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EFFECT OF PROCESS CONDITIONS ON WATERBORNE WOOD COATING PERFORMANCE APPLIED BY DIPPING

Krasimira ATANASOVA[1], Viktor SAVOV[1]

Abstract: *Bio-based commercial coating systems are still not widely used to protect wooden elements and constructions used outdoors. In some cases, this is due to insufficient information about the technology and conditions of the film formation process. The present research aims to determine the influence of the process conditions on the properties of a coating applied by dipping on spruce, beech, and beech plywood surfaces. A waterborne one-component bio-based varnish system was used. The study researched the following parameters: amount of varnish applied, varnish penetration into the wood, and roughness of the surfaces after coating and drying. The variables investigated were the dipping orientation to the grain direction in the wood specimens, the wood surface treatment before coating, and the dipping time. Polynomial regression models were derived. It was established that with a single dip for 5 seconds, surfaces with a good appearance were obtained, but the varnish amount exceeded the norms recommended by the manufacturer several times. When axially dipping spruce and beech specimens, the varnish amount was the least when the surfaces were sanded with P150 grit size sandpaper. For the plywood specimens, the treatment had no effect. In tangential dipping, the characteristics of the wood species determined the varnish amount and the roughness parameter values. The sanding process had a more significant influence than the sandpaper grit size. The penetration was affected by the wood species characteristics, the wood surface treatment before coating and the dipping time. In axial dipping, the penetration was times greater than in tangential dipping.*

Key words: *waterborne coating, bio-based coating, dipping, spruce, beech, beech plywood.*

1. Introduction

Waterborne coating systems are usually emulsions or colloidal dispersions. Water is an ecological dispersion medium that is less expensive than organic solvents and is available nearly everywhere [20]. It does not change the colour of the product in which it is included. Waterborne one-component coatings dry physically. They

[1] University of Forestry, 10 St. Kliment Ohridski Blvd., 1797 Sofia, Bulgaria;
Correspondence: Krasimira Atanasova; email: k_atanasova@ltu.bg.

show less loss of adhesion strength after ageing compared to solvent-based ones [14]. The adhesion of physically drying systems is mainly mechanical [5, 7]. A prerequisite for achieving high mechanical adhesion of coating is to increase the roughness of its substrate [8, 25, 29]. Sanding can increase the substrate roughness [17, 28]. At the same time, sanded wood surfaces are unstable due to wetting [7, 18, 19, 24]. Due to the short-term contact of the liquid with the substrate during film formation, instability is limited to the surface layer (grain raising) [23]. In addition to sanding, grain raising is affected by the amount of applied liquid system [7] and by the wood substrate characteristics (structure, direction of wood grains, density, chemical composition, etc.) [13, 25, 26]. Sanded surfaces swell significantly, but grain raising can be controlled by changing the sanding parameters [13]. Grain raising increases when the liquid system amount rises [7], and the wood substrate density decreases [13, 25].

Bio-based systems are mixtures in which synthetic polymers extracted from fossil resources (or parts of them) are replaced by bioproducts. Bioproducts are a natural part of the circular economy.

The waterborne bio-based systems offered in the Bulgarian commercial network have relatively high prices, and insufficient information about the coating technologies determines their low consumption.

