego obróbce termicznej w atmosferze pary wodnej o temperaturze 125 – 130°C przez czas 7.5 h. W efekcie obróbki termicznej barwa drewna klonu zmienia się z jasno brązowo-białej do brązowo-czerwonej. Barwa drewna w przestrzeni CIELab jest opisana współrzędnymi L=63.31 ± 1.96; a=11.12 ± 0.47; b=19.22 ± 0.55. Trwała zmiana koloru drewna klonowego, będąca efektem obróbki termicznej w atmosferze pary wodnej, poszerza możliwości jego zastosowania w budownictwie, sztuce i wzornictwie.
Author address:

Ladislav Dzurenda,
Faculty of Wood Technology, Technical University of Zvolen,
T.G.Masaryka 24, 96053 Zvolen, SLOVAKIA,
e-mail: dzurenda@tuzvo.sk
Influence of the cutting mode on the overall vibrations generated by the woodworking milling machine

ZHIVKO GOCHEV\textsuperscript{1}, GEORGI VUKOV\textsuperscript{2}, PAVLIN VITCHEV\textsuperscript{1}, VALENTIN ATANASOV\textsuperscript{1}, GEORGI KOVACHEV\textsuperscript{1}

\textsuperscript{1}\textsuperscript{1}Department of Woodworking machines, Faculty of Wood Industry, University of Forestry
\textsuperscript{2}\textsuperscript{2}Department of Mathematics and Physics, Faculty of Wood Industry, University of Forestry

Abstract: Influence of the cutting mode on the overall vibrations generated by the woodworking milling machine. The current study investigates the changes in the overall vibrations, generated by the universal woodworking spindle milling machine in relation to some fundamental parameters characterizing the cutting mode: the cutting speed ($V$), the feed speed ($U$) and the thickness of the out-cut layer ($h$). On the basis of these experiments and the obtained results we determined the degree of influence of the investigated parameters on the intensity of the vibrations generated by this type of machines.

Key words: wood shaper, milling, vibration severity, vibration velocity.

INTRODUCTION

The dynamic behavior of any mechanical system is characterized by the magnitude of its vibrations. On the intensity of the vibrations depends the reliability performance of the machine. Intensive vibrations result in faster wear of the machine elements on one hand, and in worsening the surface quality on the other.

Wood processing through milling is one of the most frequently used methods for wood cutting in the woodworking and furniture industries. The quality of the machined surfaces depends on the selection of the optimal cutting mode, which in term influences the dynamic behavior of the working shaft of the machine and the cutting tool.

The main reasons leading to increased vibrations generated during milling could be divided into several groups:

- Vibrations, resulted from the technical performance of the milling machine – the main reason for their arousal is the poor balancing of the rotating elements as well as the misalignment in the belt pulleys (Vukov, 2008);

- Vibrations, generated by the cutting tool – the not-well balanced cutting tool could strongly influenced the magnitude of the overall machine’s vibrations. More over there is a tendency for the up-to-date cutting tools to operate at ever-higher rotational speed (Dinkov, 1990);

- Vibrations, resulted from the milling mode – in the cutting process there is an interaction between the cutting tool and the machined article. These interactions results in formation of cutting forces, which depend on the cutting speed and the feed rate. When the latter are increased, an increase in the vibration energy is observed as well (Iskra et al, 2000; Keturakis et al., 2007).

According to some authors the type of the machined material could influence the magnitude of vibrations. In one of their studies, Lustun and Lucaci (2010) investigated the influence of different wood materials (from oak, beech and fir) on the vibration performance of a woodworking machine with numerical control (NC). Their results showed changes in the vibrations when articles from beech and fir were processed. These results they explained with the presence of early and late wood. When the articles from beech wood were processed the
authors detected a constant vibration amplitude, which they explained with the more homogenous structure of this wood type (Lustun et al., 2010).

The objective of the current study was to investigate the changes in the magnitude of the overall vibrations, generated by the woodworking spindle moulder machine in relation to some fundamental parameters characterizing the cutting mode: the cutting speed (V), the feed speed (U) and the thickness of the out-cut layer (h).

METHODS

The experiments have been performed on the woodworking milling machine, type FD-3. The machine is equipped with a three phase electric motor with power $N = 3$ kW which, by means of a belt drive, provides the following rotational speeds of the machine shaft: 4000, 6000 and 8000 min$^{-1}$. The machine is presented in Figure 1.

![Figure 1. General view of the woodworking milling machine, type FD-3](image)

The machine is also equipped with a roll feeder; model PA-118, driven by self-powered electric motor which could ensure feeding speed of the machined articles from 2 to 32 m.min$^{-1}$.

![Figure 2. Roll feeder, model PA-118: a – general view; b – feeding rolls; c – gear](image)
For the milling process a monolithic cutting tool has been used with technical characteristics presented in Table 1, where $D$ is the diameter of the milling cutter, $d$ – diameter of the bore, $B$ – milling width, $\beta$ – angle of sharpening, $\gamma$ – front angle of cutting, $z$ – number of teeth.

Table 1. Technical characteristics of the cutting instrument

<table>
<thead>
<tr>
<th>General view of the cutting tool</th>
<th>$D$ [mm]</th>
<th>$d$ [mm]</th>
<th>$B$ [mm]</th>
<th>$\beta$ [$^\circ$]</th>
<th>$\gamma$ [$^\circ$]</th>
<th>$z$ [no]</th>
<th>Material of the teeth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140</td>
<td>30</td>
<td>6</td>
<td>47</td>
<td>18</td>
<td>6</td>
<td>Hard alloy (HM)</td>
</tr>
</tbody>
</table>

The processed articles are from pine wood ($Pinus sylvestris$ L.) with density $\rho = 470 \text{ kg.m}^{-3}$, moisture $W = 9 \%$ and dimensions $1000 \times 50 \times 50 \text{ mm}$.

The experiments have been carried out at the three possible speed frequencies of the cutting tool ($n$), namely 4000, 6000 and 8000 min$^{-1}$. The cutting speed ($V$) varies depending on the speed of rotation in accordance with the following equation (Gochev, 2005)

$$V = \pi D n, \text{ m.s}^{-1},$$

where:

$D$ – diameter of the cutting tool, $m$;

$n$ – rotation frequency of the cutting tool, $s^{-1}$.

In the current study the changes in the magnitude of the overall vibrations, measured on the non-rotating parts of the machine have been investigated in relation to the cutting speed ($V$), feed speed ($U$) and the thickness of the output layer ($h$).

In the course of the study, the three variables are measured at three levels which are presented in explicit and coded form in Table 2.

Table 2. Values of the variable factors $V$, $U$ and $h$

<table>
<thead>
<tr>
<th>Variables</th>
<th>Minimal value</th>
<th>Medium value</th>
<th>Maximal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cutting speed $V = x_1 \text{ [m.s}^{-1}]$</td>
<td>29</td>
<td>-1</td>
<td>44</td>
</tr>
<tr>
<td>feed speed $U = x_2 \text{ [m.min}^{-1}]$</td>
<td>2</td>
<td>-1</td>
<td>6</td>
</tr>
<tr>
<td>thickness of the output layer $h = x_3 \text{ [mm]}$</td>
<td>4</td>
<td>-1</td>
<td>8</td>
</tr>
</tbody>
</table>

The measurements were performed in accordance with a preliminary designed matrix $B_3$ for three factorial experiment plan of G.Box of second order which is shown in Table 3. In addition to the experiments, according to the requirements of the $B_3$ matrix for each individual experiment, five additional experiments are carried out under conditions corresponding to the middle of the factor space, i.e. $x_1 = 0, x_2 = 0$ and $x_3 = 0$. On the basis of these measurements
the error variations $S_g^2$ have been determined. For the statistical analysis an average value from three independent measurements for each combination of factors in the experimental matrix have been used.

Table 3. Planning matrix for three factorial experiment for measurement of overall vibrations

<table>
<thead>
<tr>
<th>№ exp.</th>
<th>$x_1 = V$, m.s$^{-1}$</th>
<th>$x_2 = U$, m.min$^{-1}$</th>
<th>$x_3 = h$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1 29</td>
<td>-1 2</td>
<td>-1 4</td>
</tr>
<tr>
<td>2</td>
<td>-1 29</td>
<td>-1 2</td>
<td>1 12</td>
</tr>
<tr>
<td>3</td>
<td>-1 29</td>
<td>1 10</td>
<td>-1 4</td>
</tr>
<tr>
<td>4</td>
<td>-1 29</td>
<td>1 10</td>
<td>1 4</td>
</tr>
<tr>
<td>5</td>
<td>1 59</td>
<td>-1 2</td>
<td>-1 4</td>
</tr>
<tr>
<td>6</td>
<td>1 59</td>
<td>-1 2</td>
<td>1 12</td>
</tr>
<tr>
<td>7</td>
<td>1 59</td>
<td>1 10</td>
<td>-1 4</td>
</tr>
<tr>
<td>8</td>
<td>1 59</td>
<td>1 10</td>
<td>1 12</td>
</tr>
<tr>
<td>9</td>
<td>-1 29</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>10</td>
<td>1 59</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>11</td>
<td>0 44</td>
<td>-1 2</td>
<td>0 8</td>
</tr>
<tr>
<td>12</td>
<td>0 44</td>
<td>1 10</td>
<td>0 8</td>
</tr>
<tr>
<td>13</td>
<td>0 44</td>
<td>0 6</td>
<td>-1 4</td>
</tr>
<tr>
<td>14</td>
<td>0 44</td>
<td>0 6</td>
<td>1 12</td>
</tr>
<tr>
<td>15</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>16</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>17</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>18</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>19</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
<tr>
<td>20</td>
<td>0 44</td>
<td>0 6</td>
<td>0 8</td>
</tr>
</tbody>
</table>

The variations in the magnitude of the vibrations, generated by the tested machine and their relationship to the variables were assessed by measuring the root mean square value of vibration velocity ($v$, mm.s$^{-1}$ (r.m.s)) at different working modes of the machine. The measurements have been performed at four measuring points located on two bearing housings of the main shaft of the machine (two measurement points on each bearing housing). The measurement points on each bearing housing are located mutually perpendicular and radial to the main shaft of the machine (Fig. 3).
In the current study, the measurement points are defined as follows:

- For the gearbox located in proximity to the driven belt pulley, hereinafter referred to as “lower bearing housing”, the measurement points are indicated by \( D_x \) – in the direction parallel to the feed direction and \( D_y \) – in direction perpendicular to the feed direction;

- For the bearing housing located in proximity to the working top of the machine and the cutting tool, hereinafter referred to as “upper bearing housing”, the measurement points are indicated by \( G_x \) – in direction parallel to the feed direction and \( G_y \) – in direction perpendicular to the feed direction.

The requirements given in BDS ISO 10816-1 were strictly followed throughout the experiments.

For the measurement of the vibration velocity a vibration meter, model Vibrotest 60 (Brul & Kjaer Vibro) has been used. The vibration meter is equipped with a sensor picking up vibration accelerations, model AS-065 (Brul & Kjaer Vibro) (Fig. 4).

A magnet is used for fixing the sensor to the bearing housings of the predetermined measurement points. To ensure the good fixation, the bearing housings have been cleaned out of paint, dust and other contaminants.
RESULTS AND DISCUSSION

From the experimental study and the results obtained we observed significantly higher vibration values at measurement points \( G_x \) and \( G_y \), which are located on the bearing housing in proximity of the cutting tool (upper bearing housing) compared to the vibrations measured at points \( D_x \) and \( D_y \) (lower bearing housing). Therefore, in the current study, the vibration behavior of the machine is monitored and analyzed based on the vibrations measured at points \( G_x \) and \( G_y \).

After applying the method of regression analysis and statistical analysis of the data (by specialized software QStatLab.5) the regression equations (2) and (3) have been derived. These equations are used to predict the vibration magnitude in the range of the investigated factors in the measurement points \( G_x \) and \( G_y \).

Regression equation for measurement point \( G_x \):
\[
\hat{y} = 2,448 + 2,797x_1 + 0,199x_2 + 0,305x_3 + 3,424x_4^2 - 0,125x_5^2 - 0,040x_6^2
- 0,391x_1x_2 + 0,186x_2x_3 - 0,182x_1x_3
\]
(2)

Regression equation for measurement point \( G_y \):
\[
\hat{y} = 2,477 + 1,619x_1 + 0,098x_2 + 0,052x_3 + 1,504x_4^2 - 0,110x_5^2 - 0,025x_6^2
- 0,181x_1x_2 + 0,261x_2x_3 - 0,421x_1x_3
\]
(3)

where:
\( x_1 \) – cutting speed, coded;
\( x_2 \) – feed speed, coded;
\( x_3 \) – thickness of output layer, coded.

The calculated correlation coefficients for the two derived regression equations are as follow: for equation (2) \(- R^2 = 0,99\); for equation (3) \(- R^2 = 0,92\).

On the basis of the regression coefficient values for both equations it could be concluded that the highest influence on the vibrations’ magnitude had the cutting speed \( V \) with regression coefficients 2,797 and 1,619. As the cutting speed, respectively the rotation frequency of the cutting tool increases, the vibration speed increases as well.

The other two measured factors exerted almost equal influence on the vibration velocity. However, in the measurement point \( G_x \) a slightly higher influence had the thickness of the output layer (with regression coefficient 0,305), while in measurement point \( G_y \) the feed speed with regression coefficient 0,098 exerted a bit higher influence.

The changes in the vibration speed at measurement points \( G_x \) and \( G_y \) in relation to the cutting speed are presented in Figures 5 and 6.

From the results on the Fig. 5 is visible that with an increase of the cutting speed \( V \) from 29 m.s\(^{-1}\) to 40 m.s\(^{-1}\) the vibrations magnitude decreased at all three assessed feed speeds \( U \). Increasing the cutting speed \( V \) above 40 m.s\(^{-1}\) resulted in an increase of the vibrations and when the \( V = 45 \) m.s\(^{-1}\) their magnitude is equal to those observed at \( V = 29 \) m.s\(^{-1}\). At cutting speed ranged from 25 m.s\(^{-1}\) to 45 m.s\(^{-1}\), a distinct difference in the values of the vibration velocity for the three feed speed was observed. At the low feed speed \( U = 2 \) m.min\(^{-1}\) the vibrations had lower values compared to the those generated at feed speeds \( U = 6 \) and \( U = 10 \) m.min\(^{-1}\). It is worth to be noted that when the cutting speed is above 48 m.s\(^{-1}\), the vibrations’ magnitude is equal at the three feed speeds and increased significantly by increasing the feed speed. The maximal value of the vibration velocity \( v = 7,67 \) mm.s\(^{-1}\) (r.m.s.) was reached at \( V = 59 \) m.s\(^{-1}\), the maximal tested cutting speed.
Figure 5. Assessment of vibration velocity $v$ at point $G_x$ in relation to the cutting speed $V$ at different feed speeds $U$

Regarding the vibrations’ magnitude, measured at points $G_x$ (Fig. 5) and $G_y$ (Fig. 6) it could be concluded that they showed lower values at measurement point $G_y$, where the maximal value was $v = 4.5$ mm.s$^{-1}$ (r.m.s.) measured at the highest cutting speed $V = 59$ m.s$^{-1}$.

Figure 6. Assessment of vibration velocity $v$ at point $G_y$ in relation to the cutting speed $V$ at different feed speeds $U$

The changes in the vibration velocity, measured at point $G_y$ in relation to the cutting speed at three different thickness of output layer $h$ are presented in Figure 7. Slight decrease in the vibrations’ magnitude was observed at the lower level of the tested cutting speed range. At values of the cutting speed from $29$ m.s$^{-1}$ to $44$ m.s$^{-1}$ a clear differentiation in the vibrations’ magnitude in relation to the thickness of the output layer has been observed.
Figure 7. Changes in vibration velocity $v$ in point $G_y$ in relation to the cutting speed $V$ at different thickness of the output layer $h$

For the graphical representation of the changes in the vibration magnitude in relation to the feed speed at the three thicknesses of output layer $h$, the values of the vibration velocity $v$, measured at point $G_x$, have been used (Fig. 8).

Figure 8. Changes in vibration velocity $v$ in point $G_x$ in relation to the feed rate $U$ at different thickness of the output layer $h$

It is visible from the graph that with an increase in the thickness output layer $h$, the magnitude of the vibrations increased at one and the same feed speed $U$. A very slight difference in the vibration velocity between three thicknesses of the output layer $h$ was observed at feed speed ranging from 2 to 5 m.min$^{-1}$. However, with an increase in the feed
speed \( U \) above 6 m.min\(^{-1}\) the difference increases and it was more significant between \( h = 4 \) mm and \( h = 8 \) mm compared to \( h = 8 \) mm and \( h = 12 \) mm.

CONCLUSIONS

Considering the results of our study, we found out that for this type of milling machines higher vibration velocity \( v \) was observed at the upper bearing housing of the main shaft of the machine which could be explained with the overhanging shaft. Mounting of the cutting tool additionally changes the weight of the working shaft in its upper edge, which could also be regarded as a reason for the increased vibrations, measure at the upper bearing housing of the machine in comparison to those measured at the lower bearing housing.

The obtained results confirmed the influence of the assessed factors on the overall vibrations, generated by the milling machine. The highest influence on the increased magnitude of the vibrations had the cutting speed \( V \), followed by the feed speed \( U \) and the thickness of the output layer \( h \).

On the basis of our results and in terms the magnitude of the overall vibrations, generated by such milling machines in processing articles made out of Scots pine (\textit{Pinus sylvestris} L.) the following optimal values are recommended: cutting speed \( V \in (40\!\!-\!\!45) \text{ m.s}^{-1} \); feed speed \( U \) up to 5 m.min\(^{-1}\); thickness of the output layer \( h \) up to 8 mm. When \( h > 8 \) mm, the feed speed should be \( U < 4 \text{ m.min}^{-1} \).

REFERENCES


ACKNOWLEDGEMENTS

This work has been supported by the Scientific Research Sector at the University of Forestry – Sofia, Bulgaria, under contract No 22/19.01.2016.

Streszczenie: Wpływ parametrów skrawania na drgania całkowite generowane na frezarce dolnowerzecionowej. W artykule zbadano zmiany drgań generowanych przez uniwersalną frezarkę dolnowerzecionową do obróbki drewna w odniesieniu do podstawowych parametrów charakteryzujących proces skrawania: prędkość skrawania (V), prędkość posuwu (U) i wysokość skrawanej warstwy (h). Na podstawie otrzymanych wyników określono stopień wpływu badanych parametrów na natężenie drgań generowane przez tego rodzaju maszynę.
Author address:

Zhivko Gochev
Department of Woodworking machines
University of Forestry
10 Kliment Ohrodski Blvd.
1797 Sofia, Bulgaria
e-mail: zhivkog@ltu.bg
Screw withdrawal capacity and lateral resistance in wood-PP composites exposed to low temperature

CEZARY GOZDECKI¹, MAREK KOCISZEWSKI¹, JACEK MIROWSKI², STANISŁAW ZAJCHOWSKI²

¹) Institute of Technology, Kazimierz Wielki University in Bydgoszcz
²) Faculty of Chemical Technology and Engineering, University of Science and Technology in Bydgoszcz

Abstract: Screw withdrawal capacity and lateral resistance in wood-PP composites exposed to low temperature. The results of tests on the withdrawal capacity and lateral resistance of screw fasteners embedded in wood-polymer composites are presented in the study. Wood flour and industrial wood particles of four various sizes and polypropylene were used. Five kinds of composites with 40% constant of wood filler content and polymer were made by means of injection moulding, and then exposed to low temperature. It was noticed that using a larger size of a wood particle caused a lower screw withdrawal capacity and higher lateral resistance of composites. Exposing composite material to low temperature results slight increase of screw withdrawal capacity and higher lateral resistance.

Key words: WPC, wood-plastic composite, polypropylene, screw withdrawal, lateral resistance

INTRODUCTION

A special advantages of wood-plastic composites (WPCs) result from the possibility of free formulation of their physical and mechanical properties. Typical WPC containing apart from standard polymer fillers such as wood flour, wood particles and wood fibres (Bledzki and Faruk 2003, Cui et al. 2008), and industrial soft WPCs (Gozdecki et al. 2015), other lignocellulosic particles like sawdust and wood sanding flour (Gozdecki et al. 2007) or flax fibres (Madsen i inn. 2015) juta, kenaf fibres, bamboo (Hojo i inn. 2014) rice husk (Yao et al. 2008). Using WPC in new applications a speciality entails using different modes of connecting. However, one of the most classic modes of connecting are screw connections (Gozdecki 2016). Such a connection belongs to conventional construction systems, is easy to make and does not need using special tools. A lot of study into an effect of the level of wood filler content in a WPC on withdrawal capacity (WC) and lateral resistance of a screw were carried out e.g. Falk et al. 2001, Kociszewski et al. 2007 and Haftkhani et al. 2011 among others. However, WPCs that are used to make a variety of outdoor products e.g. garden furniture, small architectural pieces, balustrades, platforms, details of roof slopescan are frequently exposed to water, strongly heated or low temperature.

Influence of high or cyclic temperature on the physical and mechanical properties of WPCs and polymers were studied by several researchers (Gozdecki i Kociszewski 2008, Najafi et al. 2010, Da Costaa et al. 2007, Gozdecki 2013, Yang et al. 2013). The results obtained by them on the mechanical properties of WPCs are different and difficult to compare, however. Therefore, the investigations were carried to determine an effect of a low temperature on screw WC and screw lateral resistance (SLR) of WPC.

MATERIALS AND METHODS

The polypropylene (PP) used in this study was homopolymer Moplen HP648T (Basell Orlen Polyolefins, Poland). Its density was 0.9 g/cm³, and its melt flow index was 53 g/10 min (230°C/2.16 kg). Two kinds of wood materials were used to prepare composites: Lignocel BK 40/90 wood flour (mesh 300-500) produced by J. Rettenmaier & Söhne GmbH
+ Co, and industrial soft wood particles (WPs). The WPs were screened by an analytical sieve shaker LAB-11-200/UP using the sieves of 5, 10, 18, 35 and 60 mesh to obtain four particle sizes: very small, S1, 0.25–0.5 mm; small, S2, 0.5–1 mm; large L1, 1–2 mm; and very large L2, 2–4 mm. Before the mixing process, WPs were dried to obtain 1-2% moisture content. Next, WP and PP were mixed at a ratio of 40:60 by weight in a one-step mixing process in the feed zone of an AH-80 injection molding machine. Test WPCs specimens of the size 50x50x20 mm were made by injection molding using a temperature of 130-185°C from feed zone to die zone. Afterwards, WPCs were stored in a laboratory room in a temperature of approx. 21°C and humidity of approx. 65% for 7 days. According to the standard PN – EN 13446, Ø2 +/- 0.1 mm pilot holes were drilled in the samples, perpendicularly to the sample (a port hole in a parallel direction), on the 20 +/- 1 mm deep. To determine SLR, Ø 4 +/- 0.1 mm through pilot holes were drilled in the samples. SPAX-type screws of 4 x 50 mm were screwed into the holes prepared in such a way (Fig. 1).

![Fig. 1. Specimens size and pilot holes drilled in the samples, a) WC of a screw perpendicularly, b) WC of a screw parallel and c) SLR](image)

The samples with screws were divided into two groups. The first group was stored in a laboratory room. The second group was exposed to low temperature (-20°C) for 7 days and then seasoned in the laboratory conditions for 2 days. The samples were fixed in a testing machine in such a way as to provide axial action of the screw withdrawing force. During tests the force of SLR was applied perpendicularly to a screw on both sides of the sample. The test speed was set to 2 mm/min.

The WC of a screw was calculated, according to the following formula (1):

\[
WC = \frac{P_{\text{max}}}{dl_p}
\]

where:
- \(P_{\text{max}}\) – max. force employed to withdraw a screw (N),
- \(d\) – nominal diameter of a fastener (mm) and
- \(l_p\) – depth of fastener embedding (mm).

SLR was represented as a maximal force causing destruction WPC.

RESULTS AND DISCUSSION

The obtained data were statistically analyzed using the Statistica version 12. The two-way analysis of variance (ANOVA) was conducted to determine the significance of the effect of WP size and cooling process content on WC and SLR (Table 1).
Table 1. Two-way ANOVA test on the effects of WP size and cooling process on wood-plastic composite WC and SL (p-value)

<table>
<thead>
<tr>
<th></th>
<th>WC</th>
<th>SLR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>parallel</td>
<td>perpendicular</td>
</tr>
<tr>
<td>WP size</td>
<td>&lt;0.0001*</td>
<td>0.0021*</td>
</tr>
<tr>
<td>Cooling process</td>
<td>0.0238**</td>
<td>0.0352**</td>
</tr>
<tr>
<td>WP size x cooling process</td>
<td>0.9964ns</td>
<td>0.8699ns</td>
</tr>
</tbody>
</table>

* Significant at 0.01, ** significant at 0.05, ns nonsignificant at 0.05

The influence of a WPs size and cooling process, on the ability to maintain a screw for parallel and perpendicular loading direction and SLR is shown in Figs. 2 and 3.

Fig. 2. Effect of WP size and cooling process on wood-plastic composite WC

Fig. 3. Effect of WP size and cooling process on wood-plastic composite SLR

In general WPC exposed to the cooling process, regardless of particle size, show a slightly greater ability to maintain screws (statistical significant at 0.05). The phenomenon is common for both of screw mounted perpendicular and parallel to the sample surface (on average about 10%). The very similar situation is observed for SLR but the differences are
smaller (on average about 5%). It is difficult to state unequivocally what is the reason for such behaviour of WPC. It may be so because the cooling process causes an increase of rigidity of composite components.

Generaly WPCs show good WC and SLR regardless of size of a filler used in the testing. However, the highest value of WC were noted when the composite contained small wood particles, BK and S1. The lowest one, on average about 14 %, was shown by the composites filled with WPs L1 and L2. The differences in WC between the composites containing BK and S1 for both modes of screw embedment are statistically insignificant. A similar phenomenon can be observed for the composites containing WPs L1 and L2. The opposite behaviour was noted by SLR. An increase in the WP size from BK to L1, regardless of cooling process or not, results in increasing SLR on average by about 20%. Further increasing of WP size from L1 to L2 results in only slightly decreasing of SLR value.

When analyzing the results of effect of loading direction one on WC can notice that in any case WC value of the screw embedded in the parallel direction in the composite material is statistically higher (on average about 15%) than in the case of the screw embedded in the perpendicular direction.

CONCLUSIONS
On the basis of the performed study, we can draw the following conclusions:

1. Exposing wood-PP composite material to low temperature results in an increase in its ability to maintain a screw embedded in both directions and lateral resistance
2. The withdrawal capacity of the screw embedded in the parallel direction in the composite material is higher than in the case of the screw embedded in the perpendicular one, regardless of kind of a filler used in the tests.
3. The highest value of withdrawal capacity were noted when the composite contained small wood particles. The opposite behaviour was noted by lateral resistance. An increase in the wood particle size, regardless of cooling process or not, results in increasing lateral resistance.

REFERENCES

Streszczenie: Zdolność kompozytów drewno-PP na osiowe wyciąganie i przeciąganie wkręta, wystawionych na działanie niskiej temperatury. W pracy przedstawiono wyniki badań wytrzymałości na wyciąganie osiowe i przeciąganie boczne wkrętów zamontowanych w kompozytach drewno-polimerowych. W badaniach zastosowano mączkę drzewną, przemysłowe wióry drzewne o czterech wielkościach oraz polipropylen. Metodą formowania wtryskowego wykonano pięć rodzajów kompozytów o stałej zawartości (40%) napełniacza drzewnego, a następnie wystawiono na działanie niskiej temperatury. Zauważono, że wraz ze wzrostem wielkości cząstek drzewnych obniża się zdolność osiowego utrzymania śrub natomiast zwiększa odporność na przeciąganie boczne kompozytów. Ekspozycja kompozytów na działanie niskich temperatur powoduje wzrost obu badanych właściwości.

Author address:
Cezary Gozdecki,
Institute of Technology,
Kazimierz Wielki University
Chodkiewicza 30 str. 85-064 Bydgoszcz, Poland
gozdecki@ukw.edu.pl
Modification of the surfaces of wood cutting tools using CO\textsubscript{2} laser - SEM analysis

PAWEŁ KOŁODZIEJCZAK\textsuperscript{1}, JACEK WILKOWSKI\textsuperscript{2}, MAREK BARLAK\textsuperscript{3}, PAWEŁ CZARNIAK\textsuperscript{2}, ZBIGNIEW WERNER\textsuperscript{3}, JERZY ZAGÓRSKI\textsuperscript{3}

\textsuperscript{1} Department of Welding Engineering, Warsaw University of Technology - WUT
\textsuperscript{2} Department of Mechanical Processing of Wood, Warsaw University of Life Sciences - SGGW
\textsuperscript{3} Plasma and Ion Technology Division (FM2), National Centre for Nuclear Research Świerk - NCBJ

Abstract: Modification of the surfaces of wood cutting tools using CO\textsubscript{2} laser - SEM analysis. SEM analysis of the surfaces of wood cutting tools modified by CO\textsubscript{2} laser is presented. The aim of the conducted research was to study the influence of CO\textsubscript{2} laser beam on surface topography of WC-Co cutting edges used in wood based material machining. There images obtained on SEM as well as cutting edge spallings, scratches and cracks on the surface subjected to modification are revealed.

Keywords: WC-Co tools, CO\textsubscript{2} laser treatment, SEM analysis

INTRODUCTION

Laser treatment can be used in order to improve tribological behaviour of the tool surface topography. The process of changing the surface properties depends on different parameters like power, focus diameter, pulse duration, frequency. By the way of an example, laser texturing of the coated commercial cemented carbide inserts (WC-Co) manufactured by Sandvik was described. [Da Silva et al. 2013; Karatas et al. 2007; Neves et al. 2013].

The cutting edge machining with laser beam is a useful improvement in comparison to conventional method. High edge quality can be achieved by using frequency-converted diode-pumped solid-state laser with pulse durations of about 12 ps [Ostendorf et al. 2014].

ArF excimer pulsed lasers ($\lambda = 193\,\text{nm}$, $\tau \approx 30\,\text{ns}$) and CO\textsubscript{2} ($\lambda = 10.6\,\mu\text{m}$, $\tau \approx 80\,\text{ns}$) can be used to remove selectively Co from the surface. A large difference of melting points between Co (1495°C) and WC or W\textsubscript{2}C (2780-2860°C) should result in preferential vaporization of Co thus improving the system by structural modifications at the surface. A laser irradiation of suitable energy can indeed, modify the surface of materials, leaving the bulk unaltered [Cappelli et al. 1999; Arroyo et al. 2010].

To achieve the spot size near 1 mm in experiments a CO\textsubscript{2} laser was used. Most of investigations were made by pulse laser beam, but the influence of continuous laser beam on the properties of the cemented carbide tools surface was also studied. Using an unfocused laser beam allows for increasing the area of the treatment.

The aim of the research conducted in this work was to study the influence of CO\textsubscript{2} laser treatment on WC-Co cutting edges, designed for wood based materials machining.

MATERIALS AND METHODS

The commercially available cemented carbide tools inserts with the dimensions of 29.5×12.0×1.5 mm\textsuperscript{3}, manufactured by Faba company and presented in Fig. 1 were used in the investigations. Before processing the inserts were washed in high purity acetone under ultrasonic agitation.
Fig. 1. Cemented carbide tools inserts

The WC-Co surface was treated using the beam of Wegmann-Baasel CO₂ laser of 2.5 kW maximum cw power. The ring-shaped beam of the mode close to TEM₁₀₀ can be focused to a diameter of 0.5 mm by a focusing head with 5 inch ZnSe lens. A controlled flow rate Argon as a shielding gas was provided to the surface. The main parameters of the modification with laser beam are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>CO₂</td>
</tr>
<tr>
<td>Wavelength λ</td>
<td>10.6 µm</td>
</tr>
<tr>
<td>Mode</td>
<td>TEM₁₀₀</td>
</tr>
<tr>
<td>Focus diameter</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Power</td>
<td>1300 W</td>
</tr>
<tr>
<td>Feed rate</td>
<td>600 mm/min.</td>
</tr>
<tr>
<td>Focal length ƒ</td>
<td>5 inch</td>
</tr>
</tbody>
</table>

Fig. 2 presents the working stand for the tool modification. The treatment processes were provided at Warsaw University of Technology.

The surface quality of the virgin and the laser treated samples were examined with the use of Scanning Electron Microscopy (SEM). The magnification of the observations was from ×50 to ×2000. The presence of elements at the surface of the samples and their homogeneity was verified by Energy Dispersive X-ray Spectroscopy (EDS) analysis. In both, SEM and
EDS investigations, the accelerating voltage was 20 kV. SEM and EDS investigations were provided at National Centre for Nuclear Research Świerk.

RESEARCH RESULTS

The modification carried out according to the methodology described above changed significantly the edge surface topography, especially in the area of laser beam influence. Sometimes a serious spalling occurred on the border between the modified and unmodified zones. This phenomenon can be caused by high temperature gradient on the border of modified and unmodified zone and simultaneously by an increased level of strain (Fig. 3). The area of laser influence can be clearly distinguished by darker colour tinge (Fig. 4) with visible scratches on the melted crystal structure (Fig. 5), especially pronounced on the border between the mentioned above areas. (Fig. 6).

The destructive effect of laser pulses is especially visible in Fig 7, as manifested by cracks in the modified zone. EDS analysis of material decomposition at surface indicates an increased content of carbon in the area subjected to laser beam (Fig. 8) and a growth of the concentration of cobalt close to the border, outside this area (Fig. 9). It can be assumed that under the influence at high temperature caused by high energy laser beam cobalt, acting as binder for wolfram carbide, melts down and migrates to the border between the earlier mentioned zones. A limited amount of this binder in modified zone can lead to cracks.
CONCLUSIONS

The analysis of scanning images of edge surfaces WC-Co subjected to CO₂ laser beam proved a destructive character of this process. It manifests itself in spalling of cutting edge on the border between the modified and unmodified zone and scratches or cracks on the modified surface.

REFERENCES


**Streszczenie:** Modyfikacja powierzchni ostrzy skrawających do drewna przy użyciu lasera CO$_2$ - analiza z wykorzystaniem mikroskopu skaningowego. Celem przeprowadzonych badań była ocena wpływu modyfikacji laserem CO$_2$ na topografię powierzchni ostrzy skrawających WC-Co do obróbki materiałów drzewnych. Przanalizowano obrazy powierzchni wykonane na mikroskopie skaningowym (SEM). Zaobserwowano wykruszenia krawędzi ostrza na granicy strefy modyfikacji oraz rysy i pęknięcia powierzchni w strefie modyfikacji.

Author’s address:

Paweł Kołodziejczak
e-mail: pkołodzi@wip.pw.edu.pl
Warsaw University of Technology - WUT
Faculty of Production Engineering
Institute of Manufacturing Technologies
85 Narbutta St.
02-524 Warsaw, Poland

Jacek Wilkowski
e-mail: jacek_wilkowski@sggw.pl
Pawel Czarniak
e-mail: pawel_czarniak@sggw.pl
Warsaw University of Life Sciences - SGGW
Faculty of Wood Technology
159 Nowoursynowska St.
02-776 Warsaw, Poland

Marek Barlak
e-mail: marek.barlak@ncbj.gov.pl
Zbigniew Werner
e-mail: zbigniew.werner@ncbj.gov.pl
Jerzy Zagórski
e-mail: jerzy.zagorski@ncbj.gov.pl
National Centre for Nuclear Research Świerk - NCBJ
Plasma and Ion Technology Division (FM2)
7 Andrzeja Soltana St.
05-400 Otwock, Poland
Drilling features of particleboard made of selected fruit trees prunings

PIOTR KOZŁOWSKI\textsuperscript{a}, WOJCIECH KUKUŁA\textsuperscript{b}, KAROL SZYMANOWSKI\textsuperscript{c}, GRZEGORZ KOWALUK\textsuperscript{d}, PAWEŁ CZARNIAK\textsuperscript{c}, RADOSŁAW AURIGA\textsuperscript{c}, ŁUKASZ KWAŚNY\textsuperscript{e}

\textsuperscript{a} Department of Applied Entomology Warsaw University of Life Sciences - SGGW
\textsuperscript{b} Department of Plant Pathology, Warsaw University of Life Sciences - SGGW
\textsuperscript{c} Department of Mechanical Processing of Wood, Warsaw University of Life Sciences— SGGW
\textsuperscript{d} Department of Technology, Organization and Management in Wood Industry, Warsaw University of Life Sciences— SGGW
\textsuperscript{e} Geomatics and Land Management, Warsaw University of Life Sciences— SGGW

Abstract: Drilling features of particleboard made of selected fruit trees prunings. In this work the selected mechanical and physical properties of wood based panels originated from fruits trees pruning, namely: plum trees, apple trees, as well as drilling ability, were analyzed. As reference material were used panels based on particles produced from pine wood in industrial conditions. All three kinds of samples were subjected to tests in order to assess modulus of elasticity (MOE), modulus of rupture, (MOR), and volumetric density. Moreover, drilling process of above mentioned materials regards to axial force and torque was analyzed. It can be concluded that lower volumetric (bulk) density (more vulnerable material to densification) resulted in the higher MOE or MOR value for reference panels. Besides, such machinability indicator as axial force turned out the highest for apple wood what is in coincidence with high volumetric density affecting drilling process similar as unit density. However, the differences between these three kinds of samples due to torque values are not so obvious. It is worth to enhance that panels made of fruit trees prunings proved significantly high value of MOE. Even the lowest value observed for apple panels (2432 N/mm\textsuperscript{2}) exceed the minimal standard requirements (according to PN-EN 312:2011) for over 52%. From friendly environmental approach these results are very promising because of the fact that fruit trees prunings are very often assumed as waste material.

Keywords: particleboard, fruit tree, axial force, drilling, torque

INTRODUCTION

Wood is the primary raw material in many branches of production. Due to the specificity of its formation, it belongs to the group of natural and renewable energy sources (Ciechanowicz 2001). So far the main source of raw materials were forest stands, but recently alternative reservoirs are being sought. Potential sources of wood raw materials are undoubtedly orchards and nurseries of fruit trees. The area of orchard crops in Poland is 349.9 thousand ha, more than 71% are apple trees (GUS 2015).

The amount of biomass obtained in fruit orchards was dependent on the age of trees and rootstock and ranged from 2.0 to 6.8 tons * ha\textsuperscript{-1} (Rabcewicz et al. 2007, Gorzelany and Matbok 2013). It estimated that wood waste generated after trimming of orchards was at the level of 0.35 m\textsuperscript{3} * ha\textsuperscript{-1} on average (Klugmann-Radziemska 2009).

Wood from orchards is a waste in the production process. Branches after annual pruning in orchards are removed and burned on prisms. This treatment is beneficial from the point of view of non-chemical fighting with bark and wood diseases (Meszka 2014).

The productivity of orchards in terms of usefulness for the wood industry requires the estimation and specifying directions of the management of apparently waste wood material. The wood cuttings obtained from the apple and plum cut branches as components for the production of three-layer particleboards were used in this work.
INVESTIGATED MATERIAL
The investigated 3-layer panels were produced in laboratory conditions from particles of three wood species:

- softwood (mostly *Pinus sylvestris* L.), as the “reference” panels,
- plum (*Prunus domestica* L.), hereinafter referred “plum”
- apple (*Malus domestica* Borkh.), hereinafter referred “apple”.

The fruit wood particles were produced from 2-3 years old prunings by cutting in laboratory knife mill, since the softwood particles were made in industrial conditions from softwood chips. The particles were then dried to moisture content ca. 3% in laboratory dryer, and sorted to face and core layer fractions. The particles used for core layer were passing the mesh 8 mm and caught on mesh size 2 mm, since the particles used for face layer passed the mesh size 1 mm and caught on mesh size 0.25 mm. The volumetric (bulk) density of used particles was as follow: reference 197/164 kg/m³, plum 157/214 kg/m³, apple 277/245 kg/m³, face/core layer respectively. The main production parameters were: assumed density 700 kg/m³, thickness 16 mm, face layers share 32%, urea-formaldehyde resin Silekol S-123, resination 10% core, 12% face layers, pressing time coefficient 15 s/mm. The curing time of resin with hardener in 100°C was about 85 s. The pressing temperature was 200°C. No hydrofobizing agents have been added. Prior the further tests the produced panels were conditioned in 20°C/65% relative moisture content to constant weight.

METHODS
The modulus of rupture (MOR) and modulus of elasticity when bending the tested panels (MOE) were investigated according to PN-EN 310:1994 standard. As many as 12 samples of each panel type was used to complete the mentioned tests.

Drilling was carried out using a standard CNC machine BUSELLATO Jet 130 (Italy 2004). Brand new Leitz single blade with PCD (polycrystalline diamond) drill (ID No: 091193) was used. Spindle speed was set to 6000 rpm and feed 0.2 mm per revolution. Each panel type was tested 10 times. During drilling the measurement and recording of the axial force and torque signals took place. For this purpose the special platform with a piezoelectric sensor (Kistler 9345) was used. The analysis of the signals was carried out in the LabView environment.

RESULTS AND DISCUSSION
The results of testing of modulus of rupture and modulus of elasticity when bending the investigated panels is presented on Fig. 1. As it can be seen, the highest value of modulus of rupture, 16.8 N/mm² was achieved for reference panels, since the lowest, 12.8 N/mm² for apple panels. It should be mentioned that according to PN-EN 312:2011 requirements for P2 type 16 mm thick panels, applied for interior equipment and furniture production, used in dry conditions, the minimal modulus of rupture is 11 N/mm². It means that all tested panels meet the mentioned requirements. In case of modulus of elasticity, the highest and the lowest values were achieved in the similar order as it was mentioned above. The highest MOE was found for reference panels, and it was 3179 N/mm², since the lowest MOE value, 2432 N/mm² was for apple panels. According to PN-EN 312:2011 standard requirements, the minimal MOE value is 1600 N/mm². This means that all the tested panels meet the requirements of the standard. Comparing the achieved results of bending tests to the PN-EN 312:2011 standard requirements it should be mentioned, that the MOR and MOE values of all the tested panels significantly exceed the minimal requirements. It is especially clearly displayed in case of MOE, where even the lowest value, 2432 N/mm² for apple panels exceed the minimal requirements for over 52%, when the highest achieved value for reference panels is almost 100% higher than minimal required value.
The reason of different MOR and MOE values of tested panels can be different bulk density of the particles used for panels production. Concerning the weighted average bulk density values, based on weight fraction share (32/68% mass, face/core respectively), the bulk fraction share of reference panels particles was lowest: 175 kg/m$^3$. In the same conditions the weighted bulk density for plum panels particles was 195 kg/m$^3$, when for apple panels – 255 kg/m$^3$. This means that the weighted average bulk density ratio of particles was like 1:1.12:1.46 reference : plum : apple respectively. In case of wood-based materials, which are produced by densification (pressing) the previously shredded raw material, as particleboards are, the bending properties are strongly correlated to the bulk density of raw material. Since the assumed target density of produced panels was the same for all panels, the densification of the reference panels particles, where the bulk density was the lowest, was finally the highest. This is the reason of better cross-bonding of the particles by higher bonding surface. When the bulk density of the particles increase, the particles are less densified during pressing and the fixing area gets smaller. Due to decreasing densification, the bending properties of the produced panels are reduced.

As it was proved in below mentioned results, (Fig. 2) during drilling of earlier described panels, the highest value of axial force was obtained in case of samples made of apple fruit trees prunings, 157.7 N, whereas the lowest value was observed for samples consisted of plum particles, 88.9 N. This fact can be explain according to some principles referred to drilling process. As it is commonly known, the influence of material density on axial force unlikely to torque is much more significant. The similar remarks according influence of density on the forces during drilling were found by Kowaluk et al. (2010). Keeping in mind similar values of volumetric density of reference wood (175 kg/m$^3$) or plum wood (195 kg/m$^3$) in comparison to apple wood (255 kg/m$^3$), this results seems to be reasonable. Probably, as a consequence of differences in degree of particle deformation it came up creation of more homogeneous material what gave similar effect on drilling process as density increase.
Fig. 3 presents results of torque measurement. The values were as follow: for material origins from apple wood 0.507 Nm, for plum wood 0.440 Nm, for reference wood 0.425 Nm. In this case, the comparable level of torque is a typical phenomenon regards to sensitivity of this kind of machinability indicator in the light of processed material density. Therefore, the changes in material homogeneity are not so clearly visible as it happened in case of axial force.

Fig. 2. Results of axial force for tested materials during drilling

Fig. 3. Results of torque for tested materials during drilling
CONCLUSIONS

The above mentioned research on the machinability (by drilling) of the particleboards produced of selected fruit trees prunings, show, that there is significant influence of the bulk density of the raw materials on panels properties and their machinability. The axial force during drilling the panels made of apple wood is remarkably higher than for the remaining tested materials. It should be marked that the bulk density of the apple wood particles was higher compare to reference particles for over 40% and 49% for face and core layer particles, respectively. However, the higher bulk density of particles provides the lower mechanical parameters of the produced panels.

REFERENCES

1. CIECHANOWICZ W., 2001: Bioenergia, a energia jądrowa, Wyższa Szkoła Informatyki i Zarządzania, Warszawa
7. PN-EN 312:2011 Particleboards – Specifications

Streszczenie: Podatność na wiercenie płyt wiórowych wytworzonych z wiórów pozyskanych z drzew owocowych. W niniejszej pracy przeanalizowano zarówno wybrane właściwości mechaniczne i fizyczne płyt drewnopochodnych wytworzonych z materiału pochodzącego z gałęzi drzew owocowych (wiśnia, jabłoń) jak i podatność na wiercenie. Jako materiału porównawczego użyto płyty wyprodukowanej w warunkach przemysłowych z wiórów drewna sosnowego. Wszystkie trzy rodzaje płyt poddano testom aby wyznaczyć moduł sprężystości przy zginaniu (MOE), wytrzymałość na zginanie (MOR) i gęstość nasypową. Ponadto, przeanalizowano proces wiercenia wymienionych wcześniej materiałów pod kątem siły osiowej i momentu obrotowego. Na podstawie wyników można przypuszczać że mniejsza gęstość nasypowa (bardziej podatny materiał na zagęszczanie) spowodowała wzrost wartości MOE i MOR próbek kontrolnych. Poza tym jeden z wskaźników skrawalności czyli siła osiowa okazał się największy w przypadku płyty wytworzonej z drewna jabłoni co może wynikać z wysokiej gęstości nasypowej mającej podobny wpływ na proces wiercenia jak ciężar właściwy. Jednakże różnice między tymi trzema rodzajami materiału pod kątem momentu obrotowego nie są już tak oczywiste. Należy jednak podkreślić, że płyty wyprodukowane z gałęzi drewna owocowego wykazały się bardzo wysoką wartością MOE.
Nawet najniższe wartości zaobserwowane dla płyt z gałęzi jabłek (2432 N/mm²) przewyższają minimalne wymagania (zgodnie z PN-EN 312:2011) nawet o 52%. Z proekologicznego punktu widzenia wyniki te są bardzo obiecujące ponieważ bardzo często przyjmuje się, że gałęzie drzew owocowych są surowcem odpadowym.

Author’s address:

Piotr Kozłowski, Wojciech Kukula, Karol Szymanowski, Grzegorz Kowaluk, Paweł Czarniak, Radosław Auriga, Łukasz Kwaśny
Warsaw University of Life Sciences
Faculty of Wood Technology
159/34 Nowoursynowska Str.
02-787 Warsaw
Poland
piotr_kozlowski@sggw.pl
wojciech_kukula@sggw.pl
karol_szymanowski@sggw.pl
grzegorz_kowaluk@sggw.pl
paweł_czarniak@sggw.pl
radoslaw_auriga@sggw.pl
lukasz_kwasny@sggw.pl
Accelerated ageing-induced effects on surface properties of wood veneers treated with a modified water-based coating system

JOZEF KÚDELA

Department of Wood Science, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Slovak Republic

Abstract: Accelerated ageing-induced effects on surface properties of wood veneers treated with a modified water-based coating system. This work investigates accelerated ageing-induced effects on quality of tree-of-heaven veneer surfaces finished with a water-based coating system applied in several colour hues. This coating system has been modified for surface treatment intended for outdoor exposure. The issues studied were: colour stability, morphological changes in the treated wood expressed through its roughness parameters, and its resistance against wetting with liquids.

The results demonstrate that the coating system had a high resistance against photo-degradation. Under the wet mode (UV radiation with rainfall simulation), some colour changes were present, and the coating turned darker and more matt. These changes, however, were not immediately observable visually.

The ageing induced a moderate increase in roughness and it also enhanced the variability of the roughness parameters. Higher values of roughness and waviness parameters were obtained perpendicular to the grain course.

The experimental results confirmed an appropriate water-resistance of the coating system tested. The contact angles occurring during wetting with water exceeded 90°. This ensured effective protection for wood surface against water during ageing, and the overall stability of the system wood solid-coating.

Key words: surface treatment, wood, coating material, accelerated ageing, colour, roughness, wetting, contact angle

INTRODUCTION

In outdoor conditions, wood surface layers are exposed to radiation, moisture, heat/frost, pollutants and other factors acting in interactions. As such, these layers are subject to degradation. The first ageing-associated changes are manifested as colour variations induced by degradation of lignin, and to some extent also hemicelluloses.

The further ageing-related wood surface degradation impairs its morphology. The surface roughness and waviness increase, and the wood surface texture may turn plastic (FEIST 1990, KÚDELA and HIRACKÝ 2014). The changes in wood structure are responded by changes in other surface properties (WILLIAMS et al. 2001, KISHINO a NAKANO 2004, TOLVAJ et al. 2011, HUANG et al. 2012).

One of wood surface protection methods against outdoor effects is application of an appropriate coating material. Evidently, the function of wood surface treatment is not only to improve the look but also to protect. In exterior, this protective function should mean mainly inhibiting impacts of UV radiation, rain water and other harmful factors.

In case of surface-treated wood, the early degradation phases cause wood discolouration and gloss reduction (SAHA et al. 2013a, OLSSON et al. 2014). The discolouration may be due to the degraded coating but also due to the degraded wood surface. Contrarily, the gloss reduction indicates the degraded coating alone (OLLSON et al. 2014).

Coatings are also intended to protect wood against water, so the coating resistance against water or also other liquids is a fundamental characteristic. The surface wettability with liquids is assessed based on the contact angle value – the measure of the tested-material affinity for water.

The current trends in investigating the ageing of wood surface treated with coating materials aimed to improve the surface colour stability are several: using nano-particles for coating modification on organic-inorganic base, wood surface pre-treatment with inorganic

Our research objective was to study the accelerated ageing-induced effects on the surface treatment quality. The surface quality changes were assessed through visually observed changes in morphological and physical characteristics of wood surface treated with a water-based coating system. The system was applied in several colour hues, and it was modified for use in outdoor conditions.

MATERIALS AND METHODS

Accelerated ageing was simulated on specimens prepared of 0.5 mm thick veneers of tree of heaven (Ailanthus altissima), the specimens size was 80 x 35 mm. The veneers were firstly coated with an impregnation primer varnish Iruxil W-I, adjusted by adding fungicides and insecticides and micronized pigments (iron oxides). The aim was to improve protection against negative UV radiation effects. The primer varnish was applied in 9 colour hues (natural, pine, teak, oak, chestnut, walnut, dark walnut, mahogany, ebony).

The final coat was a transparent top varnish Iruxil WP-600 Natural, intended for outdoor performance. The average thickness of the primer was 25 μm, the average thickness of the top varnish was 30 μm.

The accelerated ageing was simulated in a xenotest Q-SUN Xe-3-HS. The ageing conditions in the xenon test chamber followed the standard ASTM G 155. The ageing mode was set „wet“ simulating wood exposition to both UV and rain (Table 1).

The radiation intensity was 0.35 W·m⁻² with a radiation wave length of 340 nm, following the Standard. This value corresponds to the mean annual value for the temperate zone. The accelerated ageing cycle consisted of two steps, covering altogether 120 min. The ageing process represented 250 cycles, 500 hours in total (Table 1).

The colour space coordinates L*a*b* of all the surface-treated specimens were measured several times: before the accelerated ageing (referential values) and during the ageing after 50, 100, 200, 300 and 500 hours. The colour variation was evaluated objectively, with using a spectrophotometer Spectro-guide 45/0 gloss. The total colour change \( \Delta E^* \) in the individual ageing phases were calculated according to the equation:

\[
\Delta E^* = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2},
\]

where \( L^* \) is brightness (lightness) of the colour, \( a^* \) – coordinate between red and green, \( b^* \) – coordinate between yellow and blue, measured spectro-photometrically.

The roughness and waviness profiles of wood surface finished with the discussed coating system were scanned with a Surfcom 130 A (Fig. 3).

The roughness was measured parallel to and perpendicular to the grain, at two measuring spots in the two anatomical directions, in each specimen. The sampling length was 2.5 mm; the evaluation length was 25 mm. There were investigated two basic roughness parameters – arithmetic mean deviation of the roughness profile (Ra) and the maximum height of
the assessed profile ($R_z$). In both ageing regimens, the roughness parameters were measured before the ageing and after 500 ageing hours.

The surface treated specimens were wetted with two liquids – diiodomethane (apolar liquid) and redistilled water (polar-apolar liquid).

Equally as the roughness measuring, the surface wetting was also measured twice: prior the starting and after the finishing of the ageing process. We used a goniometer Krüss DSA30 Standard (Fig. 4a) with an accessorical software DSA3 for drop shape analysis.

The drop was applied in a volume of 0.0018 ml. Then, a camera scanned the drop’s shape parallel to the grain, for 60 seconds.

RESULTS AND DISCUSSION

The values of colour coordinates $L^*a^*b^*$ measured on wood veneer surface treated with coatings of nine colour hues and subject to ageing depended on the pigment type. The changes in coordinates together with the overall colour change $\Delta E$ are in Fig. 1. The graphs show that the better colour stability over the ageing process was typical especially for darker-hued specimens (ebony, dark nut, mahogany, chestnut). On the other hand, the lighter hues (pine, teak and oak and natural) manifested less colour stability.

The coordinate $a^*$, especially in lighter-hued specimens imitating pine, teak and mahogany decreased moderately with time, shifting towards to green. Contrarily, in the case of oak, this coordinate increased. The coordinate $b^*$ moderately decreased for all hues, shifting towards blue. Fig.1 manifests that $b^*$ decrease was steeper in case of pine, natural, oak and teak hue. Ebony and dark walnut did not manifest observable changes.

The coordinate $L^*$ also decreased with the ageing time, which means that the specimens darkened gradually. Qualitatively similar results for spruce wood treated with various hues can be found in Reinprecht and Pánek (2015).
The major ageing-induced colour changes were observed after 50−100 hours, which well corresponds to LANDRY and BLANCHETT (2012). The results confirmed that the coating system modification with nano-particles on inorganic base was an effective protection against UV radiation; and, according to LANDRY and BLANCHETT (2012), WAN et al. 2014, this modification has better results than modifications on organic base. Even better colour stability of the coating system was observed in the outdoor regimen with rain simulation (KÚDELA et al. 2016).