For these reasons, in the Furniture Production department of the University of Forestry, Sofia, a complex study is being conducted on the properties of waterborne coating system, named "Bio-based wood stain", and the coating performance. In previous studies, it was found that the Bio-based wood stain is a low-viscosity liquid system. The flow time is 21 s using a 4 mm flow cup. According to the calculations, the solid content of the varnish system is 17%. The dry coating is extremely thin using the selected application varnish amount (according to the manufacturer's recommendations). The solidified coatings were hydrophobic but water-permeable, according to the standard CSN EN 927 – 5 [4]. If applied by brush, the coatings should be at least two layers. The two-layer coatings have a rich colour and a faint pearl-like gloss. Their adhesion strength is above the required limit [12]. Different adhesion strength values were obtained for various wood substrates (spruce - 2.7 N/mm^2, beech - 3.1 N/mm^2, and beech plywood 2.9 N/mm^2 [6]). Applying a certain amount of stain is necessary to achieve a uniform colour and good spreading on the surfaces of different wood species, not corresponding to the recommendations of the manufacturer. When applying the next layer, the colour becomes more saturated and the gloss increases. The substrate structure affected the coating performance more than the fine sanding before varnishing. According to previous studies, the basic universal parameters for technological control are the arithmetic mean deviation of the assessed profile (*Ra*), the mean width of the profile elements (*RSm*), the reduced peak height (*Rpk*), and the composite parameter *Rpk+Rk+Rvk*, where *Rk* is core roughness depth and *Rvk* is reduced valley depths. When the variance of *Rpk* values is too large and many measurements are needed, *Rk* or the composite parameter *Rpk+Rk* can be used with sufficiently high precision.

The object of the present research was to study the performance of coatings applied by dipping.

The liquid wets the surface during dipping, creating adhesion bonds in the contact area. Part of it penetrates the wood substrate, and another portion remains on the surface where it solidifies. Penetration is an essential factor in bond formation and is mainly related to the solid surface structure [9, 27]. Nussbaum [21] investigated the penetration of waterborne alkyd emulsions and solvent-borne alkyds applied to wood surfaces. Penetration was found to depend on the wood species, with penetration in the tangential direction occurring mainly through the radial rays. Systems of comparable viscosity and pigmentation also have a similar ability to penetrate the wood. Subsequent studies reported improved penetration for coatings applied to sawn and rough wood surfaces compared to planed and smooth surfaces [22]. Studies by De Meijer et al. [10, 11] add that binder type, solid matter content, drying speed, and cell capillary radius influence the penetration depth variation.

As mentioned, the investigated varnish system is low-viscosity, non-pigmented, and low solid content. This suggests high penetration, especially in the wood grain axial direction. The high degree of penetration leads to a significant varnish system consumption. In such an aspect, the research aims to determine the effect of the orientation of the grain direction at dipping of the wood specimens, the wood surface treatment before coating, and the dipping time on the amount of varnish applied, the varnish penetration into the wood, and the surface roughness after coating, when the coating system is applied by dipping.

2. Materials and Methods

2.1. Materials

Bio-based wood stain for outdoor application produced by Industrias Químicas Masquelack, S. A. - Spain was used for the study. According to the manufacturer's specifications [16], the varnish system was one-component waterborne, with a deficient volatile organic compounds (VOC) content. It should be applied by brush, roller, dipping or spraying. It quickly dries and creates a water-resistant, breathable, flexible open-pore film. The recommended amount for one-layer coating: 70 - 87 g/m^2.

The Bio-based Wood Stain is a plant-based alternative to acrylic technology [15].

For this study, specimens of spruce (*Picea abies* Karst.) with an average density of 440 kg/m^3, beech (*Fagus sylvatica* L.) with an average density of 730 kg/m^3, and beech plywood with an average density of 750 kg/m^3 were selected. The beech and spruce surfaces were plane-milled. The manufacturer (S.C. Cildro Plywood, Romania) sanded the plywood surface with P80-120 grain size sandpaper. The specimens were chosen for their lack of defects, such as knots, cracks or resin spots.

2.2. Preparation of Specimens

The materials were conditioned for a month at 20 ± 2°C and 65 ±5% R.H.

Two groups of specimens from each wood species were prepared.

To carry out the study for penetration along the length of the wood grains (axial dipping), details with a cross-section of 70 x 20 mm from spruce, 70 x 20 mm from beech, and 70 x 15 mm from beech plywood were prepared. The orientation of the wood grains from the face layer was adopted for plywood. The details were varnished three times with a two-component polyurethane (PU) varnish along its perimeter. After PU coating solidification, the details were cut with a circular saw into specimens with a length of 50 mm. They were divided into three groups: dipping without pre-treatment, dipping after sanding with *P150* grit sandpaper, and dipping after sanding with *P320* grit sandpaper.