The morphology of wood surface finished with the studied coating system was assessed through roughness parameters $Ra$, $Rz$ measured parallel and perpendicular to the grain, before and after accelerated ageing. The results are summarised in Fig. 2.

After 500h ageing, there was observed an increasing trend in roughness. The increase was most conspicuous in case of parameter $Ra$ perpendicular to the grain. At the same time, there increased variability of roughness parameters values parallel to the grain (Fig. 2).

KÚDELA and IHRACKÝ (2014) show that under the same ageing conditions, wood roughness in untreated wood significantly increases. This means that the relevant surface treatment was high resistant against degradation effects induced by UV radiation and water in their mutual interaction. Simultaneously, the surface treatment protected the wood surface against these degradation effects. In our case, the roughness variability was not as obvious as reported by Van den BLUCKE et al. (2007) who investigated roughness parameters variability in five surface treatment types subject to 200 ageing cycles.

The specimens surface treated with the coating system tested was found resistant against water, which is evident from the contact angle values beyond 90°. Consequently, the coating system guaranteed effective protection for wood surface against water during ageing. The characteristic course in contact angle within the one-minute interval from the first contact of the testing liquid with the surface is in Fig 3.

The average contact angle values $\theta_0$ and $\theta_{60}$ (at the moment of application and after 60 seconds of wetting) together with other statistical characteristics are in Table 2.
The results show that during wetting with water, the contact angle values exceeded 90° during the whole wetting process. This ascertains the high resistance of the surface treatment against water. After 500 accelerated ageing hours, the contact angle values ranged within 80°–85°. Enhanced wetting may be supposed due to micro-fissures propagating from the substrate into the coating, as the result of transverse buckling of the veneers. The coating, as such, however, maintained water-resistant even after the ageing.

<table>
<thead>
<tr>
<th>Basic statistical characteristics</th>
<th>Contact angle θ₀</th>
<th>Contact angle θ₆₀</th>
<th>Contact angle θ₀</th>
<th>Contact angle θ₆₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 hours</td>
<td>500 hours</td>
<td>0 hours</td>
<td>500 hours</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x (°)</td>
<td>93.9</td>
<td>84.8</td>
<td>91.6</td>
<td>80.9</td>
</tr>
<tr>
<td>s (°)</td>
<td>1.8</td>
<td>4.8</td>
<td>1.8</td>
<td>5.2</td>
</tr>
<tr>
<td>v (%)</td>
<td>1.9</td>
<td>5.6</td>
<td>1.9</td>
<td>6.5</td>
</tr>
<tr>
<td>n</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Diiodomethane</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x (°)</td>
<td>68.2</td>
<td>59.4</td>
<td>63.6</td>
<td>58.7</td>
</tr>
<tr>
<td>s (°)</td>
<td>3.0</td>
<td>3.0</td>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>v (%)</td>
<td>4.4</td>
<td>5.0</td>
<td>4.5</td>
<td>5.1</td>
</tr>
<tr>
<td>n</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
</tbody>
</table>

Wood wetting with the test apolar liquid (diiodomethane) was more conspicuous than with water, compelled by interactions among unsaturated apolar forces occurring during the initial phase of the wetting process, mostly immediately after the first contact between diiodomethane and the substrate (KUDELA 2014). The average contact angle values ranged from 63° to 68°. After 500h ageing, the diiodomethane contact angle values showed decrease analogically to the water contact angle values (Table 1).

Qualitatively similar values were obtained by LANDRY and BLANCHETT (2012). These authors investigated the accelerated ageing effects on water-wetting of pine wood surface treated with two types of acrylate coats. SAHA et al. (2013a) investigated pine thermo-wood coated with polyurethane-acrylate coat containing CeO₂ nanoparticles. The contact angle values obtained by these authors after artificial ageing were higher than the original ones, however, in all cases significantly lower than 90°.

The wetting of surface-treated wood is modified due to wood surface degradation caused by ageing (LANDRY and BLANCHETT 2012, SAHA et al. 2013a). In our case, the contact angle changes were small, which provides evidence for minimum degradation of the coating tested.

CONCLUSION

The colour changes provided evidence that the coating system used was appropriately resistant against photo-degradation. During the ageing, certain colour changes were generated: the coatings turned somewhat darker under the coupled effect of UV radiation and water, and they also got more matt. These changes, however, were hardly visible.

Darker hues showed better colour stability compared to the lighter ones. The former, containing more micronized pigments, iron oxides, were more effective in protecting the wood surface against the UV-induced effects.

The ageing induced moderate increase in roughness, enhancing, in such a way, variability in roughness parameters. In all cases, the higher roughness parameters were recorded perpendicular to the grain.

The experimental results of wetting of surface-treated specimens with specific liquids have confirmed that the tested coating system was resistant against water. This ensured effective protection for wood surface against water impact during ageing, and the overall stability of the system wood solid-coating was well preserved.

63
ACKNOWLEDGEMENT:
This work was funded by the following: the Scientific Grand Agency of the Ministry of Education SR and the Slovak Academy of Sciences (Grant No. 1/0822/17 “Surface modification of wood and coating materials in order to improve stability of the wood – coating material system.”). This paper has been included into the project APVV-16-0177 “Progressive modifications of the wood surface, film-forming materials and their interactions at the phase interface.”

REFERENCES


**Streszczenie:** Wpływ procesu przyspieszonego starzenia na właściwości powierzchniowe fornirów wykończonych zmodyfikowanym wodnym systemem powłokotwórczym. W pracy omówiono wyniki badań wpływu przyspieszonego starzenia na jakość powierzchni fornirów wytworzonych z drewna bożodrzewia gruczołowatego (Ailanthus altissima Mill.), wykończonych zmodyfikowanym, wodnym systemem powłokotwórczym, w kilku wersjach kolorystycznych. W celu określenia zmian właściwości powierzchni, w efekcie oddziaływania procesu przyspieszonego starzenia badano: zmiany barwy, chropowatość powierzchni oraz zwilżalność. Wyniki badań wykazały, że zastosowanie systemu powłokotwórczego w istotnym stopniu uodporniło powierzchnię przed fotodegradacją oraz działaniem wilgoci. Ponadto proces przyspieszonego starzenia w umiarkowanym stopniu wpływał na wzrost chropowatości powierzchni.

**Author address:**

Prof. Dr. Jozef Kúdela
Department of Wood Science
Faculty of Wood Sciences and Technology
Technical University in Zvolen
T. G. Masaryka 24
960 53 Zvolen
Slovak Republic
e-mail: kudela@tuzvo.sk
Influence of milling and sanding on wetting and on thermo-dynamical characteristics of spruce wood surface

JOZEF KÚDELA1), LEOŠ MRENICA1), ĽUBOMÍR JAVOREK 2)

1) Department of Wood Science, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Slovak Republic
2) Department of Manufacturing Technology and Quality Management, Faculty of Environmental and Manufacturing Technology, Technical University in Zvolen, Slovak Republic

Abstract: Influence of milling and sanding on wetting and on thermo-dynamical characteristics of spruce wood surface. The aim of this paper was to investigate the influence of spruce wood mechanical treatment on wood surface wetting with standard apolar and polar-apolar liquids. Experimentally measured contact angles formed by drops situated on different treated spruce wood surfaces were used for calculation of wood surface free energy together with its disperse and polar components. The experimental results show that the diverse mechanical treatments of spruce wood surface differed in their impact on the wetting process and surface free energy of spruce wood. The milled surfaces displayed worse wetting compared to the sanded ones. This was reflected in higher contact angle values. The determined surface free energy values of spruce wood were higher for sanded surfaces, with notably higher polar component. In case of milled surfaces, their surface energy was lower, with equilibrated disperse and polar components. These results show that each of the surface treatments tested meets requirements for ensuring appropriate surface treatment quality. More suitable, however, from this viewpoint was the wood surface treated by sanding.

Keywords: spruce wood, sanding, milling, wetting, contact angle, surface free energy

INTRODUCTION

Study of wood wetting with liquids is obligatory for understanding interactions at the interface between wood and various materials, such as coating, gluing and similar (PIAO et al. 2010, PETRIČ and OVEN 2015, HUBBE, et al. 2015). According to this work, the wood surface wetting with liquids is a complex process, dependent on the liquid chemistry and behaviour, substrate behaviour and the interactions between the wood substrate and the liquid used. In addition, there are many secondary factors given by the specific properties of the liquid and the substrate concerned. Wood surface morphology and its chemistry can be considered as prominent factors influencing wood wetting with liquids. Consequently, we may suppose that the variations of spruce wood surface morphology induced by milling and sanding (KÚDELA et al. 2016), should play an important role in wood wetting with liquids.

The wettability of solid material surface with liquids is assessed based on the contact angle size. Contact angle values measured at the interface with a liquid standard serve as a base for deriving the wood surface thermodynamic characteristics – surface free energy and its components. Contact angle also serves as an important indicator to predict the adhesion of coating materials and glues to the substrate.

The basic problem in studying wood wetting processes with liquids is experimental determining the contact angle corresponding to the equilibrium conditions sensu the Young equation and a series of other problems connected with variable morphology and chemistry of wood surface. Wood wetting has been subject to a detailed analysis (PIAO, et al. 2010, PETRIČ and OVEN 2015, HUBBE, et al. 2015) provided with the results assembled from several hundred works.
In this paper, the impact of milling and sanding of spruce wood on its wetting with standard liquids will be studied and the wood surface energy will be evaluated.

MATERIALS AND METHODS
The experimental measurements were carried out on specimens prepared of spruce wood. The test specimens were firstly conditioned at a relative air humidity of 65% and a temperature of 20°C to an equilibrium moisture content of 12%.

One set of the conditioned specimens were milled on their radial and tangential faces with a milling cutter ELU MOF 177E with a power of 1800W/1100W. The rotation speed was 14130 rpm, the specimen feed speed was 315 mm/min, the cut depth was 2 mm.

The other set was sanded, equally on their radial and tangential faces, with a grinding machine SKIL Baseline – type 1100, with a power of 560 W. The abrasion belt dimensions were 76 mm × 457 mm, the grain sizes were three: P80, P120 and P150. The cutting speed was 200 m/min, the adherence pressure was 41 N.

The contact angle values were measured on the radial and tangential surfaces on the spruce specimens immediately after their milling or sanding. The measuring appliance was a goniometer DSA 30 Standard. The testing liquids were two: redistilled water and diiodomethane, as a polar-apolar and apolar variant - Table 1. The liquids were chosen following KÚDELA (2014).

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$\gamma_L$</th>
<th>$\gamma_L^d$</th>
<th>$\gamma_L^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>72.80</td>
<td>21.80</td>
<td>51.00</td>
</tr>
<tr>
<td>diiodomethane</td>
<td>50.80</td>
<td>50.80</td>
<td>0.00</td>
</tr>
</tbody>
</table>

A drop with a volume of 0.0018 ml was applied on the surface and then the camera scanned its profile along the grain, until the complete drop soaking into the substrate. From the parameter d course (Fig. 1), there was determined the time $t_e$, which means the moment when the advancing angle is reversed to a receding one. The contact angle value corresponding to this moment was considered as an „equilibrium“ contact angle – $\theta_e$. On each specimen, the contact angle was measured at three different spots.

![Fig. 1 Drop profile with the scanned parameters](image)

The contact angle value at the moment of the drop release $\theta_0$ and the equilibrium contact angle $\theta_e$ were used for calculating the contact angle for ideally smooth surface $\theta_w$ (LÍPTÁKOVÁ and KÚDELA 1994). This angle was subsequently used for calculating surface free energy values and its components.

The wood surface free energy was derived by using the following equation adapted from NEUMANNA et al. (1974)

$$\cos \theta = \frac{(0.0137 \cdot \gamma_S - 2.00) \cdot \sqrt{\gamma_S \cdot \gamma_L} + \gamma_L}{\gamma_L \cdot (0.0137 \cdot \sqrt{\gamma_S \cdot \gamma_L} - 1)}$$

and the disperse and polar components $\gamma_S^d$ and $\gamma_S^p$ were calculated according to KLOUBEK (1974).
RESULTS AND DISCUSSION

The results show that the variations in spruce wood surface morphology induced by surface milling and sanding, described in KúDELA et al. (2017), were also manifested during wood surface wetting with standard liquids. The drop applied on wood surface was continually spreading over the surface, at the same time soaking into the wood.

In case of wetting spruce wood radial surfaces, the average time necessary for reaching the equilibrium $t_e$ was 18.5 seconds, with a standard deviation of 2.6 seconds for all milling variants. In the case of tangential faces, under the same conditions, the wood wetting was somewhat faster, with an average $t_e$ 15.6 seconds. The equilibrium time values observed for wetting milled spruce wood surfaces with diiodomethane corresponded to the values obtained with using water.

In all sanded surfaces, the wetting time with water was significantly shorter, reaching $t_e$ in 3.3–4.8 seconds. The sanded surface wetting with diiodomethane was even faster than with water.

Beech wood surfaces treated by milling and sanding also manifested significant changes in their contact angle values $\theta_0$, $\theta_e$ and $\theta_w$. In the case of sanding, there has not been found grain size influence on contact angle values. The contact angle $\theta_0$ and $\theta_w$ values for the radial and tangential milled and sanded surfaces are in Fig. 2.

Figure 2 shows that the milled radial surfaces wetted better than the tangential ones, both in the case of water and diiodomethane. The wetting of sanded surfaces with the liquids concerned was much better than the wetting of milled surfaces. This was evident not only on shorter time necessary to attain the equilibrium state but also on lower values of all the contact angles discussed. In all cases, the spruce wood surface wetting was better when the wetting liquid was apolar. Qualitatively similar results were obtained for beech wood (KúDELA et al. 2016) whose structure is different from spruce.

The contact angles $\theta_0$ and $\theta_e$ depend on wood surface morphology and on wood surface chemistry (LIPTÁKOVÁ et al. 1995). KúDELA et al. (2017) report lower roughness parameters values in milled surfaces compared to the sanded ones, which was primarily true for roughness measured across the fibres. Along the grain, the differences were negligible and there were neither significant differences between the surfaces sanded with papers grain size P 120 and P 150 and the milled surfaces. This means that the differences in wetting seem mainly generate from different chemical structure of milled and sanded surfaces at atomic
level. The same is evident from different values of the contact angle $\theta_w$. This angle (angle of ideal smooth surface) exclusively depends on the surface chemistry (Liptáková et al. 1995). Therefore, different contact angle $\theta_w$ values indicate different changes in spruce wood chemistry, induced by milling and sanding.

The works Gardner et al. (1991), Liptáková et al. (1995) show that different treated spruce wood surfaces displayed several forms of carbon and oxygen atoms occurring in different quantities. Variously treated surfaces also manifested oxygen and carbon atomic concentrations in various O/C ratios. In the milled surfaces, this ratio decreased, associated with hydroxyl groups amount decreasing. The last cited authors also assume partial overlapping between polar groups of polysaccharidic components and plasticised lignin or some extractive substances drifted out to the surface due to high temperature during milling. Kúdeľa et al. (2016) reveals an important role of the milling method and the cutting tool quality.

On the other hand, during sanding, the hydroxyl groups proportion increased considerably. We suppose that this surface treatment caused severe distortions in cell walls in the surface layer; wood fibres were pulled out and damaged mechanically. The consequence was depolymerising polysaccharides and enhanced spruce wood surface hydrophilicity.

The contact angle values $\theta_w$ were also used for calculating wood free surface energy $\gamma_s$ and its disperse and polar components $\gamma_d$ and $\gamma_p$. The surface free energy calculated in this way, with water use, was higher for sanded surfaces with higher polar component (Fig. 3). In the milled surfaces, their surface energy was somewhat lower, without significant difference between the components.

The contact angle values $\theta_w$ were also used for calculating wood free surface energy $\gamma_s$ and its disperse and polar components $\gamma_d$ and $\gamma_p$. The surface free energy calculated in this way, with water use, was higher for sanded surfaces with higher polar component (Fig. 3). In the milled surfaces, their surface energy was somewhat lower, without significant difference between the components.

The surface free energy determined with the aid of diiodomethane was markedly lower, consisting practically of the disperse component alone. There were not statistically significant treatment-dependent differences in these surface free energy values.

The results obtained imply that the spruce wood surface free energy values and the disperse and polar components values of this energy varied according to the liquid standard used. The apolar diiodomethane can only serve for determining the disperse component of surface free energy as the disperse component of diiodomethane is bigger or equal to the disperse component of spruce wood, in absence of polar component. There has been confirmed that in the case of diiodomethane, the
equilibrium state at the interface arises as early as at the beginning of the wetting process. The \( \gamma_{SVd} \) values determined with water were smaller than the \( \gamma_{SVd} \) values obtained with using diiodomethane. The disperse component of the surface free energy determined with the aid of water is not realistic, as the disperse component of the surface free energy of water is lower than the same component in wood. On the other hand, water is suitable for determining the polar component of surface free energy of spruce wood, as the polar component of the surface free energy of water is higher than the same characteristic in wood (KÚDELA 2014). Interactions among polar forces at the interface between wood and water followed gradually, from the wetting process beginning up to the equilibrium manifestation at time \( t_e \), which depended on the polarity of the liquid standard used.

The final surface free energy of spruce wood is the sum of the disperse and polar shares obtained in this way. The average free surface energy values were: 79.8 mJ/m\(^2\) for milled radial surface and 61.8 mJ/m\(^2\) for milled tangential surface.

In the case of sanded surface, the average surface free energy values were equal, representing 94.6 mJ/m\(^2\) for both surfaces.

The surface free energy values determined in this way are significantly higher than the values obtained with using a single liquid only.

The results document that the wood surfaces treated by milling and sanding both meet requirements for wood surface treatment with coating materials. In these terms, however, the best properties were found for the wood surface ground with a sand paper with a grain size of P150.

CONCLUSION

The way of spruce wood surface treatment had major impact on wood wetting process, and, subsequently, it also significantly influenced the surface free energy values and the components values of this energy.

The milled surfaces manifested poorer wetting performance compared to the sanded ones. This was responded by longer time necessary for the testing liquid drop spreading over the milled spruce wood surface and also on higher contact angle values. The milled surfaces also had lower surface free energy than the sanded ones.

The results document that both milled and sanded surfaces meet the requirements for spruce wood surface treatment with coating materials.

ACKNOWLEDGEMENT:
This work was funded by the following: the Scientific Grand Agency of the Ministry of Education SR and the Slovak Academy of Sciences (Grant No. 1/0822/17 “Surface modification of wood and coating materials in order to improve stability of the wood – coating material system.”). This paper has been included into the project APVV-16-0177 “Progressive modifications of the wood surface, film-forming materials and their interactions at the phase interface”.

REFERENCES
3. KLOUBEK J., 1974: Calculation of surface free energy components of ice according to its wettability by water, chlorobenzene and carbon disulfide. J. Colloid Interface Sci., no. 46, 185–190.

Streszczenie: Wpływ operacji frezowania i szlifowania na właściwości powierzchni drewna świerkowego. Celem pracy było zbadanie wpływu obróbki mechanicznej (frezowania i szlifowania) drewna świerkowego na zwilżalność jego powierzchni. Do pomiaru swobodnej energii powierzchniowej wykorzystano wartości kątów zwilżania cieczami referencyjnymi (wodą i dijodometanem), które wyznaczone zostały metodą osadzenia kropli na powierzchniach drewna świerkowego o różnym poziomie chropowatości. Wyniki badań wskazują, że powierzchnia drewna świerkowego poddana obróbce frezowaniem i szlifowaniu charakteryzuje się zróżnicowaną zwilżalnością oraz wartością swobodnej energii powierzchniowej. Powierzchnia drewna świerkowego po frezowaniu odznacza się mniejszymi wartościami kątów zwilżania przez to większą wartością swobodnej energii powierzchniowej niż powierzchnia drewna świerkowego poddana szlifowaniu.

Author’s address:
Prof. Dr. Jozef Kúdela
Department of Wood Science
Faculty of Wood Sciences and Technology
Technical University in Zvolen
T. G. Masaryka 24
960 53 Zvolen
Slovak Republic
e-mail: kudela@tuzvo.sk
Surface roughness after machining of medium density fiberboards designed for deep milling

RAFAŁ KUTYŁA, PIOTR PODZIEWSKI, PATRYK KRÓŁ, KAROL SZYMANOWSKI

Wood Mechanical Processing Department, Warsaw University of Life Sciences – SGGW

Abstract: Surface roughness after machining of medium density fiberboards designed for deep milling. The article presents results of research of MDF for deep milling. Tests were carried out for 5 different boards available on the Polish market. Boards were machined on a CNC machine using helical diamond end mill. The samples were subjected to densities and roughness tests. It has been shown that changes in density on the cross-section of the plate are reflected in the roughness of the obtained surface after milling.

Keywords: MDF, Roughness, deep milling.

INTRODUCTION

Nowadays use of wood-based materials means mainly use of fiber boards and particle boards. This is mainly due to the reduction of large-scale timber harvest and the increase in market demand for wood-based products.

Medium-density fiberboard (MDF) as a sub-group of fiber boards has several advantages over so-called solid wood - these advantages include: smooth and uniform surface, free from defects in the form of knots or grains; dimensional stability and shape; uniform in-material structure. The basic disadvantage of MDF panels is their low aesthetic appeal - which involves the need for its refinement - by laminating or coating with painting products.

Previously mentioned features made MDF boards an excellent alternative to solid wood for so called deep milling - obtaining a three-dimensional structure (Fig. 1). There are a number of MDF products for this type of treatment.

Fig. 1. Three-dimensional geometry, fiberboard.

The vertical density of MDF panels is not uniform. The surface layers – treated with the highest pressure during the pressing process - are the most concentrated while the inner layers are less. This effect increases with the total density increase of board.

The purpose of this work was to determine and compare the surface roughness after deep milling of the boards intended for this purpose and the standard ones.
MATERIALS AND METHODS

The characteristic features of MDF boards that meet the requirements of deep milling are high density (> 700 kg/m³) and construction of fine fibers. The study uses boards of different manufacturers having the above-mentioned characteristics (tab. 1). Density of tested materials was measured using GreCon DAX, obtained density profiles are shown in fig. 2.

Tab. 1. Materials (fiberboards) used in the study.

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>Mean density [kg/m³]</th>
<th>Field of application (according to manufacturer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>SWISS KRONO MDF</td>
<td>750</td>
<td>General, suitable for surface finishing</td>
</tr>
<tr>
<td>II</td>
<td>KRONOSPAN MDF PLUS</td>
<td>750</td>
<td>Construction</td>
</tr>
<tr>
<td>III</td>
<td>KRONOSPAN MDF MR</td>
<td>750</td>
<td>Increased resistance to increased humidity</td>
</tr>
<tr>
<td>IV</td>
<td>Egger MDF-MB E1 CE</td>
<td>800</td>
<td>Fine-grained, higher density in the core of the board</td>
</tr>
<tr>
<td>V</td>
<td>Finsa FIBRALAC TOP</td>
<td>785</td>
<td>Fine-grained, designed for milling and lacquering</td>
</tr>
</tbody>
</table>

Fig. 2 Density profiles of tested materials

Preparation of the material for the study consisted in performing the planning - milling the board surface to a suitable depth (1, 3, 5, 7 and 9 mm) at a tool rotational speed of 23000 rpm. Tool used in the treatment was a 20mm diameter CMT endmill with spiral polycrystalline diamond blade (PCD). The milling was carried out on a 4-axis machining center Biesse ROVER A3.30.

Surface roughness test was performed with the Mitutoyo SJ-201. The device can measure from -200μm to +150μm. The single measurement consisted of 5 sections of 2.5mm length. 8 measurements were taken for each of the 5 depths. In addition, the uncut surface of the plate was measured.
RESULTS AND DISCUSSION

The obtained roughness is shown in the graph (fig. 3).

![Graph showing roughness results](image)

**Fig.3 Roughness of obtained surfaces.**

The surface of the raw plate is characterized by a roughness of about 3 μm. This size is the smallest of the measurements obtained, which may be due to prior sanding, which is the standard step of the surface finish of the board during its production.

In the milling range to 1-3 mm depth, as the depth of milling increases, the surface roughness increases. Between 5 and 9 mm there is a slight difference in roughness that is statistically insignificant. The reason for this may be a slight difference in plate density below the depth of 4 mm.

CONCLUSIONS

Roughness determination of the surfaces after milling can provide conclusions as follows:

1. The density within the panel affects the roughness of the surface after treatment. The increased density of the core layer will provide lower surface roughness.
2. MDF intended for deep milling (increased density, fineness) is characterized by better surface quality than standard MDF.
3. To obtain a less rough surface after milling, it has to be considered: milling depth and the plate density profile.

REFERENCES

2. NICIEWICZ D., SALA C., 2013: Technologiczne aspekty produkcji MDF, Warszawa
3. NICIEWICZ D., SALA C., 2014: Właściwości i zastosowanie płyt MDF, Warszawa
4. ZAKRZEWSKI W., STANISZEWSKA A., 2002: Dokładność obróbki drewna cięciem, Poznań

Author's address:
Rafał Kutyła, Piotr Podziewski, Patryk Król, Karol Szymanowski
Warsaw University of Life Sciences
Faculty of Wood Technology
159/34 Nowoursynowska Str.
02-787 Warsaw
POLAND
rafael.kutyla@gmail.com
piotr_podziewski@sggw.pl
patryk_krol@sggw.pl
karol_szymanowski@sggw.pl
Lowering of formaldehyde emission from wood based panels by modification of polycondensation adhesives with natural fillers, additives and activators

JÁN MATYAŠOVSKÝ1), JÁN SEDLIAČIK2), MÁRIA ŠMIDIARIAKOVÁ2), IGOR NOVÁK3), PETER JURKOVIČ1) PETER DUCHOVIČ1)

1) VIPO a.s., Partizánske, Gen. Svobodu1069/4, 958 01 Partizánske, Slovakia
2) Faculty of Wood Sciences and Technology, Technical University, Masaryka 24, 960 53 Zvolen, Slovakia
3) Polymer Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 845 41 Bratislava 45, Slovakia

Abstract: Lowering of formaldehyde emission from wood based panels by modification of polycondensation adhesives with natural fillers, additives and activators. Modification of polycondensation resins were directed to urea-formaldehyde adhesives with the application in woodworking industry. Fibril proteins of skin, mainly collagen and keratin, polymer polyphenolic molecules of vegetable tannins are significant and perspective biopolymers for selected technical applications e.g. bonding and lowering of formaldehyde from UF bonded materials. Tested modifications confirmed the influence of additives on viscosity of adhesive mixtures and their applicability for gluing of wood based panels with enhanced bonding quality and formaldehyde emissions.

Key words: UF adhesive, collagen, keratin, mimosa, quebracho, modifier, gluing, plywood, formaldehyde

INTRODUCTION

In woodworking industry, at present, polycondensation urea-formaldehyde (UF) resins are the most used adhesives for wood based panels. Their wide utilisation is allowed by their relative low price, high reactivity, availability of raw material and easy applicability, after hardening they provide transparent, but fragile bond. UF adhesives are thermo-reactive resins hardening in wide interval of temperatures with short time of condensation and they are resistant against micro-organisms. A major disadvantage is their low water and moisture resistance and consequent toxicity caused by the hydrolysis and release of formaldehyde (fd) from finished products. Many contemporary researches describe emission of formaldehyde mainly from three sources: the residual formaldehyde present in the resin, formaldehyde formed by the polycondensation reaction between hydroxymethyl groups and formaldehyde released by hydrolytic degradation of hardened resin, especially under conditions of increased humidity and increased temperature.

Formaldehyde adversely affects the respiratory system, eyes, skin, genetic material, reproductive organs, and has a strong effect on the central nervous system (Příhoda 1988). The research of modification of adhesives is aimed on utilisation of products, which are easy accessible and their application save the costs for resin production. On the market, there is large amount of biopolymers, which as secondary raw material can be used for modification of adhesives with the aim to keep and/or increase the quality of adhesives and also glued joints. Leather and food industry produces amount of different biopolymer waste, which pollutes the environment (Pünterer 1995, Buljan et al. 1997, Matyašovský et al 2011).

The shear strength of glued joint directly depends on the resistance against humidity. Suitable modification of adhesive mixtures can reach better cross-linking of the structure of hardened adhesive, increase of durable chemical bonds and lowering of the hydrolysis of adhesive. The research aimed not only on the study of properties of wood and adhesives, but as glued products are also the subject exposed to the environment in which they are located, and also to study their interactions (Šmidriaková et al. 2011).
Langmaier et al. (2004) in his experiments used hydrolysate of chromium waste from leather industry obtained by enzymatic hydrolysis. Nonisothermal thermogravimetric method (TGA) was used at investigation of condensation reactions of dimethylolurea (DMU) and its mixtures with different weight content of urea, hydrolysate, or acid hardener. Glutaraldehyde (GA) is chemical matter, which is often tested for modification of hardeners; there is the assumption, which is completely cross-linked into the structure of the adhesive. Maminski et al. (2006) investigated melamine-urea-formaldehyde (MUF) adhesive, they added GA into the hardener in form of 50% water solution. Shear strength of birch samples glued with modified adhesive was significantly higher in comparison with the reference sample. Also, there is a direct bond of GA with chemical compounds of wood, what significantly increase the strength of glued joint. The percent of fibre destruction was much higher, modified adhesive proved stronger interaction adhesive-wood.

The stability of amino-plastic thermoset adhesives is important hygienic parameter, therefore the research effort is aimed on reduction, and/or avoiding of formaldehyde release from glued material. Wang and Pizzi (1997) tested modification of UF resins with succinaldehyde and they stated strong increase resistance of glued joints against water. Zhang et al. (2010) stated, that UF resin with low molar ratio (1.00) can be modified with suitable modifiers for lowered content of free formaldehyde and higher resistance against water. FTIR spectroscopy was used for investigation of the influence of amount of modification agents on character of hardened resin. Thermo-oxidative stability of different materials and biopolymers was tested by differential scanning calorimetry (DSC). The method is based on determination of the end of induction period, or the beginning of the main oxidation process (Šimon et al. 2001, Šimon et al. 2006).

MATERIAL AND METHOD
In the experimental research, there were applied:
- UF resin KRONORES CB 1639F,
- hardener RODA M 210 pH = 7.4, overall nitrogen as N weight 21.5%, amidic nitrogen weight 4.5% (Duslo Šaľa, Slovakia).

For modification, there were applied activators and selected modifiers:
0. Reference sample of UF resin – KRONORES CB 1639F,
1. Collagen hydrolysate – prepared from leather collagen waste in VIPO,
2. Starch – native corn starch – MERIZET® 100,
3. Mimosa extract – WEIBULL TANAC – polyphenolic molecules of vegetable tannins,
4. Quebracho extract – UNITAN – polyphenolic condensed tannins,
5. Glutaraldehyde 50% (GLT) – PROTECTOL GA-50, pH = 3.7,
6. Methyol derivate (MOD) – pre-condensate prepared in VIPO,
7. Lecithin from soy – phospholipids, (lecithin – phosphatidyl choline),
8. Methyl ester fat 99.8% – prepared in VIPO,
9. Extract from olive leaves – oleuropein, phenylethanoid, polyphenolic compounds,
10. Keratin hydrolysate – prepared from sheep wool in VIPO.

Quality of gluing was tested according to standards EN 314-1 and EN 314-2. Three-layer plywood of birch (Betula) veneer was prepared for determination of physical and mechanical properties at following conditions: pressing pressure 1.8 MPa, temperature 105 °C, time 5 resp. 6 min. Plywood were conditioned at the temperature of 20 ± 2 °C and relative humidity 65 ± 5%. Tested pieces were pre-treated for the class 1:
- immersion in water 20 °C for 24 hours,
- constant rate rate loading,
– disruption after 30 ± 10 seconds,
– accuracy of 1 N.

Formaldehyde emissions from five-layer plywood were tested according to the test method JIS A 1460 “Building boards. Determination of formaldehyde emission. Desiccator method” according to following conditions:
– volume of desiccator: 9-11 dm³,
– loading coefficient: 1800 cm²,
– temperature of 20 ± 0.5 °C,
– test duration 24 h,
– the analytical method: acetylacetone method with spectrophotometric evaluation.

EXPERIMENTAL PART
Experimental research was aimed on preparation of adhesive mixtures and testing their influence on – viscosity, thickness swelling, strength of glued joint and formaldehyde emission.
Adhesive mixtures were prepared according to following scheme:
0 – Reference sample – 100% UF resin + 20% technical flour + 4% hardener
1 – UF resin + 18% technical flour + 2% collagen + 4% hardener
2 – UF resin + 18% technical flour + 2% native starch + 4% hardener
3 – UF resin + 18% technical flour + 2% mimosa powder + 4% hardener
4 – UF resin + 18% technical flour + 2% quebracho powder + 4% hardener
5 – UF resin + 20% technical flour + 2% glutaraldehyde 50 % + 4% hardener
6 – UF resin + 20% technical flour + 2% methylol pre-condensate + 4% hardener
7 – UF resin + 20% technical flour + 2% lecithin from soy + 4% hardener
8 – UF resin + 20% technical flour + 2% methyl ester fat + 4% hardener
9 – UF resin + 20% technical flour + 2% extract from olive + 4% hardener
10 – UF resin + 20% technical flour + 2% keratin + 4% hardener

RESULTS AND DISCUSSION
For determination of applicability of proposed additives into UF resin KRONORES CB 1639F, adhesive mixtures were prepared with parameters comparable to reference sample.

Determination of viscosity
The influence of addition of modified additives on the viscosity of UF adhesive mixture is presented in Table 1. Viscosity was determined on rotation viscometer at the temperature of 20 °C, measurements were carried out at round b5 (Dr = 4,5), b6 (Dr = 8,1) or b7 (Dr = 13,5).

<table>
<thead>
<tr>
<th>UF adhesive mixture No.</th>
<th>Viscosity at b6 (mPa.s)</th>
<th>Viscosity at b5 or b7 (mPa.s)</th>
<th>Average viscosity (mPa.s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4319</td>
<td>4480</td>
<td>4400</td>
</tr>
<tr>
<td>1</td>
<td>5637</td>
<td>5666</td>
<td>5651</td>
</tr>
<tr>
<td>2</td>
<td>4612</td>
<td>4480</td>
<td>4546</td>
</tr>
<tr>
<td>3</td>
<td>4978</td>
<td>5007</td>
<td>4992</td>
</tr>
</tbody>
</table>
Results of dynamic viscosity of UF adhesive mixtures confirmed, that these additives are suitable for modification and there is necessary lowering of technical flour added into UF resin.

**Determination of thickness swelling**
The influence of addition of modified additives on the thickness swelling of prepared plywood is presented in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Thickness swelling after 2 h</th>
<th>Thickness swelling after 24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>avg x (%)</td>
<td>stdev s (%)</td>
</tr>
<tr>
<td>0</td>
<td>20.61</td>
<td>2.3635</td>
</tr>
<tr>
<td>1</td>
<td>23.50</td>
<td>2.6062</td>
</tr>
<tr>
<td>2</td>
<td>23.70</td>
<td>1.7765</td>
</tr>
<tr>
<td>3</td>
<td>14.97</td>
<td>1.9857</td>
</tr>
<tr>
<td>4</td>
<td>19.08</td>
<td>2.0115</td>
</tr>
<tr>
<td>5</td>
<td>19.21</td>
<td>2.7882</td>
</tr>
<tr>
<td>6</td>
<td>19.16</td>
<td>3.0429</td>
</tr>
<tr>
<td>7</td>
<td>20.43</td>
<td>2.5885</td>
</tr>
<tr>
<td>8</td>
<td>26.57</td>
<td>3.7647</td>
</tr>
<tr>
<td>9</td>
<td>22.95</td>
<td>3.0203</td>
</tr>
<tr>
<td>10</td>
<td>17.80</td>
<td>2.6451</td>
</tr>
</tbody>
</table>

From measured values of thickness swelling of plywood test pieces after 2 and 24 h follow, that thickness swelling is improved by modifiers:
- 3 – UF resin + 18% technical flour + 2% mimosa powder + 4% hardener
- 10 – UF resin +18% technical flour + 2% keratin hydrolysate + 4% hardener
- 4 – UF resin + 18% technical flour + 2% quebracho powder + 4% hardener
- 5 – UF resin + 20% technical flour + 2% glutaraldehyde 50 % + 4% hardener
- 6 – UF resin + 20% technical flour + 2% methylol pre-condensate + 4% hardener
- 7 – UF resin + 20% technical flour + 2% lecithin + 4% hardener

**Quality of gluing**
Obtained results of the influence of modifications on shear strength of plywood test pieces are presented in table 3.
Table 3. Shear strength of plywood test pieces

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Shear strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>avg x (MPa)</td>
</tr>
<tr>
<td>0</td>
<td>1.92</td>
</tr>
<tr>
<td>1</td>
<td>2.05</td>
</tr>
<tr>
<td>2</td>
<td>2.63</td>
</tr>
<tr>
<td>3</td>
<td>2.41</td>
</tr>
<tr>
<td>4</td>
<td>2.41</td>
</tr>
<tr>
<td>5</td>
<td>2.80</td>
</tr>
<tr>
<td>6</td>
<td>2.60</td>
</tr>
<tr>
<td>7</td>
<td>1.26</td>
</tr>
<tr>
<td>8</td>
<td>1.98</td>
</tr>
<tr>
<td>9</td>
<td>2.11</td>
</tr>
<tr>
<td>10</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Note. EN 314-2 requires the value of shear strength 1.0 MPa.

Tested plywood fulfil requirement of the standard for class of gluing 1 – they are suitable on application in normal interior environment. The highest shear strength (2.8, 2.6 and 2.6) MPa were obtained for samples of glutaraldehyde 50% – PROTECTOL GA-50, native corn starch and methylol derivate – pre-condensate prepared in VIPO.

**Formaldehyde emission**

Obtained results of the influence of modifications on formaldehyde emission of tested samples are presented in table 4 and graphically presented in Figure 1.

Table 4. Formaldehyde emission stated by desiccator method

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Extinction</th>
<th>Emission [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 reference</td>
<td>0.0820</td>
<td>0.926</td>
</tr>
<tr>
<td>1</td>
<td>0.0641</td>
<td>0.714</td>
</tr>
<tr>
<td>2</td>
<td>0.0717</td>
<td>0.805</td>
</tr>
<tr>
<td>3</td>
<td>0.0694</td>
<td>0.777</td>
</tr>
<tr>
<td>4</td>
<td>0.0756</td>
<td>0.850</td>
</tr>
<tr>
<td>5</td>
<td>0.0715</td>
<td>0.802</td>
</tr>
<tr>
<td>6</td>
<td>0.0587</td>
<td>0.651</td>
</tr>
<tr>
<td>7</td>
<td>0.0644</td>
<td>0.718</td>
</tr>
<tr>
<td>8</td>
<td>0.0651</td>
<td>0.726</td>
</tr>
<tr>
<td>9</td>
<td>0.0685</td>
<td>0.767</td>
</tr>
<tr>
<td>10</td>
<td>0.0618</td>
<td>0.688</td>
</tr>
</tbody>
</table>

Measured values of extinctions of formaldehyde tested samples confirmed decreasing of emissions for each additive in comparison with reference sample. The most significant decrease of formaldehyde emission down to 30% was obtained for modification No. 6 – UF resin + 20% technical flour + 2% methylol pre-condensate + 4% hardener.
CONCLUSION
1. Lecithin from soy, collagen and keratin are mostly increasing the viscosity of UF adhesive mixtures in comparison with the reference sample from the value 4400 mPa.s up to 6098 mPa.s. There is necessary lowering of application of technical flour into UF adhesive mixtures.
2. The influence of addition of modified additives on the thickness swelling of prepared plywood was stated and the thickness swelling is improved by mimosa, keratin, quebracho, glutaraldehyde, methylol pre-condensate and lecithin.
3. Plywood fulfills requirements of the standard for class of gluing 1 – they are suitable for interior applications. Highest shear strength (2.8, 2.6 and 2.6) MPa was obtained for samples of glutaraldehyde 50%, native corn starch and methylol derivate prepared in VIPO.
4. Measured values confirmed the decrease of formaldehyde emissions for all additives in comparison with the reference sample. The most significant decrease of formaldehyde emission down to 30% was obtained for modification No. 6 – UF resin with methylol pre-condensate.

REFERENCES
5. ASTM D 6007-02 „Standard test method for determining formaldehyde concentration in air from wood products using a small scale chamber“.

ACKNOWLEDGEMENTS
This work was supported by the Slovak Research and Development Agency under the contracts No. APVV-14-0506, APVV-15-0124, APVV-16-0177.

Streszczenie: Obniżenie emisji formaldehydu z płyt drewnopochodnych poprzez modyfikację klejów polikondensacyjnych naturalnymi wypełniaczkami, dodatkami i aktywatorami. W ramach pracy przeprowadzono modyfikację żywic polikondensacyjnych (mocznikowo-formaldehydowych) z zastosowaniem naturalnych wypełniaczy, dodatków i aktywatorów. Jako modyfikatory wykorzystano m.in. białka (głównie kolagen i keratynę), garbniki, skrobię, aldehyd glutarowy, lecytynę z soi, ekstrakt z liści drzewa oliwnego. Badania wykazały istotny wpływ wprowadzonych modyfikatorów na uzyskane wartości lepkości żywic klejowych. Ponadto wykazano wpływ modyfikacji żywic klejowych na wybrane właściwości sklejek wytworzonych z ich użyciem (tj. spęcznienie, wytrzymałość spoin klejowych, emisja formaldehydu).

Author address:
Prof. Ing. Ján Sedliačik, PhD.
Department of Furniture and Wood Products
Technical University in Zvolen
Masaryka 24
960 53 Zvolen, Slovakia
sedliacik@tuzvo.sk
Study of thermal conductivity of polymer composites

IGOR NOVÁK¹, PETER JURKOVIČ², ONDREJ ŽIGO¹, JOZEF PRACHÁR¹, JÁN MATYAŠOVSKÝ²

¹Polymer Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 845 41 Bratislava 45, Slovakia
²VIPO a.s., Partizánske, Gen. Svobodu 1069/4, 958 01 Partizánske, Slovakia

Abstract: Study of thermal conductivity of polymer composites. Electrically and thermally conductive composites made using high density polyethylene (HDPE) matrix blended with a special grade of branch-structured nickel particles were studied. Composites with high filler content were highly electrically and thermally conductive. The electrical conductivity of composites reached a value of 8.3 x 10³ S m⁻¹ when filled with 30 vol. % of the filler, and the thermal conductivity obtained using this filler content was found to be 1.99 W.m⁻¹ K⁻¹. The percolation concentration of the filler within the HDPE matrix, which was determined from electrical conductivity measurements, was determined to be 8 vol. %.

Keywords: thermal conductivity, electrical conductivity, high density polyethylene

INTRODUCTION

Thermally and electrically conductive materials are designed by blending polymeric matrices with the convenient fillers. A filler with high electrical conductivity often also possesses high thermal conductivity and vice versa. Such fillers include graphite [1, 2], exfoliated graphite and graphene [3, 4], metals [5] and metalized fillers [6]. However, the oxidation of certain metals (e.g., aluminium, copper, iron) causes them to become electrically insulating, although they still maintain high levels of thermal conductivity. Sometimes, this effect can be advantageous; for instance, particularly in electronic devices, high thermal conductivities are required to facilitate heat release, but for safety reasons, it is desirable that electrical conductivities be kept low.

This paper presents results pertaining to the preparation and characterization of electrically and thermally conductive composites, the production of which is based on a high-density polyethylene (HDPE) matrix and nickel powder. The surface and adhesive properties of these composites are also discussed.

EXPERIMENTAL

Materials and preparation of composites

High-density polyethylene (HDPE BP 5740 3VA, British Petrol, UK, melting temperature = 129.3 °C, melting enthalpy = 199 J/g) was used as the matrix, while a special grade of fine nickel particles with the trade name Inco Type 210 (Novamet Ltd. Sins, England) was used as the filler. Composites were prepared by mixing both components in the 50-ml mixing chamber of a Brabender Plasticorder PLE 331 (Germany) at 180 °C for 10 min at a mixing speed of 35 rpm.

Electrical conductivity measurements

The electrical conductivities of composites were determined at room temperature using a two-point method (insulating/semiconductive samples) or a four-point method (conductive samples above the percolation threshold) in a van der Pauw arrangement using a Keithley 237 High-Voltage Source Measurement Unit and a Keithley 2010 Multimeter equipped with a 2000-SCAN 10 Channel Scanner Card. Circular gold electrodes were
deposited on both sides of the measured samples. Each measurement was repeated at least 2–3 times.

**Thermo-physical measurement**

For thermal conductivity measurements, specimens with dimensions of $4 \times 4 \times 0.5$ cm were compressed and moulded at 170 °C for 3 min using a laboratory press (Fontijne 200, The Netherlands).

**Surface properties measurements**

The polarities of composites were characterized simply by measuring the contact angles of re-distilled water droplets placed on the surface of the HDPE/nickel composites. The contact angles were measured using a Surface Energy Evaluation System (SEE) equipped with a CCD camera (Masaryk University, Czech Republic). Six drops of re-distilled water (with a volume of 3 µl) were placed on a cleaned composite surface. At least six contact-angle measurements were obtained and averaged.

**RESULTS AND DISCUSSION**

**Thermal conductivity**

The dependence of the thermal conductivities of composites ($k_c$) upon volume filler content is shown in Fig. 1. A non-linear increase of $k_c$ with increasing filler content was observed in the whole concentration region. This increase is a common behaviour of composites filled with thermally conductive fillers. In describing the thermal conductivity of a heterogeneous material, we must take into account the influence of various parameters, including the geometry and orientation of filler particles in the matrix, the filler concentration and the ratio between the filler’s thermal conductivity and the thermal conductivity of the matrix. Based on these factors, many different models have already been developed, but none of these has general validity. Most previously published models were established for polymers filled with spherical particles and partly for fibres, flakes and irregularly shaped particles. Usually, these models also consider uniform particle-size distribution and even dispergation of the filler within the matrix. The nickel particles used in this work exhibited far more complicated behaviour than that predicted by the simple morphology for which the thermal conductivity models were commonly developed. At the submicron level, the filler is formed by roughly spherical particles; however, these particles link to one another and form branched, chain-like morphologies. For this reason, it is difficult to select any one model that correctly describes the experimental results. The Hashin–Shtrikman model [6] is considered one of the best for estimating the lower bound when no information about particle distribution in the matrix is available. As can be seen in Fig. 1, the Hashin Shtrikman model describes the experimental data only up to 5 vol. %, far below the common predictions for cases where up to 10-12 vol. % fillers are employed. For these higher concentrations, the experimental data are significantly higher than those calculated from the model, indicating that nickel particles cannot be considered as individual particles dispersed within a matrix.
Electrical conductivity

The dependence of the electrical conductivities of HDPE/nickel composites on filler volume content is shown in Fig. 2. Electrically conductive composites composed of an insulating polymeric matrix and electrically conductive filler demonstrate typical sigmoidal behaviour, as shown in Fig. 2. The percolation effect is experimentally observed in the dependence of conductivity versus filler content and manifests itself as a dramatic increase in conductivity (by several orders of magnitude) in a rather narrow filler concentration range within the area of the percolation threshold. In general, the percolation effect is a well-known phenomenon observed in filler-matrix systems as abrupt extreme changes in certain physical properties within rather narrow concentration ranges of heterogeneity. The effect is explained as the formation of conductive paths (through the matrix) in such a way that the conductive particles are in close contact at a filler concentration corresponding to the percolation threshold. The percolation threshold is a mathematical term related to percolation theory, which is the formation of long-range connectivity in random systems. In engineering, percolation is the slow flow of fluids through porous media or current flow through a heterogeneous conductor. However, in mathematics and physics, percolation generally refers to simplified lattice models of random systems and the nature of the connectivity within them. An important task is to find the so-called percolation threshold, that is, the critical value of the occupation probability such that infinite connectivity (percolation) first occurs. For the composites investigated in this study, the conductive network begins to develop at a filler content of 3.5 vol. %, and the network is developed at 14.6 vol. %. The percolation threshold was arbitrarily determined as 8 vol. %.
Figure 2. Electrical conductivities of the HDPE/nickel composites

**Surface properties**

The dependence of the contact angle on the volume filler content is shown in Fig. 3. The presence of nickel in the HDPE matrix leads to a decrease in contact angles, indicating that the hydrophilicity of the surface increases. The contact angle of water on the neat HDPE (93°) decreases to 80° as the nickel is increased by filling with 60 wt.% of the filler (13 vol. %). The next incremental increase in filler content causes no further change in the contact angle. This behaviour corresponds to the development of a filler network, as discussed above. When this filler network has developed, further increases in the filler content do not lead to further changes in either the electrical conductivity or the contact angle.

CONCLUSIONS

A new type of electrically and thermally conductive composites based on an HDPE matrix and nickel particles was prepared and investigated. The percolation concentration of
the filler within the HDPE matrix, as determined from electrical conductivity measurements, was found to be 8 vol. %. Composites with high filler content were highly electrically and thermally conductive; the electrical conductivity of composites reached $8.3 \times 10^3$ S.m$^{-1}$ when the composite was filled with 30 vol. % of the filler. In this case, the thermal conductivity of the composite was found to be four times higher than the thermal conductivity of neat matrix. The presence of nickel in the HDPE matrix leads to a decrease in the contact angles, indicating that the hydrophilicity of the surface increases. The contact angle of water on neat HDPE (93°) decreased to 80° as the nickel was increased via filling with 60 wt.% of the filler (13 vol.%). Further increases in the filler content did not lead to further changes in the contact angle.

REFERENCES

ACKNOWLEDGEMENTS
This contribution was supported by Ministry of Education of Slovak Republic and Slovak Academy of Sciences, project VEGA, No. 2/0199/14 and project APVV-15-0124.

Streszczenie: Badanie przewodnictwa cieplnego kompozytów polimerowych. Badano kompozyty elektrotechniczne i termoprzewodzące wykonane na bazie matrycy z polietylenu o wysokiej gęstości (HDPE) napełnionej cząstek niklu. Kompozyty o wysokiej zawartości napełniacza charakteryzowały się wysoką elektro- i termoprzewodnością. Przy napełnieniu 30% przewodność elektryczna kompozytów osiągnęła wartość $8.3 \times 10^3$ Sm$^{-1}$, zaś przewodność cieplna wyniosła 1,99 Wm$^{-1}$K$^{-1}$. Stężenie perkolacji napełniacza w matrycy HDPE, określonej na podstawie pomiarów przewodnictwa elektrycznego, wynosiło 8 %.

Author address:
Ing. Igor Novák, PhD.
Dúbravská cesta 9
845 41 Bratislava, Slovakia
email: igor.novak@savba.sk
Metallocene polyolefins grafting designed for hot-melt adhesive compositions

IGOR NOVÁK¹, JURAJ PAVLINEC¹, IVAN CHODÁK¹, JOZEF PREŤO², VLADIMÍR VANKO²

¹Polymer Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 84541 Bratislava, Slovakia
²VIPO a.s., Gen. Svobodu1069/4, 958 01 Partizánske, Slovakia

Abstract: Metallocene polyolefins grafting designed for hot-melt adhesive compositions. The hot melt adhesives based on metallocene polyolefin are frequently used for various applications, e.g. for bindings of books. The grafting of the polar functional groups to the selected metallocene polyolefin has been investigated. The amount of grafted RXP polymer and the efficacy of grafting increase with increasing of the AA concentration in the feedstock.

Keywords: metallocene polyolefin, hot-melt adhesive, bonding of book,

INTRODUCTION

The hot melt adhesives based on metallocene polyolefin are frequently used for various applications, e.g. for bindings of books. For this aim the investigation of relations between the adhesive structure and ultimate properties of metallocene polymer is necessary. The basic experiments consist in development of the material composition from commercially available components, and the targeted modifications of basic components are performed aimed to enhance certain parameters of the adhesive. The metallocene polyolefin-based adhesive development has been modified to increase its polarity and adhesive properties by more polar polymers grafting.

The polyolefin plastomer (POP) RESINEX PE, RXP 1502 (RXP) is metallocene copolymer of ethylene with an unknown amount of octene. Octene incorporation into the polyethylene chain as compared to the PE homopolymer results in a reduction in the melting point of the polymer to 70 °C. The polymer is partially soluble in toluene at RT, which also points to reduced crystallinity. This fact significantly affects access to the modification POP by radical polymerization using acrylic acid (AA). This concerns in particular the selection of a suitable process for initiating growth of the PAA chains bound to macromolecules RXP (RXP-g-AA), also in the vaccination of a surface of the granules, powder or grafting the entire volume.

To prepare a hydrophilic polymer on the surface of the PP fibers used Buchenska the transfer reactions of the polymerizing the monomer during grafting. This is time-consuming and inefficient process due to the large amount of unbound homopolymer. Moreover, the macromolecules RXP contain no tertiary H and are less reactive in the transfer reactions, assuming lower efficacy of grafting.

Efficient way of grafting used to initiate of modification peroxides and hydroperoxides molecules accumulated on polyolefin after activation controlled by thermal oxidation. The initiation to form peroxide and hydroperoxide the high temperature is used (for PE, PP temperature of 90 °C), or oxidation initiated by peroxides (BPx, DKPx, etc.) as well as various types of radiation. Such approach to grafting of polymers is mainly used for surface modification of foils and fibers.
In this contribution the grafting of the polar functional groups to the selected metallocene polyolefins has been investigated. As grafting agents the acrylic acid (AA) has been used.

RESULTS AND DISCUSSION

RXP activated by ozone and used in suspension for grafting in AA water solution is illustrated in Figure 1. When the activated RXP powder is suspended in an aqueous AA solution, grafting in heterogeneous system can have the advantage of limited production of the homopolymer. Active centers on the macromolecules are initiated primarily grafting. AA monomer in fact gradually diffuses into the surface layers of polymer particles RXP, while homopolymerization in solution AA is limited. Sufficient affinity for the monomer of the polymer provides the right to a surfactant. The result: grafting has taken place. The polymer does contain peroxide groups in sufficient concentration, but the appreciable disintegration occurs up to about 110 °C. Temperature of 60 °C used in the experiments is too low to generate free radicals to initiate grafting.

In Table 1 the conditions of RXP grafting along with the determination of PAA concentration of samples 4, 5 and 6 are summarized. The amount of grafted RXP polymer and the efficacy of grafting increase with increasing of the AA concentration in the feedstock. Efficacy is relatively low and reaches the value 0.25-0.5. The presence of PAA in grafted RXP-g-AA was measured by FTIR analysis. (Figure 2) FTIR spectra were measured on a Nicolet 8700TM. For samples 4, 5 and 6, other than a valence bands pertaining CH deformation vibration (region of 2800-3000 cm⁻¹), typical of PE appeared bands of the CO and COC bonds (1715 and 1170 cm⁻¹) to suggests the presence of PAA chains. Figure 2 shows the FTIR spectra of the prepared graft polymers and a variety of polyacrylic acid PAA. The values of the FTIR absorbance for acid carbonyl compounds at about 1715 cm⁻¹ and the reference band at 1464 cm⁻¹ show the proliferation of PAA graft quantity depending on the amount of AA in the feedstock.