For the penetration test in the direction tangential to the wood grains (tangential dipping, side of the details), test specimens with a cross-section of 70 x 70 mm were cut: 27 pieces for spruce, 27 pieces for beech, and 27 pieces for beech plywood. A three-layer PU coating was applied on all sides, without one face. The specimens were divided into three groups: dipping without pre-treatment, dipping after sanding with *P150* grit, and dipping after sanding with *P320* grit. It was sanded after PU coating solidification.

2.3. Test Procedures

Moisture content was measured with a contact hydrometer (Hydromette Compact, Gann, Germany).

The weight method measured the varnish amount, and before measuring, the varnish was wiped from the PU-varnished surfaces.

The time for which the coatings were dry to the touch was measured.

The degree of penetration was assessed visually by the wood colouration. Two indicators were used: maximum penetration depth and penetration intensity (the uniformity and saturation of the visible colouration of the wood due to penetration).

The roughness parameters were measured using a Mitutoyo SJ-210 surface roughness tester with a tip radius of the diamond stylus R = 5 µm, according to standard ISO 3274:1996 [1]. The settings are presented in Table 1.

Roughness parameter measurement settings Table 1

Settings	Units	Dipping direction relative to wood grains	
		tangential	axial
Profile	-	R	R
Profile filter	-	Gauss	Gauss
Cut-off length (*l*)	mm	2.5	2.5
Number of cut-off lengths (*n*)	-	6	4
Evaluation length (*ln*)	mm	15	10
Measuring speed	mm/s	0.25	0.25

The measurement was carried out in the same evaluation lengths after each treatment.

The following parameters were selected for analysis and evaluation:

- arithmetic mean deviation of the assessed profile (*Ra*) according to standard ISO 4287:1997 [3];
- core roughness depth (*Rk*), reduced peak height (*Rpk*), reduced valley

depths (*Rvk*), according to standard ISO 13565-2:1996 [2];
- the composite parameter *Rpk+Rk+ Rvk*.

2.4. Regression Models

Experiments were based on optimal composition Bm-type plans [30].

The polynomial used has the form from Equation (1).

These are the structure of the wood substrate and, in particular, the direction of the wood grains; grain raising, density, hardness, and moisture content of wood; temperature and humidity of the environment; speed of dipping and extraction of the details, etc.

$$Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_{11} \cdot x_1^2 + b_{22} \cdot x_2^2 + b_{12} \cdot x_1 \cdot x_2 \quad (1)$$

where:

x_1 and x_2 are the controllable factors

b_0 – the coefficient which reflects the influence of the uncontrollable factors for the particular model.

The coefficients in front of the controllable factors (b_1, b_2, b_{11}, b_{22}, b_{12}) reflect the magnitude and direction of the specific influence. The degree of agreement of the model with the measured data values is represented by the correlation coefficient R^2. With R^2 = 1, there is a 100% model fit.

Controllable factors were selected for the present experiment:

- dipping time (x_1), at change levels: 5 seconds; 30 seconds; 55 seconds;
- surface treatment (x_2), at change levels: untreated surface within the experiment; surface sanded with *P150* grit sandpaper; surface sanded with *P320* grit.

With the change levels chosen in this way, the interpretation of the models considers that the sanding process is affected differently by the sandpaper grit size. In such an aspect, the models related to beech and spruce were used only and exclusively to determine the influence of the controllable factors at the selected levels.

QSTASTLAB software was used to create and verify the regression models.

2.5. Preliminary Experiments

A preliminary experiment was conducted to determine the value of the lowest level of the dipping time variation. The behaviour of Bio-based wood stain drops with a volume of 2.5 µl on specimens identical to those of the tangential dipping series was observed. The reported equilibrium wetting angles were between 25° and 45° for all surfaces. The shortest absorption time was reported for spruce, which was less than *5* seconds. This value was the lowest level of the "dipping time" factor. According to the experiment plan requirements, the other levels were chosen for technological reasons.