![Figure 1. RXP activated by ozone and in suspension grafted by AA water solution](image-url)
Table 1. Grafting of RESINEX PE RXP 1502: oxygen plasma, 3 hours, source power 300W, gas flow 5 l/min

<table>
<thead>
<tr>
<th>Preparation in toluene (150 ml)</th>
<th>sample 4</th>
<th>sample 5</th>
<th>sample 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>activated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RXP [g]</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>AA [ml]</td>
<td>16</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>grafted PAA [% in sample]</td>
<td>33.6</td>
<td>15.6</td>
<td>8.6</td>
</tr>
<tr>
<td>Grafting Efficacy</td>
<td>0.49</td>
<td>0.32</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 2. FTIR spectra, samples: 4 – red, 5 - violet, 6 - cyclamin, PAA – blue.

CONCLUSION

The activated RXP powder suspended in an aqueous AA solution cannot be grafted due to, very low temperature 60 °C, that is too low to generate free radicals to initiate grafting. The amount of grafted RXP polymer and the efficacy of grafting increase with increasing of the AA concentration in the feedstock. Efficacy was relatively low and reached the value 0.25 - 0.5. FTIR absorbance for acid carbonyl compounds at about 1715 cm\(^{-1}\) and the reference band at 1464 cm\(^{-1}\) show the proliferation of PAA graft quantity depending on the amount of AA in the feedstock.

REFERENCES

2. YALVAC S., KARJALA T., O´BRYAN E., 2005: Adhes & Seal Ind.12, 34.
ACKNOWLEDGEMENT
The authors are grateful for financial support to the Slovak Research and Development Agency project No. APPV-14-0566.

Streszczenie: Poliolefiny metalocenowe jako kleje topliwe. Kleje topliwe oparte na poliolefinach metalocenowych są często stosowane w różnych aplikacjach, m.in. do klejenia książek. W artykule zbadano wpływ implantacji polarnych grup funkcjonalnych do wybranych poliolefin metalocenowych. Ilość implantowanego polimeru RXP oraz wydajność implantacji rośnie wraz ze wzrostem koncentracji kwasu akrylowego w surowcu.

Author address:
Ing. Igor Novák, PhD.
Dúbravská cesta 9
845 41 Bratislava, Slovakia
email: igor.novak@savba.sk
Antibacterial modification of polymeric veneers by atmospheric discharge plasma

IGOR NOVÁK¹, IVAN CHODÁK¹, JÁN SEDLIAČIK², ONDREJ ŽIGO¹
JÁN MATYAŠOVSKÝ³, PETER JURKOVIČ³

¹Polymer Institute, Slovak Academy of Sciences, 845 41 Bratislava, Slovakia
²Faculty of Wood Sciences and Technology, Technical University in Zvolen, 960 53 Zvolen, Slovakia
³VIPO a.s., Gen. Svobodu1069/4, 958 01 Partizánske, Slovakia

Abstract: Antibacterial modification of polymeric veneers by atmospheric discharge plasma. Polyvinylchloride (PVC) veneers are widely used in many applications for modern furniture production. The research was aimed on examining the impact of antibacterial agents as triclosan and chlorhexidine bound to the surface of PVC.

Key words: antibacterial modification, polymeric veneer, plasma, veneered furniture

INTRODUCTION
Polyvinylchloride (PVC) veneers are widely used in many applications for modern furniture production¹, but infections resulting from application of this polymer represent the main clinical complication². Low-temperature plasma can be suggested as the appropriate procedure for the hydrophilization of the polymeric surface. Due to the plasma treatment the surface free energy of the polymer is increased as a result of introduction of polar functional groups on the treated surface, thus making the surface of PVC more hydrophilic³. Antibacterial surface modification has several advantages, because it does not influence the bulk properties of the polymer, antibacterial agents are not released from the polymer volume, and the technique is relative simple and effective⁴. In the first step, formation of functional groups on the polymer surface is necessary via the plasma species and in the second step end-functionalized polymer brushes are formed on polymer surface via radical graft polymerization of acrylic acid (AA), that is anchored on the plasma treated polymeric surface. Finally biomolecules are immobilized on plasma pre-treated polymeric surface and carboxyl groups of AA are activated and they are ready to provide the immobilization sites⁵.

RESULTS AND DISCUSSION
The PVC veneer was first cleaned with dichloromethane to remove impurities. Then the PVC veneer activation was carried out under dynamic conditions at atmospheric pressure and room temperature with the DCSBD equipment developed at Comenius University (Department of Experimental Physics, Faculty of Mathematics, Physics and Informatics) in Bratislava. Immediately after plasma treatment the PVC veneer was immersed into 10 vol. % aqueous solution of AA for 24 h at 30 °C in order to initiate of radical graft polymerization of AA onto activated surface of PVC veneer. This solution contained also 0.1 wt. % sodium meta-bisulfite as a relevant reductant to inhibit AA homopolymerization. The PVC sample pre-prepared by such way was then immersed into solution of triclosan and/or chlorhexidine. The first solution was prepared as 2 w/v % solution of triclosan in absolute ethanol and the latter as 2 w/v% solution of chlorhexidine in 70 v/v. % isopropanol aqueous solution for 24 h at 30 °C in an oven. The antibacterial treated samples were thoroughly washed and then dried for 24 h at room temperature to constant weight.
CONCLUSION
This contribution was aimed at examining the impact of selected antibacterial agents, namely triclosan and chlorhexidine bound to the surface of PVC. DCSBD plasma treatment led to increased wettability and surface free energy by introducing characteristic oxygen groups. A DCSBD plasma generator was used as activator of the PVC surface for efficient binding of acrylic acid and for its transformation to polymeric form by radical polymerization. Thus the bound acrylic acid created polymer brushes on the polymer surface that provided physical forces to bind antibacterial agents in an effective manner. The presence of triclosan and chlorhexidine was confirmed by different surface analysis techniques. Moreover the antibacterial effect of such treated PVC was proven by in vitro bacterial tests against E. coli and S. aureus when adhesion of bacteria to polymer was effective diminished.

REFERENCES

ACKNOWLEDGEMENTS
The authors are grateful for financial support to the Slovak Research and Development Agency project No. APPV-14-0566, APPV-14-0506, APPV-16-177.

Streszczenie: Antybakteryjna modyfikacja fornirów polimerowych poprzez atmosferyczne wyładowanie plazmowe. Forniry polichlorowinylowe są szeroko wykorzystywane w wielu zastosowaniach do produkcji nowoczesnych mebli. Celem badań było określenie wpływu czynników antybakteryjnych, takich jak triclosan i chlorheksydyna, osadzonych na powierzchni PVC.

Author address:
Ing. Igor Novák, PhD.
Dúbravská cesta 9
845 41 Bratislava, Slovakia
email: igor.novak@savba.sk
A study on properties of wood dust created during windows manufacturing

TOMASZ ROGOZIŃSKI¹, CZESŁAW DEMBIŃSKI¹, ALENA OČKAJOVÁ², ZBIGNIEW POTOK¹

¹Department of Furniture Design, Poznań University of Life Sciences, Poznań, Poland
²Department of Technology, Faculty of Natural Sciences, Matej Bel University Banska Bystrica

Abstract: A study on wood waste properties and its creation during windows manufacturing. The paper presents the results of research on the properties of waste chips generated in the manufacturing of windows. It has been found that the properties of pinewood waste are different depending on the type of technological operation. On the other hand, the same technological operations for other than pine wood species (oak, meranti) are the source of finer chips with higher bulk density.

Keywords: woodworking, CNC, wood dust

INTRODUCTION

Mechanical woodworking processes are connected with creation of large amount of waste in the form of small particles. They can be called chips, shavings, sawdust or dust depending on the size of particles, the working operation type and parameters. In the manufacturing of wood products more and more universal CNC machines are used which can perform various technological operations with the use of different tools in a wide range of machining parameters. As a result, the waste created during these operations is often characterized by considerable dimensional variability (Dolny and Adamiczyk 2002). This hinders the efficient operation of extraction systems. This operation is anyway often ineffective due to the size of the waste zone, the variability of the direction of the tool movement and the penetration of the tool in the material, especially in the drilling or pocket milling (Palubicki and Rogozinski 2016, Trofimov 2010, Varga et al. 2006). The use of solid wood in the manufacturing of windows is advantageous from the viewpoint of dust control. The processing of wood composites more fine waste particles are produced. But even so, it can be expected that even under these conditions, especially where high cutting speeds and small chip thickness are used, fine dust particles can be also created. They are a real source of air pollution in woodworking plants. The finest wood dust particles due to their size may not be sufficiently removed from the working station causing the remaining in the air of the inhalable and respirable fractions of dust (Rautio et al. 2007, Rogozinski et al. 2015).

The aim of the study was to demonstrate the variability of the basic properties of pine wood waste generated in the production of windows and to compare the characteristic of chips from working of different wood species during the same technological operation. Particular emphasis was placed on the dimensional variability of generated waste particles.

MATERIALS AND METHODS

Samples of waste generated during milling holes and longitudinal milling of pine sticks on the CNC machine ACCORD 25FX (SCM, Italy) were taken to determine the properties of pinewood chips. Then the profile and tenons are made in the elements of windows frames using another CNC machine type UNICONTROL 10 (Weinig, Germany). The next of samples was taken from this technological station. In order to demonstrate the variability of the properties of the waste created on this machine, depending on the species of wood used in the production of the windows, the waste chips from the longitudinal milling of
the oak and meranti wood has also been sampled. Woodworking parameters including in the tests are summarized in table 1.

Table 1. Woodworking data

<table>
<thead>
<tr>
<th>Machine</th>
<th>Operation</th>
<th>Tool</th>
<th>Tool geometry</th>
<th>Feed speed [m/min]</th>
<th>Rotation speed [min(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCORD 25</td>
<td>milling of lock hole</td>
<td>shank cutter</td>
<td>D=20 mm</td>
<td>3</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>milling of rebate</td>
<td>cutter head</td>
<td>D=129 mm</td>
<td>3</td>
<td>9000</td>
</tr>
<tr>
<td>UNICONTROL 10</td>
<td>tenoning</td>
<td>a set of cutter heads</td>
<td>D=340 mm h=60 mm d=30</td>
<td>5.5</td>
<td>4000</td>
</tr>
<tr>
<td></td>
<td>profile milling</td>
<td>a set of cutter heads</td>
<td>D=205 mm h=92/50 mm</td>
<td>6.5</td>
<td>5500</td>
</tr>
</tbody>
</table>

Determination of bulk density and tapped bulk density of wood shavings were done according to the Polish standard PN-74/Z-0400.02. In the purpose of determination of angle of repose the method described in the standard PN-74/Z-0400.07 was used.

Particle-size distribution of shavings created during windows manufacturing was performed by sieving method according to the standard PN-ISO 2591-1:2000. In the purpose of sieve analysis a sieving machine RETSCH 200AS Digit was used. It was equipped with a set of sieves with mesh sizes 4000, 2000, 1000, 500, 250, 125 and 63 µm. Sieving analysis is a method frequently used for determination of particle size analysis of wood chips (Rogoziński and Očkajová 2013, Očkajová et al. 2008, Očkajová et al. 2010).

RESULTS

The results of bulk densities and angle of repose of shavings created during woodworking operations performed at windows manufacturing are shown in table 2. The lower bulk density characterizes the waste from longitudinal milling (rebate milling and profile milling). During these operations large shavings are produced, however milling of stiles made of meranti and especially oak wood is a source of finer shavings (Fig. 1-6) than created during milling of pine wood. Operations of tenoning and milling of lock hole are connected with cutting of wood perpendicular to the fibres. These way of woodworking is performed at small chip thickness, high cutting speed and low feed speed. These are the parameters making it easier to produce finer chips.
Table 2. Basic properties of shavings created during windows manufacturing

<table>
<thead>
<tr>
<th>Machine</th>
<th>Operation</th>
<th>Wood</th>
<th>Bulk density kg/m³</th>
<th>Tapped bulk density kg/m³</th>
<th>Angle of repose</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCORD 25</td>
<td>milling of lock hole</td>
<td>pine</td>
<td>103.0</td>
<td>137.4</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td>milling of rebate</td>
<td>pine</td>
<td>53.3</td>
<td>66.6</td>
<td>33.3</td>
</tr>
<tr>
<td>UNICONTROL 10</td>
<td>tenoning</td>
<td>pine</td>
<td>144.0</td>
<td>185.7</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td>profile milling</td>
<td>pine</td>
<td>18.7</td>
<td>19.4</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>profile milling</td>
<td>oak</td>
<td>44.7</td>
<td>55.2</td>
<td>33.7</td>
</tr>
<tr>
<td></td>
<td>profile milling</td>
<td>meranti</td>
<td>42.7</td>
<td>47.5</td>
<td>37.7</td>
</tr>
</tbody>
</table>

Figure 1. Particle size distribution of pine wood shavings from milling of lock hole

Figure 2. Particle size distribution of pine wood shavings from milling of rebate

Figure 3. Particle size distribution of pine wood shavings from tenoning

Figure 4. Particle size distribution of pine wood shavings from profile milling
It is confirmed by the results of particle size analysis presented on fig. 1 and 3 which show the particle size distribution of shavings created during milling lock holes and tenoning. Shavings created during these operations contain more fine particles than shavings from milling of rebate and other profiles in window stiles. A large amount of dimensionally different waste is produced in the process of windows manufacturing. In addition to fine dust particles, which are always difficult to remove from the working space, large shavings are produced. The large chips due to their mass are often not removed by an exhaust system.

The shavings remains in working area could pose a risk to occupational health by covering the area where workers move and by causing the secondary air contamination (fig. 7). These remains also hinder the operation of machines and often cause the reduction of their productivity and quality of wood machining.
CONCLUSIONS

- Shavings created during windows manufacturing differ in terms of their characteristic and size.
- Longitudinal milling of profiles and rebates is a source of larger shavings than other operation such as milling of lock hole or tenoning.
- Large shaving are not completely removed by exhaust systems from workstations. This results in necessary to look for solutions to increase the efficiency of wood chips exhaust systems. This will improve the working conditions of wood machining and its productivity.

REFERENCES

1. OČKAJOVÁ A., BELJAKOVÁ A., LUPTÁKOVÁ J., 2008: Selected properties of spruce dust generated from sanding operations, Drvna Industrija 59(1); 3–10.
2. OČKAJOVÁ A., BELJAKOVÁ A., SIKLIENKA M., 2010: Morphology of dust particles from the sanding process of the chosen tree species, Wood Research 55(2); 89–98.

ACKNOWLEDGEMENT

This work was also developed within the grant project KEGA MŠVVaŠ SR č. 009 TU Z-4/2017

Streszczenie: Badania właściwości odpadów powstałych przy produkcji okien. W pracy przedstawiono wyniki badań właściwości odpadów powstałych przy produkcji okien. Stwierdzono, że odpady z obróbki drewna sosnowego różnią się w zależności od rodzaju operacji technologicznej. Natomiast te same operacje technologiczne dla innych gatunków drewna (dąb, meranti) są źródłem wiórów drobniejszych o większej gęstości nasypowej.

Author address:

Tomasz Rogoziński,
Department of Furniture Design, Faculty of Wood Technology, Poznan University of Life Sciences,
Wojska Polskiego str.28
60-627, Poznan, Poland
email: trogoz@up.poznan.pl
phone: +48618487483
Dust creation during birch plywood production

TOMASZ ROGOZIŃSKI¹, SERGEI TROFIMOV²

¹ Department of Furniture Design – Poznań University of Life Sciences, Poznań, Poland
² Department of Technology and Design of Wood Products – The Belarusian State Technological University, Minsk, Belarus

Abstract: Dust creation during birch plywood production. The article describes the results of particle size distribution of dust created during plywood production. The plywood production was based on birch wood from Belarusian resources. The particle-size distribution of dust sampled on plywood producing line was determined by two methods. The sieve analysis was used for determination of general particle-size distribution. Then the fraction of the smallest dust particles was analyzed by the laser diffraction method. This procedure allowed the evaluation of the content of very fine particles which, when dispersed in the air, could be the inhalable and respirable fraction.

Keywords: plywood, birch wood, wood dust, particle-size analysis, inhalable fraction.

INTRODUCTION

Mechanical woodworking processes are connected with creation of large amount of waste in the form of small particles. They can be called chips, shavings, sawdust or dust depending on the size of particles, the working operation type and parameters. Wood waste particles created in the same operation are always of different sizes. So, the whole mass of particles created in certain operation is polydisperse and can contain some amount of very fine particles which can be dispersed in the air. These particles pose a health risk to workers employed in wood processing industry. The main health hazard concerns the human respiratory tract. The most dangerous diseases which can be observed in woodworkers population are cancers of the nose and sinuses (Beljo-Lučić et al. 2011, Baran and Teul 2007). Wood dust creation and air pollution with wood dust in furniture and joinery industry are well-described and particular data on this topic is widely available in the literature. This data characterizes the condition of the evaluation of the risk level, dustiness control and technological means leading towards reducing the formation of dust (Čavlović et al. 2013, Chung et al.2000, Hampl et al. 1990).

Apart from these branches of woodworking there is the large industry of wood composites production. The problem of dust creation and health risk connected with the air pollution with wood dust should be considered. There are few reports on the level of dust pollution and its effect on occupational hygiene in wood composites industry (Rogozinski et al. 2015, Rautio et al. 2007). But there are no works on the detailed description of sources and properties of the dust created in this industry. Data on dust properties are necessary for the design of processes and devices used in dust exhaust and separation.

The aim of this paper was to characterize the particle size distribution of wood dust created during plywood production. The dust was created during calibration of preformed in sanding technology. The external layers of plywood were made of birch wood veneers.

MATERIALS AND METHODS

Wood dust used in the tests was taken from separation devices installed in the plywood production line operating in the enterprise “PinskiKrev-Plywood”. The industrial plant is located in the city of Pinsk in the southern part of the Republic of Belarus.
Plywood calibration is performed by sanding method using a sandpaper with the grit sizes P60 and P80. In this purpose a sanding machine type OSUS NOVA 160/4 K / FC-MCg (Steinemann, Switzerland) is used. The machine is equipped with 4 sanding heads which operate with sanding belt with the size 1600×2800 mm.

Sampling of dust was done during the operation of the sanding machine and separation devices. It is possible due to the automatic system of dust transport from filtering device to the dust hopper during the working time of plywood production. There were taken 3 samples of dust weighting about 0.5 kg each.

Particle size analysis was done by using two methods: sieving analysis and laser diffraction analysis. The stage step particle-size analysis was performed by the method of sieving. For this purpose the set of sieves with sizes of mesh 4 mm, 2 mm, 1 mm, 0.5 mm, 0.250 mm, 0.125 mm, 0.063 mm and bottom was used. The sieves were arranged top-down in direction of meshes’ lessening and placed on a vibrating holder of a sieving machine AS 200c (Retsch, Germany) with an adjustable frequency and amplitude of oscillation. The particle size-distribution was determined by weighting of the dust remaining on each sieve after sieving on the electronic laboratory scales WPS 510/C/2 (Radwag, Poland). The sieving analysis was done three times. The average of their results was accepted as the final result of the sieving analysis procedure.

Then the dust collected in the bottom of the set of sieves was taken for laser diffraction analysis for the purpose of determining mass concentration of fine particles in the dust created during plywood production. A laser particle sizer Analysette 22 Microtec Plus (Fritsch, Germany) with measuring range 0,08 - 2000 μm was used in this stage of experiments. Particle sizes up to 100 μm were taken into consideration in the analysis. The mass fractions of these particles were calculated by MaScontrol software on the basis of particle-size distribution obtained as a result of the particle-size measurement. Then the fractions of fine dust in the whole mass of dust created in plywood sanding were calculated.

The calculation of dust fractions in the ranges 0.1 to 4 μm, 4 to 10 μm, and then next ranges with the limit of the every next 10 μm was done as follows:

$$C_i = C_{s64} \times C_{Li}$$

where:

- $C_i$ – dust fraction in the assumed size ranges of the whole mass of dust created,
- $C_{s64}$ – dust fraction collected during the sieve analysis in the bottom collector,
- $C_{Li}$ - mass fractions of the dust in the assumed ranges determined using laser diffraction analysis in the $C_{s64}$ fraction.

The methods of particle-size analysis were already used for wood dust and particularly described by Rogoziński et al. 2014.

RESULTS

Figure 1 presents the particle-size distribution of birch dust created during plywood production obtained by sieving method. The dust is rather coarse compared with dust created during sanding performed in furniture production (Očkajová et al. 2010, Očkajová et al., 2014). The fraction of the most numerous particles (46.43%) contains in the range 0.250 – 0.500 mm. The finest particles, <0.063 mm, is only 4.12% but the large amount dust created in industrial plywood sanding causes a serious risk to human health due to possible content of very fine particles which can be respirable when dispersed in air.

The dust fraction with size <0.063 mm collected in the bottom of the set of sieves was tested using the laser particle sizer. The result of this test is given on the graph presented in Fig. 2. This result confirms the earlier observations of the fibrous character of wood dust particles. Such dimensional properties of wood dust particles are the reason of an inaccuracy
of methods used in particle-size determination. So, the simultaneous application of several methods are often required for precise determination of particle-size distribution of wood dust.

Figure 1. Particle size distribution of birch wood dust by sieving analysis

Beside the fibrous shape of particles their large dimensional range is also a problem in size measuring (Rogoziński and Očkajová, 2013).

The results of determination of particle-size distribution of dust collected in the bottom of the set of sieves is presented in the Table 1 assuming the size ranges taken into consideration in this analysis. Mass fractions of the dust particles in the assumed ranges of the whole dust were calculated on the base of these results and the result of sieving analysis.

The results of the dust fractions calculation showed that the dust created during plywood sanding in the production process contains very small particles. Despite the relatively small percentages of these particles they pose the risk of serious contamination of the air due to considerable whole mass of dust created. The fraction of particles with sizes less than 10 µm is only about 0.5% but it can pose a serious problem when dust particles are dispersed in the air. The sanding machine works daily in three shifts with a stop only for the lunch break (20 minutes).

It can be assumed that the sanding performed with the paper with smaller grit sizes can be a source of more amount of very fine particles. However, Očkajová et al. (2008) have stated that the share of particles with the size smaller than 100 µm created during sanding of spruce wood is 56 – 75% depending on the sanding direction. But the finest particles were about 1.7 µm in diameter. The determination of the finest particle were done by analysis of
pictures observed by a microscope. The results of particle-size analysis of dust created in plywood production can be the base of the statement that laser particle analysis can determine submicroscopic particles with size < 1 µm, which are hard to detection by optical microscope.

Table 1. Mass fractions of the dust in the assumed ranges determined using laser diffraction analysis in the $C_{64}$ fraction and the whole mass of dust created

<table>
<thead>
<tr>
<th>Lower limit [µm]</th>
<th>Upper limit [µm]</th>
<th>Discrete distribution in the $C_{64}$ fraction $dQ_3(x)$ [%]</th>
<th>Cumulative distribution in the $C_{64}$ fraction $Q_3(x)$ [%]</th>
<th>Fractions in the whole mass of dust [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.003962</td>
</tr>
<tr>
<td>0.10</td>
<td>4.00</td>
<td>2.33</td>
<td>2.42</td>
<td>0.095826</td>
</tr>
<tr>
<td>4.00</td>
<td>10.00</td>
<td>9.12</td>
<td>11.54</td>
<td>0.375709</td>
</tr>
<tr>
<td>10.00</td>
<td>20.00</td>
<td>21.24</td>
<td>32.79</td>
<td>0.875267</td>
</tr>
<tr>
<td>20.00</td>
<td>30.00</td>
<td>18.75</td>
<td>51.53</td>
<td>0.772329</td>
</tr>
<tr>
<td>30.00</td>
<td>40.00</td>
<td>14.64</td>
<td>66.17</td>
<td>0.603201</td>
</tr>
<tr>
<td>40.00</td>
<td>50.00</td>
<td>10.72</td>
<td>76.89</td>
<td>0.441657</td>
</tr>
<tr>
<td>50.00</td>
<td>60.00</td>
<td>7.62</td>
<td>84.51</td>
<td>0.313842</td>
</tr>
<tr>
<td>60.00</td>
<td>70.00</td>
<td>5.38</td>
<td>89.88</td>
<td>0.221457</td>
</tr>
<tr>
<td>70.00</td>
<td>80.00</td>
<td>3.60</td>
<td>93.49</td>
<td>0.148421</td>
</tr>
<tr>
<td>80.00</td>
<td>90.00</td>
<td>2.47</td>
<td>95.96</td>
<td>0.101805</td>
</tr>
<tr>
<td>90.00</td>
<td>100.00</td>
<td>1.61</td>
<td>97.57</td>
<td>0.066357</td>
</tr>
<tr>
<td>100.00</td>
<td>1 000.00</td>
<td>2.42</td>
<td>99.99</td>
<td>0.099822</td>
</tr>
</tbody>
</table>

CONCLUSION
- Dust created during birch plywood production is relatively coarse compared to results of experimental sanding of other dust species.
- Very fine particles were detected in the dust. Their presence may be a reason of air pollution and health risk. These particles can be the inhalable and respirable fractions of dust when dispersed in air.

REFERENCES


Author address:
Tomasz Rogoziński,
Department of Furniture Design, Faculty of Wood Technology, Poznan University of Life Sciences, Wojska Polskiego str.28
60-627, Poznan, Poland
email: trogoz@up.poznan.pl
phone: +48618487483
Interaction between wood density and speed of sound in spruce structural timber

ALENA ROHANOVÁ, ONDREJ BAJZA

Faculty of Wood Sciences and Technology, Technical University in Zvolen

Abstract: Interaction Between Wood Density and Speed of Sound in Spruce Structural Timber. Density of wood and speed of sound propagation are significant parameters used to detect quality of construction timber. Density of wood can be detected on small samples ($\rho_{\text{small}}$ according to EN 408) or on whole board ($\rho_{\text{board}}$ – for measuring by MTG Timber Grader). Speed of sound propagation could be measured on board Sylvatest DUO ($c_{\text{ultr}}$) or MTG Timber Grader ($c_{\text{vibr}}$) in situ.

Spruce boards (Picea abies Karst. L.) were used in the experiment. Sampling was carried out randomly (location Slovakia – 2 samplings). Density of wood ($\rho_{\text{small}}, \rho_{\text{board}}$) and speed of sound ($c_{\text{ultr}}, c_{\text{vibr}}$) was measured using all of the boards. Results show that density of wood $\rho_{\text{board}}$ is 12% higher than $\rho_{\text{small}}$, and speed of sound is 13% higher than $c_{\text{vibr}}$. Dependencies of $\rho_{\text{small}}, \rho_{\text{board}}$ ~ $c_{\text{ultr}}, c_{\text{vibr}}$ show more significant results on both devices. Results describe the interaction of monitored parameters more reliably by in situ devices application.

Keywords: spruce wood, board, small specimen, density wood, speed of sound, MTG Timber Grader, Sylvatest DUO

INTRODUCTION

Wood is an important strategic raw material with wide spectrum of use. It plays a dominant role in wooden constructions and interior elements with specific requirements on wood quality. The most important quality parameters of wood are strength, elasticity and density (POŽGAJ et al. 1997). For identification of key properties are used also acoustics characteristics as speed of sound propagation in wood.

Density of wood can be identified from the mass and volume of sample. From small ideal samples we can get the most relevant results (WEIDENHILLER and DENZLER 2009). What more it can be tested also on samples with construction dimensions with natural appearance of defects e.g. knots in situ. Results could be used in application with MTG Timber Grader device. We can assume that values of small samples density and real size board density could be different (ROHANOVÁ et al. 2010). Fig. 1 show board with small samples selections.

![Fig. 1 Samples for testing of wood density (small specimens, board)](image)

Speed of sound propagation “c” could be detected by various device. Sylvatest DUO device works on ultrasonic principle (DIVÓS and TANAKA 2005), MTG Timber Grades works with natural frequency. Various values of speed of sound propagation has been measured during testing of same board by different device (ROHANOVÁ 2013).
MATERIAL AND METHODS

Samples used for the experimental testing were of structural dimensions (herein after timber) prepared from spruce wood (*Picea abies*, L. Karst.). Testing of structural timber: 40 ×180 - 2310 mm – 102 pcs.

**Wood density** of structural timber was determined by two methods (Fig. 1):
- small clear specimens ($\phi \rho_{\text{small}} - \rho_1, \rho_2$),
- sawn timber ($\rho_{\text{board}}$).

**Speed of sound** was measured using all of the boards devices (Fig. 2):
- Sylvatest DUO ($c_{\text{ultr}}$).
- Timber Grader MTG ($c_{\text{vibr}}$).
Measured values of $\rho_{\text{small}}$, $\rho_{\text{board}}$, $c_{\text{ultr}}$ and $c_{\text{vibr}}$ were corrected to $w = 12\%$.

RESEARCH OBJECTIVE

Values of wood density and speed of sound propagation has been tested by various method and compare and by mathematical-statistical methods (Table 1).

Table 1 Basic mathematic-statistical characteristics of wood density at $w = 12\%$ ($\rho_{\text{small}}, \rho_{\text{board}}$) and sound of speed ($c_{\text{vibr}}, c_{\text{ultras}}$)

| Statistical characteristics | | | | | |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| Parameters                  | Wood density (kg.m$^{-3}$) | Sound of speed (m.s$^{-1}$) |
| n                           | $\rho_{\text{small}}$ | $\rho_{\text{board}}$ | $c_{\text{vib}}$ | $c_{\text{ultras}}$ |
| $\bar{x}$                   | 423              | 432              | 5429             | 5874             |
| $x_{\text{max}}$            | 529              | 528              | 6147             | 6443             |
| $x_{\text{min}}$            | 343              | 360              | 4046             | 5040             |
| V %                         | 8.4              | 7.7              | 7.1              | 5.1              |

Distribution of wood density $\rho_{\text{small}}$ and $\rho_{\text{board}}$ are presented in Fig. 3 and Fig. 4.
The normality of distribution of measured prediction model parameters was evaluated by three independent statistical tests (Kolmogorov–Smirnov, Lilliefors and Shapiro-Wilk). Neither of tests denied null hypothesis about normal distribution of wood density (Fig. 3, Fig. 4).

Analyze of wood density $\rho_{\text{small}} - \rho_{\text{board}}$ (Fig. 5) - high coefficient of determination ($r^2 = 0.75$)
- by standard densities (350–460 kg.m$^{-3}$) $\rho_{\text{small}}$ underestimates $\rho_{\text{board}}$, predictive error decreases linearly from 6% do 0%,
- by low densities of wood (less than 350 kg.m$^{-3}$) – values $\rho_{\text{board}}$ are 6% (21.3 kg.m$^{-3}$) higher than $\rho_{\text{small}},$
- by density 400 kg.m$^{-3}$ are values $\rho_{\text{board}}$ 3% (12 kg.m$^{-3}$) higher than $\rho_{\text{small}},$
- by density 460 kg.m$^{-3}$ are values identical $\rho_{\text{small}} = \rho_{\text{board}},$
- by high densities (over 500 kg.m$^{-3}$) are values $\rho_{\text{small}}$ just little overestimated than $\rho_{\text{board}}$ 1% (5 kg.m$^{-3}$).

$$\rho_{\text{board}} = 83,604 + 0.822 \cdot \rho_{\text{small}}$$

$r^2 = 0.76$

Fig. 3 Wood densities distribution $\rho_{\text{small}}$
Fig. 4 Wood densities distribution $\rho_{\text{board}}$

Fig. 5 Relationship between wood density $\rho_{\text{small}} - \rho_{\text{board}}$ (Picea abies, Karst. L.)
Fig. 6 Relationship between sound of speed \( c_{\text{vibr.}} - c_{\text{ultras.}} \) (Picea abies, Karst. L.)

Speed of sound propagation analyze \( c_{\text{vibr.}} - c_{\text{ultras.}} \) (Fig. 6) - high coefficient of determination \( r^2 = 0.76 \)

Ultrasonic method gives higher values in whole spectra range than vibration method \( (c_{\text{ultras.}} > c_{\text{vibr.}}) \)

- the most significant differences are on low values (4 600 m.s\(^{-1}\)) value \( c_{\text{ultras.}} > c_{\text{vibr.}} \) by 16% (728 m.s\(^{-1}\)),
- differences are reducing in common speeds (5 300 m.s\(^{-1}\)) \( c_{\text{ultras.}} > c_{\text{vibr.}} \) by 9.5% (504 m.s\(^{-1}\)),
- the smallest differences are on values 6 000 m.s\(^{-1}\): \( c_{\text{ultras.}} > c_{\text{vibr.}} \) by 4.7% (280 m.s\(^{-1}\)).

Fig. 7 Relationship between density wood and sound of speed \( c_{\text{ultras.}} \) (Picea abies, Karst. L.)
CONCLUSIONS
- wood density \( \rho_{\text{small}} - \rho_{\text{board}} \) have normal distribution,
- the largest proportion of spruce wood density is 350 – 460 kg.m\(^{-3} \), on scale (Fig.5) \( \rho_{\text{small}} \) underestimate \( \rho_{\text{board}} \), prediction error decrease linearly od 6% do 0%,
- \( \rho_{\text{board}} \) in situ on boards, \( \rho_{\text{small}} \) in vitro on small samples. Recalculation equations were detected: \( \rho_{\text{board}} = 1.2 - 5.10^{-4} \rho_{\text{small}} \) and \( \rho_{\text{small}} = \rho_{\text{board}} / 1.2 - 5.10^{-4} \),
- dimensioning value of wood density is according to EN 338 (\( \rho_{\text{mean}} \)) – values are set from \( \rho_{\text{small}} \).
- speed of sound propagation: the ultrasonic method gives a whole range of values higher than the vibrational method (\( c_{\text{ultr.}} > c_{\text{vibr.}} \)),
- recalculation equations were detected: \( c_{\text{ultr.}} = 1.52 - 8.10^{-5} c_{\text{vibr.}} \) and \( c_{\text{vibr.}} = c_{\text{ultr.}} / 1.52 - 8.10^{-5} \),
- different values of speed of sound propagation have impact on \( E_{\text{dyn}} = c^2 \times \rho \).
- dynamic modules are detected in non-destructive acoustic methods – relation between static and dynamic modulus of elasticity of wood are indicator of strength classes determination.

REFERENCES

ACKNOWLEDGMENTS
This study was supported by project under the contract VEGA under contract No. 1/0395/16.

Streszczenie: Zależność pomiędzy gęstością a prędkością rozchodzenia się dźwięku w strukturze drewna świerkowego. Gęstość drewna i prędkość propagacji dźwięku są znaczącymi parametrami stosowanymi w ocenie jakości drewna budowlanego. Gęstość drewna określono na małych próbkach (według wytycznych normy EN 408), a prędkość rozchodzenia się dźwięku można mierzyć z wykorzystaniem np. aparatów Sylvatest DUO (cultr) lub Timber Grader MTG (cvibr) in situ. Próbki pobrano losowo z drewna pozyskanego na terenie Słowacji. W przeprowadzonych badaniach zastosowano metody in situ do opisania zależności pomiędzy monitorowanymi parametrami.

Author’s address:
Doc. Ing. Alena Rohanová, PhD.
Ing. Ondrej Bajza
Technická univerzita vo Zvolene, Drevárska fakulta
T. G. Masaryka 24, 960 53 Zvolen, Slovakia
rohanova@tuzvo.sk,
bajza.ondrej@gmail.com
Water jet cutting waterproof foliated plywood

MIROSLAV ROUSEK, JAKUB LISEC, ZDENĚK KOPECKÝ, LUĎKA HLÁSKOVÁ

Mendel University in Brno, Faculty of Forestry and Wood Technology, Brno, Czech Republic

Abstract: Water jet cutting waterproof foliated plywood. This paper focuses on the use of unconventional technologies for water jet cutting beam foliated waterproof plywood material. The following are the results of the experiment measuring surface roughness of cutting edge contact surface roughness and determination of damage to the lower edges of the cut material using indirect detection methods. The results are documented in tables, charts, and photographs.

Keywords: quality cutting process, unconventional technology, machining, speed shift, foil waterproof plywood, water jet

INTRODUCTION

Cutting water jet is known as progressive technology. So do not use common tools, but the actual separation process is carried out using a liquid jet. Hydrodynamic machining liquid used for material removal by the mechanical action of the impact a narrow liquid flow with high speed and kinetic energy per unit area (Barcík et al., 2012; Kelp, et al., 2001).

In terms of the use of working media we can distinguish two basic types: WJM - Water Jet Machining - pure water jet, AWJ - Abrasive Waterjet Machining - machining abrasive waterjet (Maňková, 2000).

When machining a pure water jet is based on the fact that the liquid emerging from the nozzle energy to the material would be considered given liquid jet to a rigid body. When contacting the surface beam disturbance material accumulated kinetic energy in the fluid jet will be released and its influence on the material. This translates to a sudden increase in tension in the contact zone in which there is to breach its integrity. Scope of rupture is a very small diameter (approx. 0.3 mm), under high pressure (approx. 200 to 700 MPa) is a carrier with high kinetic energy (Race et al., 2001; Valiček - Hloch, 2008). From the viewpoint of the effect of kinetic depends on its mechanical properties and also on the size of the stress (extreme, 1998).

The basic types of disturbance of the material include: damage caused by plastic deformation, stress waves propagation, cross flow spills and liquid penetration into the interior of the material between its structure. Treatment with one or more of these mechanisms the first damage and later to erosion of the material to which the fluid operated (Barcík et al., 2012). This article aims to experimentally demonstrate how different input parameters, namely different sliding speed pure waterjet influences surface quality waterproof foliated plywood.

Equipment for water-jet cutting consists of the following components:

The trap is placed against the cutting nozzle below the workpiece material. Its task is to capture and destroy energy beam that passes through the material. The most commonly takes the form of the bath height 800 mm, which is filled with ceramic balls. Another possible way is to use a pipe length of 300 mm which is filled with a special preparation for absorbing residual energy beam. The trap is conducted synchronously with the cutting nozzle head (Morávek, 1999).
Supplying working fluid.
Cleaning filters whose function is to remove impurities from the incoming working fluid and simultaneously feed the liquid into the high pressure pump.
Low-pressure pump, which enables regulation of the output pressure and controls the high pressure pump.
Reservoir pressure working fluid, which is used to compensate and maintain a constant working pressure fluid exiting from the high pressure pump.
High-pressure pump serves as a source of pressurized working fluid. It works as a double-acting piston pressure booster. Supplying liquid under pressure from 200 to 600 MPa in an amount of 2-4.5 (Race et al., 2001).
Work cutting head, which varies depending on the working fluid. The size of nozzles ensures different kinetic energy of the beam. Nozzle service life depends on the amount of minerals contained in the water and is in the range from 50 to 500 hours (Morávek, 1999).
Material handling equipment is used to infer the relative motion between the work cutting head and the workpiece.
High-pressure pipe which supplies pressurized working fluid to the working cutting head.

Using methods and performance parameters

Pure liquid jet is used mainly for cutting soft and a little tough materials. The maximum thickness of the material to be cut is dependent on the type of workpiece material on the pressure of the working fluid, the cutting speed and also on the distance from the cutting nozzle and the workpiece surface. Kerf width is 0.1 to 0.3 mm (Race et al., 2001). Cutting speed for laminates to 5, paper and paperboard 400 (Kocman, 2011).

Properties machined surface when cutting (Maňková, 2000).

The theory principle waterjet is known that when the water jet penetrates loses its kinetic energy and deflects and form typical zones that can be discerned. The use of high-energy technology are leaving visible traces of machining machined surfaces. Surface after cutting could be divided into two areas (Figure 1). Portion with a smooth surface (smooth zone) and a region of visible grooves after machining beam (knurled zone). Surface roughness grooved zone increases with increasing depth of cut and feed rate of the upper part of the cut is a result of wear of the cutting and the second grooved area at the bottom of the cut formed as a result of the deformation of wear during cutting (Barcík et al., 2012).

Fig.1: Beam trajectory (ELNA Servis s. r. o., 2015)
Fig.2: Quality of waterjet cutting (ELNA Servis s. r. o., 2015)
The quality of the cut surface is divided into five groups according to final machining quality, which is directly related to the speed of movement of the cutting head. Figure 2 graphically recognizable difference in quality of the cut. The worst quality is shown under number 1 and 5. Normal best quality designation is given in the form Q1-5 (ELNA Servis s. R. O., 2015).

Tab. 1. Indicative description of the grades of cutting the basic characteristics (CHPS s. r. o., 2015)

<table>
<thead>
<tr>
<th>Qualitative level</th>
<th>Basic characteristics</th>
<th>Roughness Ra (µm) in the upper contour</th>
<th>Roughness Ra (µm) in the lower contour</th>
<th>Dimensional accuracy (mm) in upper contour</th>
<th>Dimensional accuracy (mm) in the lower contour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q5</td>
<td>Best cut</td>
<td>&lt; 3,2</td>
<td>3,2</td>
<td>+/- 0,1</td>
<td>+/- 0,1</td>
</tr>
<tr>
<td>Q4</td>
<td>Quality cut</td>
<td>3,2</td>
<td>6,3</td>
<td>+/- 0,1</td>
<td>+/- 0,1</td>
</tr>
<tr>
<td>Q3</td>
<td>Medium cut</td>
<td>4</td>
<td>&lt; 12,5</td>
<td>+/- 0,15</td>
<td>according to the type and thickness of material</td>
</tr>
<tr>
<td>Q2</td>
<td>Rough cut</td>
<td>4</td>
<td>&lt; 25</td>
<td>+/- 0,2</td>
<td>according to the type and thickness of material</td>
</tr>
<tr>
<td>Q1</td>
<td>Separating cut</td>
<td>4,0 – 6,3</td>
<td>&lt; 40</td>
<td>+/- 0,2</td>
<td>significantly inaccurate</td>
</tr>
</tbody>
</table>

MATERIALS AND METHODS

Process design methodology for determining optimum cutting conditions, material processing folio waterproof plywood based on the following criteria: different speed, surface quality Q1-5, the possibility of producing complex shapes shape, time of production, programming effort shapes of samples, price cutting.

Cutting equipment

The material in question was working on the equipment of the company AWAC spol. s r. o. with a branch in Brno with a particular device Flow Mach 4c SERIES M - 412 high pressure pump HYPERJET 94i. The parameters of the cutting machine are the linear positioning accuracy of 0.025, the maximum sliding speed of 36 m·min⁻¹ and a maximum cutting speed of 25 m·min⁻¹. HyperPressure pump Flow called HYPERJET 94i, is rated at 648 psi pressure and provides a continuous operating pressure up to 600 MPa. Using HYPERJET pump 94i is the possibility of reaching a speed of Mach 4 spoke up. Cutting head for pure water jet cutting was elected sapphire nozzle diameter of 0.305 mm. Nozzle distance from the material of 2 mm (Flow 2015).

Material waterproof plywood foiled

This material is from the normal waterproof plywood differs in that the surface treating used paper impregnated with phenol formaldehyde resin (film). Phenolic film thickness is usually 120 g·m⁻² (Demos, 2015).

Fig. 3: Cutting system MACH 4 (Flow 2015)
Possible variations boards:

- Double Smooth:
  TWIN - the first veneer under foil beech or celtis, interior veneer of softwood
  COMBI - The first veneer under foil is beech or celtis inner longitudinal veneer of softwood cross from beech.

- One side smooth, the other with a non-slip Combi. The edges of the plywood are treated coating against moisture (King, Hrázský, 2005).

These plates are manufactured in two grades, first and second grade. Formaldehyde emission class meets the conditions of emission class E1. The degree of flammability C2 - medium combustible according to EN 335 - 3rd hazard class 3 according to EN 335 - the third most common slab thicknesses 8; 10; 12; 15; 18; 21; 25 mm format of 125x250 cm.

**Methodology for determining the roughness of the machined surface**

Measuring roughness of machined surface was carried out using a device Surftest Mitutoyo SJ 201P. Results processing facility was done in SURFTEST SJ201 version 3.20 with export afforded to Excel spreadsheet from Microsoft. The system worked in MS Windows XP Professional.

In our particular case we have been chosen trajectory corresponding to half of the smooth and corrugated zone along both sides of the longitudinal surfaces of the machined samples. Areas of smooth and serrated zones were determined using calipers on the sample with the highest feed rate, where the transitions are best seen. These were the values assigned to all the examined samples. The width of the smooth zone was determined to 72 mm. Grooved area is thus 78 mm width. We proceed from the fact 150mm thick waterproof plywood.

![Fig. 4: Representation of specific locations roughness measuring equipment SJ 201P](image)

Fig. 4 is a graphic display of the measurement of surface roughness after cutting waterjet. The digits 1 to 6 show a smooth surface, 7-12 grooved. Further, numerals 13 to 22 are measuring points which correspond to the transition between the measurements 1 to 12.

The installations were carried roughness measurement. The track has always been one measuring 25 mm according to device settings. Each were measured both longitudinal faces.
of the sample from start to finish. This approach was chosen because of better detection threshold results.

The results were displayed in the program SURFTEST SJ20 with the possibility of creating a measurement certificate. Measured data were using the clipboard exported to MS Excel where it is possible to carry out any further processing.

**Graphic processing of machined surface roughness**

Processing the results of the machined surface roughness depending on the sliding speed they were done in Statistics 12 and referred to as "2D graphs averages with deviations." Source data for graphing the results were exported from the program SURFTEST SJ201 version 3.20, which were stored in MS Excel. In each graph settings were chosen following parameters median value - the average value of the boxes - the standard error, the value of the terminal confidence interval.

**Measurement methodology edge damage waterproof plywood**

Measurement of edge damage waterproof plywood was performed using a system of analysis and image processing NIS - Elements AR, version 2.30, which consisted of a digital 5 Mpix camera Nikon DS - Fi 1 with a macro Navitar placed on a stand with a lighting device KAISER RB 5000 DL computers NIS - Elements AR, version 2.30 (Intel Pentium 4 CPU, 3.00 GHz, HD 320 gigabytes, RAM 2GB). The system worked in MS Windows XP Professional.

**Preparation of test samples**

Pressure cutting was elected 380 MPa. The direction of material processing was selected as the longitudinal - to a base longitudinal dimension of the plate.

![Fig. 5: Test samples](image)

The main criterion of detection of different quality processing folio waterproof plywood sliding speed was different. Thanks to the specific software of Flow International Corporation, which is part of the cutting device software were calculated at 140, 280, 420, 560, 700. According to the software, these speeds should match the quality Q1-5. Dimensions of test samples: the desired width of the test specimen: W = 50 mm, sample length: L = 150 mm.

**RESULTS AND DISCUSSION**

After several dozen surface roughness measurement is stated the following results. It has been shown that a change in the sliding velocity liquid jet significantly affects the quality of the machined surface. Listed below in Fig. 6, this trend is shown graphically as the waveform rising curve which illustrates the increasing roughness of the machined surface of the workpiece in dependence on the increasing sliding speeds.
Fig. 6: Influence of the feed speed in the longitudinal direction on the arithmetic mean deviation of the surface roughness of the smooth zone

In the above Figure 7 is a graphical representation that in the longitudinal direction in the grooved area is a growing trend surface roughness depending on increasing sliding speeds. This finding is entirely predictable due to predicative results from the smooth zone graphically shown in Figure 6th.

Tab. 2: The average value of the arithmetical mean deviation surface roughness

<table>
<thead>
<tr>
<th>Feed rate</th>
<th>Smooth zone $R_a$ (μm)</th>
<th>Grooved zone $R_a$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>13,43</td>
<td>30,58</td>
</tr>
<tr>
<td>280</td>
<td>16,20</td>
<td>32,11</td>
</tr>
<tr>
<td>420</td>
<td>17,22</td>
<td>36,95</td>
</tr>
<tr>
<td>560</td>
<td>19,08</td>
<td>-</td>
</tr>
<tr>
<td>700</td>
<td>19,40</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 8: Indirect method for damage detection in the longitudinal direction of the sample 140

In Figure 8 to 10 there are graphically illustrated binary image damages that occurred on the underside of the cut samples. With the naked eye can discern an upward trend.
The exact values of damage are given in Table 3.

Tab. 3: The values of the binary image damage

<table>
<thead>
<tr>
<th>Area binary image damage</th>
<th>Sample (designation)</th>
<th>Image damage (mm²)</th>
<th>% control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length measured edge</td>
<td>161,9 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>0,47</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>420</td>
<td>1,02</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>1,73</td>
<td>370</td>
</tr>
</tbody>
</table>

CONCLUSION

The aim of the research was to demonstrate different surface quality at different sliding speeds, which succeeded. Testing samples machined using clean water jet technology has been shown that with increasing sliding speed increases and surface roughness. When comparing our results with the results of the company CHPS s. r. o. (2015) according to their degrees of cut quality not reached the same quality values, which were calculated by the software firm Flow International Corporation. The issue of determining the optimization of machining associated with the resulting quality is a major concern for now.

Generally, it was demonstrated that with increasing sliding speed increases and the surface roughness of the machined surface with pure water jet in the longitudinal direction of the cutting foil waterproof plywood.

Finding the optimum machining parameters for this technology is still a major problem. When using water jet technology assessment surface quality is not for individual materials yet not defined nor the definition of surface quality. They have been issued so far no standards that would address this issue.
REFERENCES


ACKNOWLEDGMENT

This article was compiled using part of the project IGA LDF_PSV_2016019, application of advanced technologies associated with unconventional materials machining. The authors are grateful for this funding.


Author’s address:
Miroslav Rousek, Jakub Lisec, Zdeněk Kopecký, Luďka Hlásková
Mendel University in Brno
Faculty of Forestry and Wood Technology
Zemědělská 3
613 00 Brno
Czech Republic
Corresponding author: rousek@mendelu.cz
Abrasive water jet machining of foil waterproof plywood

MIROSLAV ROUSEK, JAKUB LISEC, LUĎKA HLÁSKOVÁ, ZDENĚK KOPECKÝ

Mendel University in Brno, Faculty of Forestry and Wood Technology, Brno, Czech Republic

Abstract: Abrasive water jet machining of foil waterproof plywood. The paper is focussed on the use of unconventional technology (abrasive water jet) cutting of the foil waterproof plywood material. The results of the experiment to measure the roughness of the cutting edge surface by a contact grinder and the determination of damage to the lower edge of the cut material by the indirect detection method are given. The results are documented by tables and graphs.

Keywords: quality cutting process, unconventional technology, foil waterproof plywood, water jet

INTRODUCTION

Cutting by a water jet is known as progressive technology. There are no common tools used, but the actual separation process is carried out using a liquid water jet. Hydrodynamic machining uses a liquid for the material removal by the mechanical action of the narrow liquid water jet impact with a high speed and kinetic energy per unit area (Barcík et al., 2011; Řasa et al., 2001).

In terms of use of the working media we can distinguish two basic types of water jet: Pure water jet machining (WJM) and abrasive water jet machining (AWJ) (Maňková, 2000). Cutting with the pure water jet is suitable for extremely detailed geometries, especially at softer materials (plastic materials, cork, wood, rubber). The water jet with abrasive material is able to cut stone, metals, glass and other materials. Wood processing practice knows cutting by clean native water jet as chipless cutting and abrasive water jet cutting as chip cutting (Bernd, 1993).

The basic difference between cutting by pure water jet and an abrasive water jet is by adding the abrasive to the water stream. The abrasive cutting medium is directed into a narrow liquid jet and it is increasing its cutting efficiency. Cutting performance increases by adding the abrasive, (Barcik a kol. 2011). There are two methods of adding the abrasive: the abrasive may be pulled by a liquid jet or may be added under pressure. Mixing takes place in the mixing chambers. The most commonly used abrasives include grenade, alumina, mineral sand, quartz sand or steel pulp (Maňková, 2000).

High-pressure water jet cutting

The grinding of the split material by water jet under pressure is the principle of this machining technology. The working pressure of the water most often ranges within the range 80–410 MPa for abrasive water jet. For pure water jet cutting up to 700 MPa. The high-pressure pumps with power (9-75 kW) and water flow (1,2-7,6 l·min⁻¹) serves as a source of pressurized working fluid. The jet is formed in a cutting head with a special nozzle. The size of nozzles ensures different kinetic energy of the jet. The flow of water driven through the nozzles has a speed of 600-900 m·s⁻¹ (AB JET 2016; Lipa 2001; Řasa a kol. 2005; Valiček, Hloch, 2008).

Properties of machined surface

From the water jet cutting theory is known that when the water jet penetrates some material, it loses its kinetic energy, deflects itself and form the typical zones that can be discerned.
The uses of high-energy technologies are leaving visible traces in the machining surfaces. Surface after cutting could be divided into two parts (Figure 1). Part with a smooth surface (smooth zone) and an area of visible grooves after the water jet (rough zone). Surface roughness of the rough zone intensifies with the increasing depth of cut and the feed rate of the upper part of the cut and it is a result of detrition. The second rough area at the bottom of the cut is formed as a result of the deformation wearing during cutting (Barčík et al., 2011; Maňková, 2000).

The quality of the surface is divided into five groups according to final machining quality, which is directly related to the feed rate of the cutting head. In the figure 2 is graphically recognizable difference in quality of the cut. The worst quality is shown under number 1 and the best is under number 5. Normal quality is designated as Q1-5 (ELNA Servis s. r. o., 2015).

<table>
<thead>
<tr>
<th>Qualitative degree</th>
<th>Basic characteristic</th>
<th>Roughness ( R_a (\mu m) ) in upper contour</th>
<th>Roughness ( R_a (\mu m) ) in lower contour</th>
<th>Shape accuracy (mm) in upper contour</th>
<th>Shape accuracy (mm) in lower contour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q5</td>
<td>Best cut</td>
<td>below 3.2</td>
<td>approx. 3.2</td>
<td>+/- 0.1</td>
<td>+/- 0.1</td>
</tr>
<tr>
<td>Q4</td>
<td>Quality cut</td>
<td>approx. 3.2</td>
<td>approx. 6.3</td>
<td>+/- 0.1</td>
<td>+/- 0.2</td>
</tr>
<tr>
<td>Q3</td>
<td>Medium cut</td>
<td>approx. 4.0</td>
<td>to 12.5</td>
<td>+/- 0.15</td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>Rough cut</td>
<td>approx. 4.0</td>
<td>to 25</td>
<td>+/- 0.2</td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>Dividing cut</td>
<td>4.0-6.3</td>
<td>to 40</td>
<td>+/- 0.2</td>
<td>Highly inaccurate</td>
</tr>
</tbody>
</table>

Tab. 1 Indicative description of the cutting quality levels with the basic characteristics (CHPS s. r. o., 2015)

According to type and strength of material

According to type and strength of material
MATERIAL AND METHODS

The process of methodology application for determining the optimal cutting conditions of foil waterproof plywood was based on the following criteria: Different feed rate, time of production, difficulty with programming of sample shapes, price of cutting, longitudinal and cross section.