Before starting the experiments, the measured moisture content of the control specimens was 11 ± 1% for spruce and beech, and 9 ± 1% for beech plywood.

3. Results and Discussion

3.1. Dipping, Spreading, Drying. Appearance of the Solidified Coating

3.1.1. Axial Dipping

No peculiarities were observed when dipping the specimens. After removal, a uniform homogeneous layer of Bio-based wood stain was observed. After solidification, the surfaces of the spruce and beech specimens acquired a saturated colour and a distinct texture (Figure 1). During the drying of the plywood samples in places, the stain retreated, forming pale coloured spots. They remained on the surface until the final coating solidification. Similar defects were observed on all plywood specimens. The mechanism of their appearance suggests weak adhesion bonds. That may be due to the adhesive in the plywood.

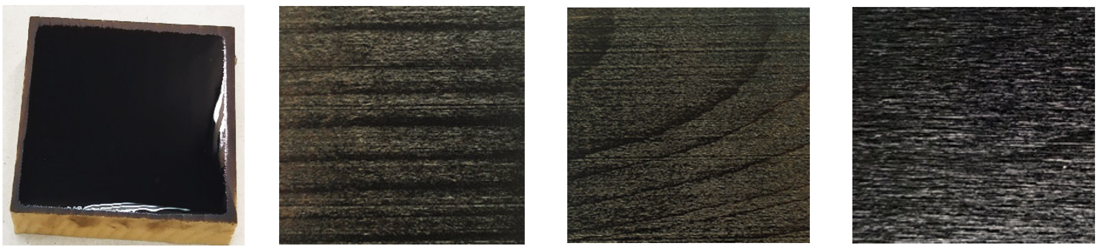
The drying time for all the specimens in axial dipping was between 40 and 50 minutes.

a. b. c.

Fig. 1. *Wood surfaces after dipping in an axial direction: a. spruce; b. beech; c. beech plywood*

3.1.2. Tangential Dipping

After removing the samples, the good wetting and uniform spreading of the liquid system were observed, while measuring the varnish amount without bubbles or irregularities (Figure 2). The coating drying time was between 100 and 120 minutes. A shorter drying time was observed when the plywood was sanded with *P320* grit. With spruce, the time increased when sanding with P*150* grit and reached 180 min for the untreated surfaces. After the coating solidification, the resulting surfaces had a saturated colour, a distinct texture, and a faint pearl-like gloss (Figure 2).



a. b. c. d.

Fig. 2. *Wood surfaces after tangential dipping: a. wet surface; b. spruce; c. beech; d. beech plywood*

The colour was darker, and the texture was more embossed than a two-layer brush-applied coating. A difference in the shades of the test samples from each group was hardly noticeable. From a decorative viewpoint, applying a second layer of the liquid system was unnecessary.

3.2. Regression Models

The derived regression models are presented in Tables 2 - 4.

The presented models differ significantly from each other. Constant values, linear models, and quadratic equations were observed.

Regression models, labels, and correlation coefficients (R^2) for spruce Table 2

Wood species	Label	Regression model	R^2
Spruce	*S1*	$Q_a = 352.020 - 50.915 \cdot x_2 + 75.835 \cdot x_2^2$	0.94
	S2	$Q_t = 291.571 + 14.553 \cdot x_1 - 24.012 \cdot x_2 - 51.242 \cdot x_2^2$	0.99
	S3	$R_a = 4.628 - 2.428 \cdot x_2 + 1.808 \cdot x_2^2$	0.98
	S4	$R_k + R_{pk} + R_{vk} = 29.644 - 15.702 \cdot x_2 + 11.438 \cdot x_2^2$	0.97
	S5	$R_k = 14.049 - 6.557 \cdot x_2$	0.96
	S6	$R_{pk} = 8.261 - 5.680 \cdot x_2$	0.92
	S7	$R_{vk} = 7.327 - 3.465 \cdot x_2 - 1.695 \cdot x_1^2 + 3.615 \cdot x_2^2$	0.99