Water jet

The considered material was machined by the equipment of the AWAC s. r. o. company, specifically the MICROSTEP AQUACUT 1501. 20 W device with a high pressure pump KMT STREAMLINE SL - V 50 PLUS. The parameters of the cutting machine are: work desk dimensions 4000 x 2500 mm, stroke 150 mm, work pressure 385 MPa. Control system MSNC, one head for cutting. Accuracy by DIN 28 206. The distance of the nozzle from the material was selected as 2 mm. Pump KMT STREAMLINE SL - V 50 PLUS pressure 414 MPa, maximum pump flow 3,79 dm$^3$\cdot min$^{-1}$ and the volume of the battery 0,96 l (KMT 2016; MicroStep 2016).

Foil waterproof plywood

Possible boards variations:

- Smooth-two-sides plywood:
  - TWIN - the first veneer under the beech or celtis foil, inner veneer made of softwood
  - COMBI - the first veneer under the beech or celtis foil, inner longitudinal veneer made of softwood, cross veneers made of beech.
- One side smooth, the other with a non-slip improvement with a Combi variant. The edges of the plywood are treated by coating against the moisture (Král, Hrázský, 2005).

These plywood are manufactured in two grades (the first and the second grade). Formaldehyde emission class meets the conditions of emission class E1. The degree of flammability C2 - medium combustible according to ČSN 335 - 3. Hazard degree 3 according to ČSN 335 - 3. The most common board thicknesses 8; 10; 12; 15; 18; 21; 25 mm, format of 125x250 cm.

Methodology for determining the quality of the machined surface

Measuring of the surface quality was carried out using a device Mitutoyo surftest SJ 201P. Results processing was done in SURFTEST SJ201 software, version 3.20 with an export to MS Excel.

![Fig. 3. Specifics locations of the roughness measuring by device SJ 201P](image)

In our particular case we have chosen a trajectory corresponding to half of the smooth and rough zone along both sides of the longitudinal surfaces of the machined samples. The areas of the smooth and the rough zones were determined using the caliper on the sample with the greatest feed rate, where the transitions were seen the best. These measured values were assigned to all the samples. The width of the smooth zone was determined as 11 mm. The width of the rough zone is thus 4 mm. We lead off from the fact of the 15 mm thickness of waterproof plywood.
In the figure 3 there are displayed of specifics locations of the roughness measuring by device SJ 201P. Line A indicates the progress of the measurement in the middle of the smooth zone and line B indicates the progress of the measurement in the middle of rough zone.

The measurements of roughness were carried out by the device. The track of one measurement has different values due to the use of the standard ČSN EN ISO 4288. In the places where the measurement was finished, another was followed up. The full length of the sample was measured from both sides. This approach was chosen because of better results demonstrability and a higher number of measurements for statistic evaluation. The results were displayed in the SURFTEST SJ20 software with the possibility of creating a measurement certificate. Measured data were exported to MS Excel where it is possible to carry out any further processing.

**Graphic processing of the machined surface quality data**

Processing of the measured data of the machined surface quality depending on the feed rate were done in Statistics 12 and referred as „2D diagram of averages with deviations.“ The source data for the diagram-creating were exported from the SURFTEST SJ201 software version 3.20, which were stored in MS Excel. In each diagram settings following parameters were chosen: expected value - average value, value of the boxes - the standard error, the value of the terminal - confidence interval.

**Methodology of the waterproof plywood edge damage measurement**

Measurement of waterproof plywood edge damage was performed using a system of analysis and image processing NIS - Elements AR, version 2.30, which consisted of a digital 5 Mpix camera Nikon DS - Fi 1 with a macro object-glass Navitar placed on a tripod with a lighting device KAISER RB 5000 DL and the NIS - Elements AR computer, version 2.30 (Intel Pentium 4 CPU, 3.00 GHz, HD 320 gigabytes, RAM 2GB).

**Preparation of the test specimens**

The cutting pressure was selected to 385 MPa. The direction of material processing was selected as the longitudinal and transverse – relating to a base longitudinal dimension of the plywood.

The standards CSN EN 326-1 used in combination with the experience of the employees of AWAC s.r.o. Brno were used to make test specimens. The main criterion of the demonstrability of different surface quality of the foil waterproof plywood was the different feed rate. Dimensions of test samples: the required width of the test sample: \( w = 15 \) mm, sample length: \( L = 150 \) mm. Abrasive material was selected as a grenade mesh 80.

**RESULTS**

After the surface roughness measurements have been stated the following results. It has been proven that a change in the feed rate of a water jet significantly affects the quality of the machined surface. Listed below in figures, this trend is shown graphically as the rising curve which illustrates the increasing roughness of the machined surface of the workpiece in dependence on the increasing feed rate.
Fig. 4. Effect of the feed rate in the longitudinal direction on the arithmetic mean deviation of the surface roughness of a smooth zone.

Fig. 5. Effect of the feed rate in the longitudinal direction on the arithmetic mean deviation of the surface roughness of the rough zone.

Fig. 6. Effect of the feed rate in the transverse direction on the arithmetic mean deviation of the surface roughness of a smooth zone.

Fig. 7. Effect of the feed rate in the transverse direction on the arithmetic mean deviation of the surface roughness of the rough zone.

Figures 4, 5, 6 and 7 show that in the longitudinal and transverse direction in the rough zone there is a growing trend of the surface roughness depending on the increasing feed rates.

<table>
<thead>
<tr>
<th>Feed rate (mm·min⁻¹)</th>
<th>Smooth zone</th>
<th>Rough zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rₐ (μm)</td>
<td>Rₐ (μm)</td>
</tr>
<tr>
<td>140</td>
<td>9.19</td>
<td>10.49</td>
</tr>
<tr>
<td>280</td>
<td>9.45</td>
<td>10.69</td>
</tr>
<tr>
<td>420</td>
<td>9.53</td>
<td>10.73</td>
</tr>
<tr>
<td>560</td>
<td>9.64</td>
<td>10.74</td>
</tr>
<tr>
<td>700</td>
<td>9.65</td>
<td>11.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feed rate (mm·min⁻¹)</th>
<th>Smooth zone</th>
<th>Rough zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rₐ (μm)</td>
<td>Rₐ (μm)</td>
</tr>
<tr>
<td>140</td>
<td>9.40</td>
<td>10.63</td>
</tr>
<tr>
<td>280</td>
<td>9.45</td>
<td>10.82</td>
</tr>
<tr>
<td>420</td>
<td>9.53</td>
<td>11.04</td>
</tr>
<tr>
<td>560</td>
<td>10.08</td>
<td>12.07</td>
</tr>
<tr>
<td>700</td>
<td>10.76</td>
<td>12.88</td>
</tr>
</tbody>
</table>
In Fig. 8 there is graphically illustrated a binary image damage that occurred on the underside of the cut samples. Accurate values are displayed in Tab. 3.

**Tab. 3 Values of the sample binary damage**

<table>
<thead>
<tr>
<th>Area of binary image damage of the transverse direction</th>
<th>Area of binary image damage of the longitudinal direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample (marking)</td>
<td>area (mm$^2$)</td>
</tr>
<tr>
<td>140</td>
<td>1.51</td>
</tr>
<tr>
<td>280</td>
<td>1.18</td>
</tr>
<tr>
<td>420</td>
<td>1.36</td>
</tr>
<tr>
<td>560</td>
<td>1.38</td>
</tr>
<tr>
<td>700</td>
<td>1.26</td>
</tr>
</tbody>
</table>

**DISCUSSION**

The aim of the article was to show a different surface quality with a changing feed rate, which has been proven. Testing samples machined using the abrasive water jet technology has been shown that with the increasing feed rate increases the surface roughness. Furthermore, the different quality of the longitudinal and transverse cuts was also documented. The cause of the different quality of the machined surface in the transverse and longitudinal directions can be found in the anatomical structure of the wood and in the cutting of individual anatomical elements. Our results are contrary to results by Barčík et al. (2011) who claim that with the increasing feed rate of the abrasive water jet occurs a qualitatively better surface and therefore a lower values of surface roughness. The same results were also achieved by Kvietková et al. (2014). When compared with our results, the trend has reversed – with increasing feed rate increases the surface roughness.

**CONCLUSION**

Finding the optimum machining parameters is for this technology still a major problem. Using this technology there is not yet defined the quality evaluating of the machined surface. There are so far no standards issued that would be concerned with this topic. Another view is the economic aspect of the machining. The present time is very influenced by the economy. The Flow International Corporation came up with interesting findings for water jet
cutting and operating economy. Thanks to the use of abrasives there is need of a lower pressure which reduces the energy demands of production. Dealing with the issue of surface quality, the company claims that with increasing pressure, each particle has much more momentum and cutting power. This makes it possible to increase the feed rate.

REFERENCES

Internet sources

ACKNOWLEDGEMENT
This paper was prepared in connection with a partial project within the projekt IGA – Aplikace progresivních technologií souvisejících s obráběním netradičních materiálů Research Plan. The author thanks for a financial support to deal with the project.

Streszczenie: Cięcie ściernym strumieniem wody foliowanej sklejki wodoodpornej. Artykuł przedstawia wykorzystanie niekonwencjonalnej technologii (ściernego strumienia wody) do cięcia foliowanych wodoodpornych materiałów sklejkowych. Zaprezentowano wyniki eksperymentu pomiaru chropowatości powierzchni cięcia i jakości krawędzi materiału. Wyniki przedstawiono w tabelach i na wykresach. Wykazano, że znalezienie optymalnych
parametrów obróbki dla tej technologii jest trudne i stanowi główne wyzwanie w dalszych badaniach.

Author’s address:

Mendel University,
Faculty of Forestry and Wood Technology,
Zemědělská 3, 613 00 Brno,
Czech Republic
tel: +420 545134527
e-mail: rousek@mendelu.cz
Surface roughness of water-based finishes on aspen poplar wood

GABRIELA SLABEJOVÁ, MÁRIA ŠMIDRIAKOVÁ, MIROSLAV MORINGA

Faculty of Wood Sciences and Technology, Technical University in Zvolen

Abstract: Surface roughness of water-based finishes on aspen poplar wood. The article deals with the roughness of transparent finishes on the surface of aspen poplar wood. The influences of the type of transparent finish and the thickness of the coating, and also the method of machining of the surface on the roughness of surface of aspen poplar wood were monitored. Aspen poplar wood was machined by one of five different ways of surface machining (milling, sanding, and three ways of pressing). Two types of transparent finish (water-based) were used to make coatings. The finishes were created in three various thicknesses. The surface roughness Ra (arithmetical mean deviation of profile) was measured. Statistical evaluation showed that the type of finish, the thickness of the coating, and also the method of wood machining affected the surface roughness. The roughness of the surface with the thinnest coating was higher than the roughness of the surface with medium thickness of the coating. The surface roughness measured across the wood grain was much higher if compared with the surface roughness measured in direction parallel to the wood grain. The surfaces with the thickness of the coating of 150 µm or more showed reduced surface roughness.

Keywords: aspen poplar wood, transparent coating, roughness, surface machining

INTRODUCTION

Aspen poplar is a deciduous tree belonging to diffuse-porous wood species. It has soft, lightweight wood. Aspen poplar wood is used to make veneer, plywood, and as a material in pulp and paper industry. In furniture industry and in manufacture of musical instruments, the poplar wood is used less.

Aspen poplar is undemanding, fast growing wood and that is why the aspen poplar wood should be more represented in the furniture industry.

Using of the aspen poplar wood for lightweight plywood was described by Gáborík and Vilhanová (2016), Dudas and Vilhanová (2013). Modification of aspen poplar wood by pressing was dealt by Gáborík and Žitný (2010). Physical and mechanical properties of aspen wood are already known and can be used in furniture construction. Not only sufficient strength, stability and durability of the furniture, but also high quality of a surface finish is required.

In the present article we focus on the surfaces roughness of water-based finishes on aspen poplar wood. We monitor the impact of wood surface machining before surface finishing on the surface roughness. At the same time, we monitor the effects of the type of finish and the thickness of the coating on the surface roughness.

MATERIALS AND METHODS

In the experimental part, tangential and radial-tangential specimens of aspen wood (Populus tremula L.) with dimensions of 100 mm × 150 mm × 22 mm, with a moisture content of 8 ± 2 % and an average density of 430 kg/m3 were used.

The specimens were machined by following technologies:

- milling – one-sided milling machine,
- sanding – belt sander with the sandpaper with grain size number P60 and then with sandpapers P80 and P120,
pressing – in the press with brushed and heated plates. Three modes of pressing were used; pressing time of 2 min (L 1), 6 min (L 2), or 10 min (L 3), pressing temperature of 140 °C (always the same), and compression of 1 ± 0.05 mm.

After machining, the specimens were coated. The coating material was sprayed pneumatically. The representative types of the transparent coating materials for interior environment were selected:
A. water-based one-component polyacrylate primer for wood – coating material Aqua Primer thix,
B. water-based one- or two-component polyurethane acrylic top coat for wood – coating material Aquakristall Pluss,
C. water-based one- or two-component polyurethane acrylic base and top coat for wood – coating material Aquasoft CFB.

Surface finish P1 was created as a coating system of two coating materials A and B. Surface finish P2 was created by the C only. The coatings were created in three film thicknesses: H1 = 50 ± 5 µm, H2 = 100 ± 5 µm, and H3 = 150 ± 5 µm.

The surface roughness was measured using the Pocket Surf MahrPortable Surface Roughness (tip radius r = 0.005 mm). The roughness was measured before surface finishing (24 hours after mechanical machining) and after the surface finishing. The arithmetic mean deviation of the profile Ra [µm] was measured (according to the standard STN EN ISO 4287). For each of the tested samples, 10 measurements were taken at set points in direction parallel to the wood grain and 10 measurements in direction perpendicular to the grain; measured on the basic traverse length of 5 cut-off of 0.8 mm. The measured values were automatically recorded in computer using the software ROUGHNESS. Subsequently, they were evaluated by mathematical and statistical analysis using the software STATISTICA.

RESULTS AND DISCUSSION
Statistical evaluation of the impact of individual factors and their interactions (wood fibres direction, the surface machining, type of finish, and coating thickness) on the surface roughness (Ra) of aspen wood before and after the surface treatment is shown in Table. 2.

Tab. 2 Analysis of variance (roughness Ra)

<table>
<thead>
<tr>
<th></th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Deviation</th>
<th>F-test</th>
<th>Probability α = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute value</td>
<td>3088,731</td>
<td>1</td>
<td>3088,731</td>
<td>11374,91</td>
<td>0.000000</td>
</tr>
<tr>
<td>Surface machining (SM)</td>
<td>80,953</td>
<td>4</td>
<td>20,238</td>
<td>74,53</td>
<td>0.000000</td>
</tr>
<tr>
<td>Type of finish (SF)</td>
<td>377,352</td>
<td>3</td>
<td>125,784</td>
<td>463,23</td>
<td>0.000000</td>
</tr>
<tr>
<td>Thickness of coating (TC)</td>
<td>94,465</td>
<td>2</td>
<td>47,232</td>
<td>173,94</td>
<td>0.000000</td>
</tr>
<tr>
<td>Direction of wood fibers (DWF)</td>
<td>126,077</td>
<td>1</td>
<td>126,077</td>
<td>464,31</td>
<td>0.000000</td>
</tr>
<tr>
<td>SM * SF</td>
<td>92,243</td>
<td>12</td>
<td>7,687</td>
<td>28,31</td>
<td>0.000000</td>
</tr>
<tr>
<td>SM * TC</td>
<td>2,440</td>
<td>8</td>
<td>0,305</td>
<td>1,12</td>
<td>0.345381</td>
</tr>
<tr>
<td>SF * TC</td>
<td>292,319</td>
<td>6</td>
<td>48,720</td>
<td>179,42</td>
<td>0.000000</td>
</tr>
<tr>
<td>SM * DWF</td>
<td>25,445</td>
<td>4</td>
<td>6,361</td>
<td>23,43</td>
<td>0.000000</td>
</tr>
<tr>
<td>SF * DWF</td>
<td>52,023</td>
<td>3</td>
<td>17,341</td>
<td>63,86</td>
<td>0.000000</td>
</tr>
<tr>
<td>TC * DWF</td>
<td>0,172</td>
<td>2</td>
<td>0,086</td>
<td>0,32</td>
<td>0,728292</td>
</tr>
<tr>
<td>SM * SF * TC</td>
<td>12,937</td>
<td>24</td>
<td>0,539</td>
<td>1,99</td>
<td>0,003665</td>
</tr>
<tr>
<td>SM * SF * DWF</td>
<td>25,507</td>
<td>12</td>
<td>2,126</td>
<td>7,83</td>
<td>0,000000</td>
</tr>
<tr>
<td>SM * TC * DWF</td>
<td>0,835</td>
<td>8</td>
<td>0,104</td>
<td>0,38</td>
<td>0,929116</td>
</tr>
<tr>
<td>SF * TC * DWF</td>
<td>1,308</td>
<td>6</td>
<td>0,218</td>
<td>0,80</td>
<td>0,567771</td>
</tr>
<tr>
<td>SM * SF * TC * DWF</td>
<td>2,542</td>
<td>24</td>
<td>0,106</td>
<td>0,39</td>
<td>0,996443</td>
</tr>
<tr>
<td>Error</td>
<td>162,923</td>
<td>600</td>
<td>0,272</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows, that the impact of all four factors is highly statistically significant. Among two-factor interactions, only two interactions were statistically insignificant (surface
machining – coating thickness, coating thickness – wood fibres direction). Among three-factor and four-factor interactions, only one interaction was statistically significant (surface machining – type of finish – direction of wood fibres).

Significantly less roughness was reached by the surface finish P1, if compared with the finish P2 (Fig. 1). In the graph in Fig.1, all three coating thicknesses were evaluated as one file.

![Graph showing surface roughness](image)

Fig. 1 Dependence of Ra on mechanical machining (longitudinal and transverse directions to wood fibres; surfaces with and without surface finish).

The graph in Fig. 2 shows the surface roughness for the individual coating thicknesses. The finish P1 significantly reduced the roughness of the wood surface even in the thinnest film H1 (50 µm). The surface roughness of the coating P1 in coating thicknesses H2 (100 µm) and H3 (150 µm) was very similar. The differences in surface roughness of the P1 in the thickness H3 between the individual ways of machining were insignificant (Fig. 2). If comparing with initial roughness, the surface finish P2 in the coating thickness of H1 and H2 caused an increase in roughness on the pressed surfaces. On all the tested surfaces, the surface finish P2 in the coating thickness H3 showed a lower value of the surface roughness when compared with the initial roughness.

In terms of machining of the wood surface, it can be seen that milled and then sanded surfaces showed the highest value of surface roughness in both directions (parallel and perpendicular to the wood grain) before surface finishing (Fig. 1). The results showed significant differences in the roughness between the surfaces machined by milling, sanding, and pressing, and especially the significant differences in surface roughness between the two anatomical directions. Our results confirmed the conclusions of authors KÚDELA et al. (2016), GÁBORÍK and ŽITNÝ (2010), GÁBORÍK and ŽITNÝ (2007), LIPTÁKOVÁ and KÚDELA (2000), and JOURDAIN et al. (1999) who concluded that direction of wood fibres influences the wood surface roughness highly statistically significantly. Surface roughness in individual directions affects also other properties of the coating, for example the gloss (SLABEJOVÁ et al. 2016).
The surface finish P1 caused reduction in the roughness on all the surfaces in longitudinal and transverse directions. The evaluation in Fig. 1 and Fig. 2 shows that water-based finish coating system P1 (primer A plus top coat B) showed lower roughness than initial roughness – already in thin coatings (50 µm). The finish P2, which was made of only one water-based coating material (C) reduced the surface roughness only in coating thickness of 150 µm.

Primer substance Aqua Primer thix in the finish P1 has function to equalize the surface and bind well the other coatings – the top coating material Aquakristall plus CFB (in our experiments). This feature of the basecoat material could significantly reduce the surface roughness of aspen wood. If comparing the surface finish P1 with the finish P2 in terms of the roughness, to finish the surface of aspen wood it is more appropriate to use coating system than only one coating material. The similar results on beech wood were also described by SLABEJOVÁ and MOZA (2010), and SLABEJOVÁ (2016).

CONCLUSION
Roughness expressed as mean arithmetic deviation of profile Ra is defined as one of the factors by which the quality of a surface finish and the quality of the surface of a substrate can be determined. Based on the results obtained, we can state:

• After the surface finishing using water-based coating materials, lower surface roughness was obtained by a coating system of primer and top coatings than by the coating formed by the only coating material (base and top in one).

• Less roughness is reached if applying a thicker coating. When creating a surface finish, it is important to maintain the recommended maximum thickness – considering the aesthetic and physical-mechanical properties of the coating.

• From the evaluated and also commonly used technologies for surface machining of aspen wood before surface finishing with water-based coating materials, the pressing ensures the lowest roughness (Ra characteristics).

• After applying a smaller amount of water-based coating material (base and top) on the pressed surface, the cut wood fibres raise, the pores are not sufficiently filled, and so the surface roughness is increased.
REFERENCES

ACKNOWLEDGEMENTS
The authors are grateful for the support by VEGA grant No. 1/0626/16 and VEGA grant No. 1/0822/17.

powierzchni maleje wraz ze wzrostem grubości powłoki wykończeniowej – najmniejszą wartość chropowatości zanotowano dla powłok o grubości 150 μm. Pomiar chropowatości powierzchni w poprzek włókien wykazywała znacznie większe wartości w stosunku do pomiaru wzdłuż włókien.

Author’s address:

Gabriela Slabejová, Mária Šmidriaková
Department of Furniture and Wood Products
Faculty of Wood Sciences and Technology
Technical University in Zvolen
T.G. Masaryka 24
960 53 Zvolen
Slovakia
slabejova@tuzvo.sk
smidriakova@tuzvo.sk
Physical-mechanical properties of surface finish on aspen poplar wood

GABRIELA SLABEJOVÁ, MÁRIA ŠMIDRIAKOVÁ, MIROSLAV MORINGA

Faculty of Wood Sciences and Technology, Technical University in Zvolen

Abstract: Physical-mechanical properties of surface finish on aspen poplar wood. The article deals with the hardness of transparent coatings and the impact resistance of the coatings on aspen poplar wood. Transparent finishes, the thickness of coating, and the method of machining of aspen poplar wood were monitored. Aspen poplar samples were machined by one of five different ways of surface machining (milling, sanding, and three ways of pressing). Two types of transparent finish (water-based) were used to make coatings. The coatings were created in three various thicknesses. The hardness of transparent finish was tested by the pencil test and the impact resistance of the coating was measured. The evaluation of the results has shown that the properties of the surface finish were influenced by the type of finish, the thickness of coating, and by the methods of wood machining.

Keywords: aspen poplar wood, transparent coating, surface machining, hardness, impact resistance

INTRODUCTION

Wood products are mainly finished by coating materials. To achieve a high quality surface finish, it is needed to machine the wood surface most appropriately and to choose a high-quality coating material. “One of the promising methods of wood surface treatment is smoothing” (Gáborík and Žitný, 2010). Smoothing by rolling or pressing can cause a reduction in the surface roughness and an increase in hardness of the wood surface. Improved surface properties of wood can increase the quality of finish. Stability of pressed wood was dealt by KÚDELA and REŠETKA (2012), and WANG and COOPER (2005).

Currently, in ecological and hygienical terms, the water-based coatings are given to the forefront. It is necessary to know all the properties of the advanced coating materials: aesthetic properties, physical, mechanical, and chemical properties, and durability. Optimization of water-based coating materials according to the selected properties of the coating films was dealt by FATIMIN et al. (2006). Addition of nano-filler particles into the coatings to improve physical and mechanical properties of the coatings was dealt by VEIGEL et al. (2014).

In the present article, we focus on hardness of the surface finish and resistance to impact of the finish on aspen wood. The surface finishes were made of water-based coating materials. We monitored the impact of the type of machining of wood surface, the type of finish and thickness of the coating on hardness of the surface finish and its resistance to impact.

MATERIALS AND METHODS

In the experimental part, tangential and tangential-radial specimens of aspen wood (Populus tremula L.) with dimensions of 100 mm × 150 mm × 22 mm, with a moisture content of 8 ± 2 %, and an average density of 430 kg/m3 were used.

The specimens were machined by following technologies:
• milling – one-sided milling machine,
• sanding – belt sander with the sandpaper with grain size number P60 and then with sandpapers P80 and P120,
• pressing – in the press with brushed and heated plates. Three modes of pressing were used; pressing time of 2 min (L 1), 6 min (L 2), or 10 min (L 3), pressing temperature of 140 °C (always the same), and compression of 1 ± 0.05 mm.

After machining, the specimens were coated. The coating material was sprayed pneumatically. The representative types of the transparent coating materials for interior were selected:

A. water-based one-component polyacrylate primer for wood – coating material Aqua Primer thix (varnish based on a special self-crosslinking polyacrylate dispersion),
B. water-based one- or two-component polyurethane acrylic top coat for wood – coating material Aquakristall Pluss (varnish based on a polymerizing polyurethane acrylate dispersion),
C. water-based one- or two-component polyurethane acrylic base and top coat for wood – coating material Aquasoft CFB (varnish based on a polyurethane acrylate copolymer dispersion).

Surface finish P1 was created as a coating system of two coating materials A and B. Surface finish P2 was created by the C only. The coatings were created in three coating thicknesses: H1 = 50 ± 5 µm, H2 = 100 ± 5 µm, and H3 = 150 ± 5 µm.

On the surface finished specimens, the surface hardness was determined according to the standard EN ISO 15184 Paints and varnishes – Determination of film hardness by pencil and the impact resistance was determined according to the standard STN 67 3082/a Testing of impact resistance of paint coatings.

RESULTS AND DISCUSSION

The results of the test „Determination of film hardness by pencil“ are shown in Fig. 1. The surface hardness was determined by the pencil the first breached the surface of the coating as visible scratch.

If compared the two finishes, the surface finish P2 showed greater hardness. The finish P1 had the lowest hardness in coating thickness H1 on the wood surface machined by sanding and pressing in L3 mode. The greatest surface hardness (level 8) was measured on the specimens with the finish P1 in the coating thicknesses H2 and H3 on milled wood surfaces. Overall, the greatest hardness (degree of 11) was measured on the finish P2 in coating thickness H2 on specimen machined by pressing L1 and L2. The lowest hardness (degree 5) was measured on the finish P2 in a coating thickness H1 on sanded surface.

The extent of damage of the surface was evaluated according to the standard STN 67 3082/a. After the weight had fallen on the steel ball placed on the surface of the tested specimen, the diameter of the intrusion on the surface was assessed. The average values of diameters of intrusions at a drop height of 400 mm are shown graphically in Fig. 2.

Fig. 2 shows, that at the drop height of 400 mm, the intrusions on milled and sanded surfaces were larger than the intrusions on pressed surfaces. The smallest intrusion (diameter) occurred in the finish P2-H2 on L1 pressed specimens. The largest intrusion was in the finish P2-H1 on sanded specimens. The graph in Fig. 2 shows that pressing of the surface increased on average the impact resistance of the coatings – if compared with the milled and sanded surfaces.

Fig. 3 shows degrees of damage for surface finishes P1 and P2 (for a drop height of 400 mm) evaluated according to the standard STN 67 3082/a. Based on the results we can state that the greatest damage and cracking occurred on milled surfaces and in one case on the pressed L1 surface. The best impact resistance was reached by the coating system P2-H2; on all the surfaces, the coating system showed the damage of 3 (visible light cracks on the surface, typically one to two circular cracks around the intrusion). At the drop height of 400 mm, in all the surface finishes, less damage than level 3 was not achieved.
Fig. 1 Surface hardness of finishes P1 and P2; in different thicknesses for different machining of base material – aspen wood.