Regression models, labels, and correlation coefficients (R^2) for beech Table 3

Wood species	Label	Regression model	R^2
Beech	*B1*	$Q_a = 279.310 + 76.187 \cdot x_1 - 46.787 \cdot x_2 + 60.090 \cdot x_2^2 + 34.645 \cdot x_1 \cdot x_2$	0.99
	B2	$Q_t = 228.222$	0.84
	B3	$R_a = 4.588 - 1.935 \cdot x_1 + 2.928 \cdot x_2^2$	0.94
	B4	$R_k + R_{pk} + R_{vk} = 30.197$	0.86
	B5	$R_k = 13.638 - 6.165 \cdot x_1$	0.90
	B6	$R_{pk} = 7.164$	0.87
	B7	$R_{vk} = 9.398 - 5.528 \cdot x_1 + 2.637 \cdot x_2 + 8.103 \cdot x_2^2$	0.84

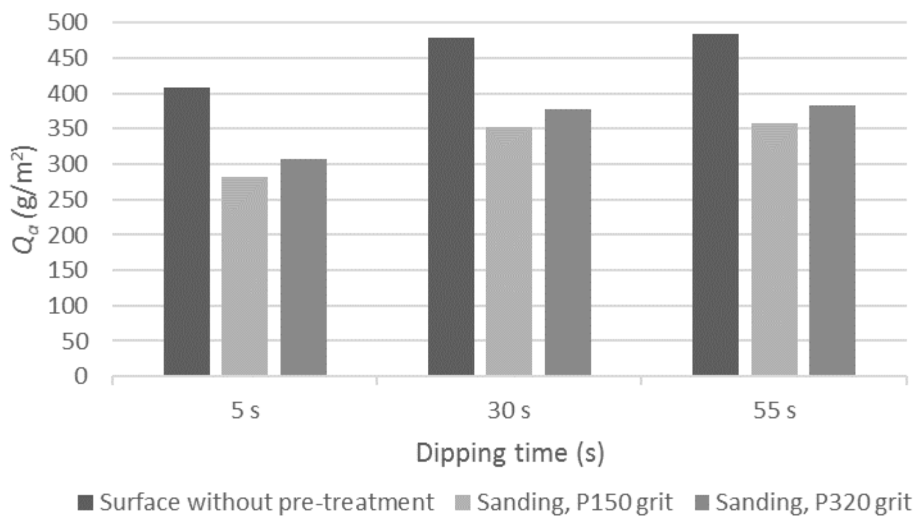
Regression models, labels, and correlation coefficients (R^2) for beech plywood Table 4

Wood species	Label	Regression model	R^2
Beech plywood	*Bp1*	$Q_a = 263.548 + 94.135 \cdot x_1$	0.90
	Bp2	$Q_t = 264.402 + 32.578 \cdot x_1$	0.94
	Bp3	$R_a = 8.611 - 1.900 \cdot x_2 + 2.143 \cdot x_2^2$	0.99
	Bp4	$R_k + R_{pk} + R_{vk} = 56.454 - 11.863 \cdot x_2 + 8.113 \cdot x_2^2$	0.97
	Bp5	$R_k = 19.193 + 2.110 \cdot x_1 - 7.670 \cdot x_2 + 9.040 \cdot x_2^2$	0.99
	Bp6	$R_{pk} = 13.983$	0.65
	Bp7	$R_{vk} = 23.274$	0.76