Fig. 2 Intrusions in finishes P1 and P2; in different thicknesses for different machining of base material – aspen wood (a drop height of 400 mm).
CONCLUSION

Based on the obtained results we can conclude that the surface finish created as a coating system of water-based coating materials achieved higher surface hardness and better impact resistance than a simple surface finish.

Higher degree of damage in the coating (after fall of the weight) occurred on milled and sanded surfaces than on the pressed surfaces.

Higher surface hardness of the finish, formed as a coating system, for thin coating films, can be achieved by pressing of the wood surface.

REFERENCES

214–220. Dostupné na internete:


ACKNOWLEDGEMENTS
The authors are grateful for the support by VEGA grant No. 1/0626/16 and VEGA grant No. 1/0822/17.


Author’s address:
Gabriela Slabejová, Mária Šmidriaková
Department of Furniture and Wood Products
Faculty of Wood Sciences and Technology
Technical University in Zvolen
T.G. Masaryka 24
960 53 Zvolen
Slovakia
slabejova@tuzvo.sk
smidriakova@tuzvo.sk
The principles of design and analysis of exhaust and pneumatic transport systems of chipped wood

SERGEI TROFIMOV¹, TOMASZ ROGOZIŃSKI²

¹ Department of Technology and Design of Wood Products – The Belarusian State Technological University, Minsk, Belarus
² Department of Furniture Design – Poznan University of Life Sciences, Poznan, Poland

Abstract: Principles of design and analysis of exhaust and pneumatic transport systems of chipped wood. The article presents results of a study of the selection of schemes and the tracing of pipes for exhaust and pneumatic transport systems of chipped wood. The theory and practice of determining the diameter of the pipe in the branches to ensure an increased functionality and energy efficiency in the design of exhaust systems in accordance with the developed TCP 510–2014 are also described.

Keywords: exhaust systems design, chipped wood, energy efficiency.

INTRODUCTION

This article presents the results of the development to improve the solution of some problems in the design of exhaust and pneumatic transport systems (SEP) in wood processing, which are used to move particles of chipped wood, ventilation and dedusting of the working area. The advantages of SEP include: automation of waste removal from the place of their formation; simplicity of design and compactness of transport elements, the possibility of placing them in cramped conditions and a complex spatial trace; high performance; low installation and operation costs; ensuring the necessary sanitary and hygienic working conditions; use of controls and automation.

As a rule, SEP requires the development of an individual project taking into account the specific conditions of the enterprise, the production, the type and location of the equipment to be serviced. They are characterized by high power consumption for driving the fan and heat losses during the heating period (in the absence of recirculation - return of exhaust air to the room). The state of the air in the work area depends on the working of SEP as well as the degree of explosive, fire and environmental safety of production. These circumstances determine the relevance of the SEP development and their design processes.

MATERIALS AND METHODS

The main factors which determine the pressure loss and energy costs for the SEP fan (fig.1) include: air flow parameters, type and quantity of wood waste particles, system configuration and pipe length, characteristics of structural materials and plant elements, and the received diameter Air ducts (preferably a value close to the calculated one and this can be allowed by technical design standards, for example [3]).
It is known from practice that up to 65–75% of the total loss of pressure and energy consumption in SEP usually occurs in air ducts. To reduce the pressure losses in the ducts, reduce their length should be reduced. It is also necessary to simplify the configuration (number of elbows) to the optimal connection scheme and arrangement of the installation elements in relation to the aggregate of the equipment to be serviced and to determine the pipe diameter, taking into account the design flow rate and the minimum required velocity of air.

The article deals with the solution of design tasks for reducing pressure losses when exhaust receivers are connected to the mainline and the method for determining the diameters of SEP branch pipes is also considered. The presented results are based on the materials of theoretical studies, practical experience and development of normative and technical documents, in particular [3].

MATERIALS OF RESEARCH

When designing the SEP (fig.1), it is necessary to solve the problems of adopting a rational scheme for connecting ducts [1]. Consider this as an example of connecting two exhaust receivers to the main duct with a branched branch (fig. 2a) or separately single branches (fig. 2b).

The pressure loss in the branched branch (Fig. 2a) is determined by formulas:

$$H_o = \left(0,0125 + \frac{0,0011}{0,146 \sqrt{c}}\right) \left(\frac{\Delta \alpha}{2} + (\Delta y - L_\alpha)^2 + \frac{\Delta \alpha}{90} 0,6 \frac{a}{v^2}\right) / 0,146 \sqrt{c} ,$$  \hspace{1cm} (1)
\[ H_u = \left(0.0125 + \frac{0.0011}{0.146\sqrt{c}}\right) L_u + \frac{\alpha}{90} 0.6v^2 / 0.146\sqrt{2c} \]  \hspace{1cm} (2)

\[ H_{bb} = H_0 + H_u; \]  \hspace{1cm} (3)

\[ \alpha = \arctg \left(\Delta x (\Delta y - L_m)/2\right), \]  \hspace{1cm} (4)

where: \( H_0, H_m \) and \( H_{bb} \) are pressure losses in a single branch, branched branch line and branched branch line in general, without taking into account the resistances of the receivers and the input to the collector or main ductwork, Pa; \( c \) – a quantity equal to \( Q / v \); \( Q \) - air flow rate, \( \text{m}^3/\text{min} \); \( v \) – average velocity of air flow, \( \text{m/s} \); \( \Delta x \) and \( \Delta y \) – the distances by fig. 2a; \( \xi_{90} \) – coefficient of local resistance at the turn of the pipe with an angle of 90°.

In formulas (1–2), the expression \( 0.146\sqrt{c} \) determines the design diameter \( d \) of the pipelines at the accepted value of \( c \). The results of computer analysis of branched branching with symmetrical connection of two receivers (fig.2a) with \( c = 1, \, v = 20 \, \text{m/s}, \, \Delta x = 5 \, \text{m} \) and \( \xi_{90} = 0.18 \) are illustrated in fig. 3.

Calculation of pressure losses in a single branch (fig. 3b) is carried out by the formula:

\[ H_{sb} = \left(\left(0.0125 + \frac{0.0011}{0.146\sqrt{c}}\right) \Delta y / 0.146\sqrt{2c}\right) 0.6v, \]  \hspace{1cm} (5)

as a result for \( \Delta y = 5, \, 10, \, 15, \, 20 \) and \( 30 \, \text{m} \). \( H_{sb} \) of 165, 329, 494, 659 and 988 Pa was obtained.

The branch calculating is done under the known static pressure (underpressure) \( H \) in the connection to the main duct line, which should be provided by the fan from the condition of normal operation of the previously calculated SEP sections.

Proceeding from this, it is necessary to find the diameter of the branch pipe at which

\[ H_z = H, \]  \hspace{1cm} (6)

where \( H_z \) – the pressure loss in the branch, Pa; \( H \) – loss of pressure in the duct main line from the initial point to the connection point of the branch, Pa.

The solution of the problem of finding the required diameter of the pipe of branch is ensured by the technique of prof. Batina N.A., which allows to calculate single (fig. 4) and branched branches (fig. 5) of SEP using nomograms [1].

![Figure 4. The scheme of single branch](image)

![Figure 5. The scheme of a branched branch](image)

The loss of pressure in a single branch (fig. 4) \( H_z \) will be equal to the available pressure \( H \) (vacuum – negative pressure) at the connection point to the main duct line:

\[ H_z = \left(\frac{\rho v^2}{2}\right) \]  \hspace{1cm} (7)
Air velocity in the branch is expressed by the formula

\[ v = \frac{Q}{60\pi d^2/4} = \frac{Q}{15\pi d^2}, \]  

(8)

after some transformations at air density of \( \rho = 1.2 \text{ kg/m}^3 \), we obtain:

\[ (7.75d)^4 / (\lambda / d + \sum \xi / l) = Q^2 l / H. \]  

(9)

The values of \( Q^2 l / H \) and \( \sum \xi / l \) in expression (9) for the calculated branch are constant, if they are known, it is possible to determine the diameter \( d \) of the branch pipeline (fig. 6).

Figure 6. The nomogram for determining \( d \)

Figure 7. The nomogram for determining \( \beta_n \)
A branched branch represents a series of single branches connected to the branch main line, either via additional lines or directly (fig. 5).

Assuming that the branch main line consists of n sections, we denote the pipe diameter \(d\), the amount of flowing air \(Q\) and the geometric length of each of the sections \(l\) respectively, the first section \(d_1, Q_1, l_1\); the second section \(d_2, Q_2, l_2\); the \(n\)-th section of \(d_n, Q_n, l_n\). The velocity of the air flow in calculating the branch line for all sections will be taken equal to \(v\).

Then the loss of pressure in the line, which should be equal to the calculated pressure \(H\), is determined by the expression

\[
\sum_{i=1}^{n} H_i = \left(\frac{\lambda_1 l_1}{d_1} + \frac{\lambda_2 l_2}{d_2} + \ldots + \frac{\lambda_n l_n}{d_n} + \Sigma \xi_p\right) \frac{\rho v^2}{2} = H,
\]

where \(\Sigma \xi_p\) – the sum of the coefficients of the local resistance of the branch line.

Assuming \(\lambda_2 d_1 / d_2 \lambda_2, \ldots, \lambda_n d_1 / d_n \lambda_n = \beta_n\), we get

\[
\left[\frac{\lambda_1}{d_1} (l_1 + \beta_2 l_2 + \ldots + \beta_n l_n) + \Sigma \xi_p\right] \frac{\rho v^2}{2} = H.
\]

Replacing in formula (10) \(l_1 + \beta_2 l_2 + \ldots + \beta_n l_n = l_p\), for \(v = Q(15\pi d^2)\), after transformations [1] we obtain an expression similar to (9):

\[
(7.75d)^2 / \left(\lambda_n / d_n + \Sigma \xi_p / l_p\right) = Q^2 l_p / H.
\]

Formulas (9) and (12) are similar, so the calculation of the branched branch line can be reduced to the calculation of a single branch. In this case, in formula (12), instead of the geometric length, the calculated length of the main line of branched branch and the value of \(\Sigma \xi_p\) are introduced, taking into account the local resistances along the entire length of the main line of branch.

To determine the calculated length \(l_p\) by the formula (12), it is necessary to calculate the values of the coefficients \(\beta\) on the basis of expression

\[
\beta_n = \left(\frac{\lambda_n}{\lambda_p}\right) d_p / d_n.
\]

Knowing \(\lambda = 0.0125 + 0.0011 / d\) and substituting in (13) we obtain

\[
\beta = \left(\frac{\sqrt{Q_p} + 0.597 \sqrt{v}}{\sqrt{Q_p} + 0.597 \sqrt{v}}\right) \cdot \left(\frac{Q_p}{Q_n}\right).
\]

where \(Q_n\) – the air flow in the area for which the coefficient \(\beta_n\) is determined; \(Q_p\) – air flow at the calculated section of the main line of branched branch.

Taking into account the fact that in SEP the air velocities in the pipeline are usually in the range \(v = 14-24\) m/s, when determining \(\beta_n\), we can take the value of \(0.597 \sqrt{v} \approx 2.5\), [1], then we can assume

\[
\beta_n = \left(\sqrt{Q_p} + 2.5Q_p\right) / \left(\sqrt{Q_p} + 2.5Q_n\right).
\]

According to the nomogram (fig. 7), it is possible to determine \(\beta_n\) for specific values of \(Q_p\) and \(Q_n\) and then pipe diameters \(d_n\) in successive sections of the main branched branch line.

**ANALYSIS OF RESULTS**

The results of the work performed have a positive experience of practical use in the woodworking industry in the Republic of Belarus and in the training of engineers. The developed recommendations and methods for calculating the branches in the design of exhaust systems make it possible to simplify the work (for example, in comparison with the
selection of pipe diameters, [4]), to improve the maintenance of technological equipment, reliability and energy efficiency of the process for the removal of chipped wood waste.

The next stage in the improvement of the project activity was the development and introduction of technical standards for the design of exhaust and pneumatic transport systems in woodworking, including the production of fuel pellets and briquettes [2, 3].

The TCP 510–2014 entered into the Register of the State Standardization Committee of Belarus.

REFERENCES
4. NAGYSZALANCZY S., Woodshop Dust Control 2nd Ed. Taunton Press.

Streszczenie: Zasady projektowania i badania systemów odpylania i transportu pneumatycznego odpadów w przemyśle drzewnym. W artykule przedstawiono wyniki badań nad doborem systemów i sposobem ustalania przebiegu przewodów pneumatycznych układów transportowych odpadów drzewnych. Opisano również teorię i zasady praktyczne wyznaczania średnic przewodów w odgałęzieniach w celu zapewnienia zwiększonej funkcjonalności i efektywności energetycznej w projektowaniu układów odciągowych zgodnie z rekomendacjami zawartymi w protokole TCP 510-2014.

Author address:
Sergei Trofimov
Firm name: The Belarusian State Technological University, Minsk, Belarus
Department of Technology and Design of Wood Products, Faculty of Forestry Engineering and Wood Technology
Address Sverdlova Street, 13a; 220006 Minsk, Republic of Belarus
Telephone: +375 17 3276217, +375 17 2922383
E-mail: tspx46@gmail.com
New solutions of “sprt” tool constructions for wood surface equalizing by face milling method

GRZEGORZ WIELOCH¹/, BOLESŁAW PORANKIEWICZ²/, JANUSZ CIELOSZYK³/, BOLESŁAW FABISIAK³/.  
¹/ University of Life Science, SGGW, Poland, obrawiel@wp.pl
²/ Lab-Tech, Radomska
³/ Zachodniopomorski Uniwersytet Technologiczny, Szczecin

Abstract: New solutions of “SPRT” tool constructions for wood surface equalizing by face milling method. Attempts to adapt new machining methods using self-rotating blade knives (SPRT) can also be recorded in wood processing. Intensive research has examined the possibility of using this type of tool during turning wood. At present, American companies have developed tools for metal milling operations based on self-propelled discs. Their adaptation for woodworking is the subject of this paper.

Keywords: SPRT tools, milling, new constructions

INTRODUCTION

In recent years, the interest in "SPRT" tools has been noticeable in metal machining: Self Propelled Rotary Tools [1,2,5,6,8,9]. The SPRT itself is caused by frictional forces that occur between the application surface and the cutting surface of the blade. The operating principle of the SPRT tool is shown in Figs. 1 and 2. No rotating blade is the moment when the cutting edge is at an angle $\lambda_s=0$. If the edge is set at an angle $\lambda \neq 0$, then the blade itself is also affected by the friction of the chip moving on the attack surface.

Attempts to adapt new rolling methods using self-rotating blade knives (SPRT) can also be observed in woodworking [10,11]. Intensive research has shown the possibility of using these tools in turning wood [7,8,9,10]. This is all the more understandable that similar types of fixed disc blades have been used for a long time in woodworking successfully in shaping due to: prolonged working time - longer cutting edge for dulling (4,5,11,12,13). Tools with self-rotating cutting blades are distinguished by a number of features highly desirable for cutting, such as increased blade life compared to fixed-blade tools or a
significant reduction in the temperature in the cutting zone, by a constant change in the position of the cutting edge of rotation. Also the possibility of using replacement blades is a great advantage of this type of solution. This is particularly evident in the tendency to construct tools with replaceable inserts on blades that are more resistant to dullness [9,10,11,12,13]. In the 1980s, Lockheed Corporation, in collaboration with Rotary Technologies Corporation, developed tools with rotary milling cutters (Figure 3). The commercial use of rotary tools began around the turn of the century. The intensification of the work on the SPRT tools was conducive to the efficient processing of hard-to-clean materials, especially the new variety of CGI (Compacted Graphite Iron) and nickel and titanium alloys (internal combustion engines, jet engines, chemical and medical equipment).

Significant role was played by the development of CAD / CAM systems supporting the construction and technology of these tools. Also advances in materials science and technological capabilities of today's CNC machine tools have enabled the production of milling tools for industrial applications at Rotary Technologies Corporation in the USA, and recently in the milling heads of PokolmFrästechnik GmbH & Co. KG.[1,6,7].

As part of the study of unconventional cutting tools, it was decided to make a cutter with a set of four roller tools for leveling the planes. Its design was inspired by the solutions used in metal cutting tools.

Figure 3. Standard milling head based on self-rotating blades

MILLING TOOLS WITH SELF-ROTATING CUTTING PLATES

To test the use of a tool with self-rotating cutting plates it was decided to use Rotary Technologies' existing rotary milling head and tailor it to the cutting conditions of wood. The standard SPRT head (equipped with four interchangeable inserts with rotating plates (Fig.3) can be equipped with a smoothing plate mounted in a special cassette next to the rotary blades.

Cutting blades are made of tool steel with a blade angle adjusted for wood processing ie 40°. The blades were selected in the form of cups as can be seen in Fig 4 and 5. This was a gentle transition of the chips through the tool insert.
Figure 4. Model of the insert used in the construction of SPRT tools

Figure 5. Elements of blade inserts with fixing elements

Like the Mitsubishi Carbide turning lathe, needle and thrust bearings are used in the cassette and the entire system is pre-tensioned by the nut. It grips one more ball bearing to the rotating wall of the element on which the cutting insert is fixed (Figs. 4, 5).

CONCLUSIONS

During the wood turning process, the edge of the cutting edge is applied to the workpiece. The result of the cutting process is the concentration of mechanical stress in the blade contact zone with the workpiece. This results in chip separation. The result of the cutting process is the molding of the milled surface.

Experience has shown that the construction and technology of turning milling tools for wood milling is much more difficult than conventional tools. The problems relate in particular to the bearing knots, the selection of the material for the tool components, the accuracy requirements of the individual parts of the tool, the high degree of assembly and the thermal effects of the cutting process.
REFERENCES
3. GRZESIK W., 2010: „Podstawy skrawania materiałów konstrukcyjnych”. Warszawa, WNT, p. 527
5. KACZMAREK J., 1971: „Podstawy obróbki wiórowej, ściernej i erozyjnej”. Warszawa WNT.
9. VASILKO K., STIAVNICKY I., 1985: „Nove pristupy k navrchovaniuia využitíu rotujúcich sustruznických nozov”. Stroirenstvi c.35. p.360
Streszczenie: Próby adaptacji nowych sposobów obróbki z zastosowaniem noży krążkowych samo-obrotowych (SPRT) odnotować można również w obróbce drewna. Intensywnym badaniem poddano możliwość wykorzystania tego rodzaju narzędzi przy toczeniu drewna. Obecnie firmy amerykańskie opracowały narzędzia do operacji frezowania metali oparte o płytki narzędziowe krążkowe samo-rotujące. Ich adaptacja do obróbki drewna jest tematem niniejszej pracy.

Author’s address:

Grzegorz Wieloch,
Warsaw University of Life Sciences
Faculty of Wood Technology
159/34 Nowoursynowska Str.
02-787 Warsaw
Poland
e-mail: obrawiel@wp.pl
Effect of laser modification of WC-Co tool-life during particleboards milling

JACEK WILKOWSKI¹, PAWEŁ KOŁODZIEJCZA², MAREK BARLAK³, PAWEŁ CZARNIAK¹, ZBIGNIEW WERNER³, BOGDAN STASZKIEWICZ³

¹ Department of Mechanical Processing of Wood, Warsaw University of Life Sciences - SGGW
² Department of Welding Engineering, Warsaw University of Technology - WUT
³ Plasma and Ion Technology Division (FM2), National Centre for Nuclear Research Świerk - NCBJ

Abstract: Effect of laser modification of WC-Co tool-life during particleboards milling. The paper describes an influence of CO₂ laser beam on performance of WC-Co cutting edge dedicated to wood-based material machining. Comparable average tool wear indicators such as average cutting distance or average relative indicators for the reference and the modified tools were obtained. High diversity of results suggests further search for better parameters of the modification process.

Keywords: WC-Co tools, laser surface modification, particleboards, milling, tool life

INTRODUCTION

WC-Co composite is widely known for many years as a material appropriate for cutting tools manufacturing [Myalska et al. 2017; Mottaghi and Ahmadian 2017; Guo et al. 2017], due to high melting temperature, high hardness, good thermal and electrical conductivity [Siemaszko et al. 2004; Rosiński et al. 2012]. This material is especially important on the market of cutting tools for wood machining, the common applications being milling cutters, drills or saw blades furniture as well for broadly speaking wood industry.

However, accelerated wearing process occurs frequently, especially at high cutting speeds during machining of chipboards containing increased fraction of mineral contaminations in comparison to MDF. Tool wear mechanism consists of two effects, namely: a continuous abrasive wear with superimposed cyclic spalling of edge zone caused by direct contact with hard mineral particles (sand). According to Porankiewicz [2003], contribution of this wear is surely higher than phenomena of edge friction against wood fibers. Thus, efforts are undertaken in order to make edge surface more tough with modification based on e.g. electron beams, plasma beams, ion beams [Barlak et al. 2016] or laser beams.

Laser application is one of methods leading to changes of surface properties and outer layer of material. This procedure is also used for modification of such composite materials like cemented carbides [Arroyo et al. 2010; Da Silva et al. 2013; Karatas et al. 2007; Neves et al. 2013; Ostendorf et al. 2014]. Laser radiation with sufficient energy can indeed change material surface without affecting the bulk. [Cappelli et al. 1999], unlike the antiwear layers that can increase the tool life [Pinkowski et al. 2015] but can also affect the bulk structure.

The aim of this researches was to examine the effect of WC-Co edge modification with laser beam on tool life during milling of standard chipboards.

MATERIALS AND METHODS

Two edges knifes with dimensions 29.5×12.0×1.5 mm³, made of sintered carbide WC-Co manufactured by Faba, dedicated to hard wood species as well as to wood based composites (Fig. 1 - upper part) were used for tests. Overall 20 edges were tested: 12 reference edges and 8 edges subjected to modification with laser beam. Modification took place in laboratory of Institute of Manufacturing Technologies, Warsaw University of Technology. Edge surface was
treated with CO₂ laser beam with max. power of 2.5 kW. Argon was used as protective gas with controlled flow-rate to surface. Other parameters of the described process were as follows: wavelength \(\lambda\) - 10.6 µm, mode - TEM\(_{10}\), focus diameter - 0.7 mm, power - 1300 W, feed rate - 600 mm/min, focal length \(f\) - 5 inch. During modification process one of the edges was damaged. Therefore, for further investigations 7 edges were used (denoted with numbers from 1 to 7).

Milling was conducted at technological laboratory of the Faculty of Wood Technology of Warsaw University of Life Sciences in Warsaw. One edge milling head of Faba company with diameter 40 mm (Fig. 1 - lower part) and CNC Busellato Jet 130 working centre, were used (Fig. 2). The cutting parameters were: feed per tooth \(\Delta z\) = 0.15 mm, feed speed \(u\) = 2.7 m/min, rotational spindle speed \(n\) = 18000 rpm. Samples of dimensions 700×330×18 mm were made of commercially available three layers P4 particle board. Basic properties of this material are summarized in Table 1. The depth of grooves amounts to 6 mm. Measurement of tool wear was carried out after each cycle of wearing that is to say after 0.7 m of feed distance, what corresponds to 293.8 m of real cutting distance. Direct tool wear indicator measured on clearance face called \(V_{B_{\text{max}}} = 0.2\) mm was assumed as tool wear criterion [Wilkowski and Górski 2011].

![Fig. 1. WC-Co knife and one edge milling head Faba](image1)

![Fig. 2. Busellato Jet 130 working centre](image2)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m(^3)]</td>
<td>740</td>
</tr>
<tr>
<td>Strength to bending [N/mm(^2)]</td>
<td>33.9</td>
</tr>
<tr>
<td>Modulus of elasticity [N/mm(^2)]</td>
<td>4179.9</td>
</tr>
<tr>
<td>Hardness in Brinell scale [HB]</td>
<td>2.6</td>
</tr>
<tr>
<td>Contribution of mineral contamination [%]</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Cutting distance was calculated until tool life criterion was obtained for the modified and unmodified (reference) edges. Relative tool wear indicator was obtained according to the following equation:

\[ RI = \frac{CL_{\text{mod}}}{CL_{\text{contr}}} \]

where: \(RI\) - average relative indicator, \(CL_{\text{mod}}\) - cutting distance for modified tools, \(CL_{\text{contr}}\) - average cutting distance for unmodified tools (reference).

**RESEARCH RESULTS**

The average cutting distance observed for the modified edges amounts 3680 m, whereas for unmodified (reference) edges - 3572 m (Table 2). It is reasonable to claim that these edges
are comparable as regards durability. Average relative indicator amounts to 1.03. In Fig. 3 tool wear curves of seven modified edges are presented. The curves of four edges (No. 1, 3, 4 and 5) have untypical course, what can be explained by rapid wear process at preliminary stage of cutting (spalling) and tool wear criterion ($VB_{\text{max}} = 0.2$ mm) was reached very fast. Therefore, very short cutting distances don’t exceed 2500 m. For the same reasons, very low values of relative indicator $RI$ were obtained for the mentioned edges: from 0.04 to 0.67 (Table 2).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>No blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting length [m] ($CL_{\text{mod}}$) $VB_{\text{max}} = 0.2$ mm</td>
<td>1061</td>
</tr>
<tr>
<td>Relative indicator ($RI$)*</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 2. Tools life indicators

* relative to the control blades, unmodified, average cutting length $CL_{\text{contr}} = 3572$ m ($RI = 1.00$), $SD = 1714$ m

** standard deviation

The remaining three kinds of edges are distinguished by conventional course of tool wear curves (No. 2, 6 and 7). The highest cutting length was obtained for edge no 6 and amounted to 9401 m what can be considered as a very beneficial result as regards tool durability (more than 2.5 times higher tool life in comparison to average value obtained for unmodified edges). A relatively high spread of results was noticed for the modified edges. Standard deviation of cutting length for the modified edges amounted to 3382 m, whereas for the reference once it showed significantly lower value of 1714 m. Large diversity of results can indicate mistakes in parameters configuration during modification process with laser beam. Therefore, further research seems to be justified.

CONCLUSIONS

Comparable average tool wear indicators (average cutting length, average relative indicator) for the laser modified and reference edges were received. High diversity of results noted for the modified edges suggests further search for better choice of modification parameters.
REFERENCES

Streszczenie: Wpływ laserowej modyfikacji powierzchni na okres trwałości ostrzy WC-Co podczas frezowania płyt wiórowych. W artykule przedstawiono wpływ modyfikacji powierzchni kompozytów WC-Co wiązką lasera CO2 na trwałość ostrzy skrawających wykonanych z tych kompozytów do obróbki materiałów drzewnych. Uzyskano porównywalne średnie wskaźniki zużycia (średnia droga skrawania, średni wskaźnik
względny) dla ostrzy modyfikowanych i kontrolnych. Duża zmienność wyników ostrzy modyfikowanych skłania do poszukiwania lepszych parametrów procesu modyfikacji.

Author’s address:
Jacek Wilkowski
e-mail: jacek_wilkowski@sggw.pl
Pawel Czarniak
e-mail: pawel_czarniak@sggw.pl
Warsaw University of Life Sciences - SGGW
Faculty of Wood Technology
159 Nowoursynowska St.
02-776 Warsaw, Poland

Pawel Kołodziejczak
e-mail: pkołodzi@wip.pw.edu.pl
Warsaw University of Technology - WUT
Faculty of Production Engineering
Institute of Manufacturing Technologies
85 Narbutta St.
02-524 Warsaw, Poland

Marek Barlak
e-mail: marek.barlak@ncbj.gov.pl
Zbigniew Werner
e-mail: zbigniew.werner@ncbj.gov.pl
Bogdan Staszkiewicz
e-mail: bogdan.staszkiewicz@ncbj.gov.pl
National Centre for Nuclear Research Świerk - NCBJ
Plasma and Ion Technology Division (FM2)
7 Andrzeja Sołtana St.
05-400 Otwock, Poland