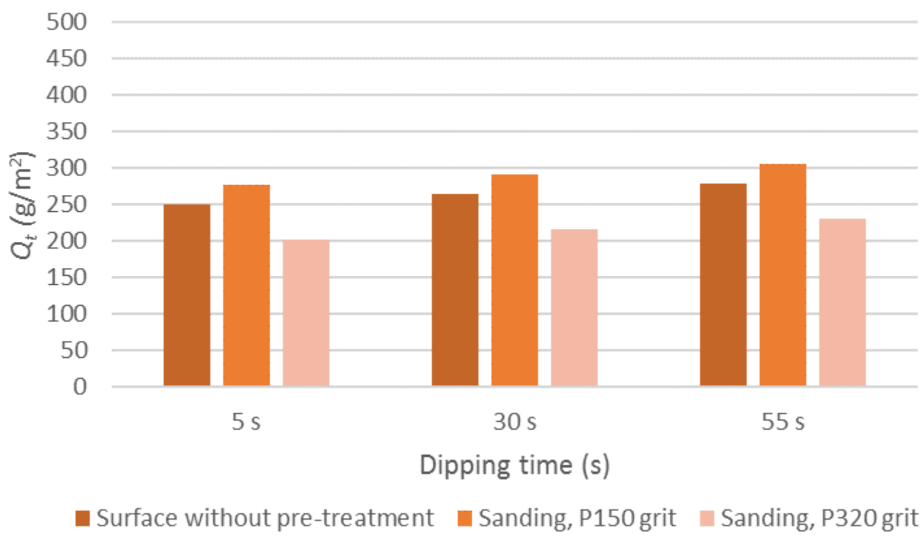
The correlation coefficient R^2 is high enough to interpret the patterns. The large values of b_0 in all equations indicate the determining importance of the volume and surface wood substrate properties (density, structure, and geometric parameters of the surface, grain raising) on the values of the investigated parameters before processing.

It is established that the influence of the direction of the wood grains when dipping is represented by models 1 and 2, which reflect respectively the amount of varnish applied (*Q*) when dipping in the axial direction of the wood grains (*Qa*) and the amount of varnish used when dipping in the transversely tangential direction of the wood grains (*Qt*) for the three groups of specimens. The treatment before coating affects the spruce samples more than dipping time. This observation corresponds with the conclusions of a study by Sansonetti et al. [26] for waterborne eco-friendly paint applied by dipping on spruce wood. As a result of sanding, *Qa* decreases and *Qt* increases. In both directions, the amount of varnish used is greater than recommended by the manufacturer. Graphical solutions of both models are presented in Figure 3.

Spruce roughness parameters are mainly affected by surface treatment before coating. Models *S3*, *S4,* and *S7* reflect the influence of the sanding process. The change in the sandpaper number from *P150* to *P320* and the change in the dipping time in S7 do not significantly impact the values of the studied parameters - Figure 4. In models *S5* and *S6,* the connections are linear, inversely. As the sandpaper number increases, *Rk* and *Rpk* decrease.

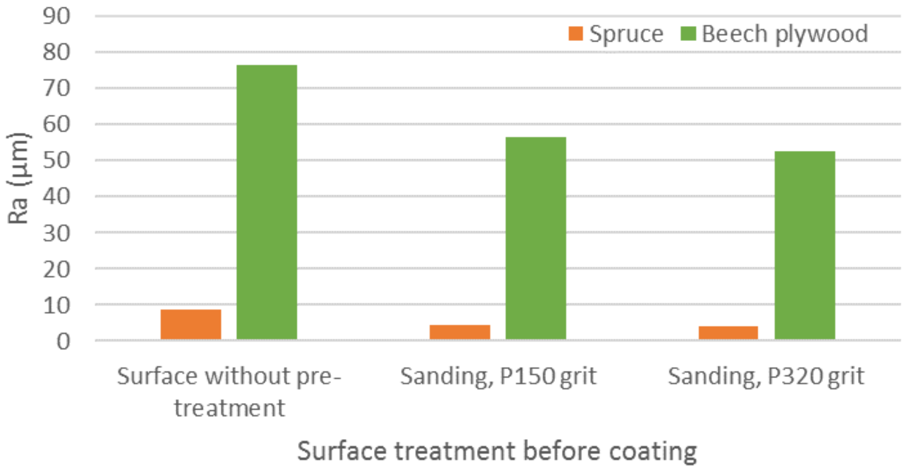


a.

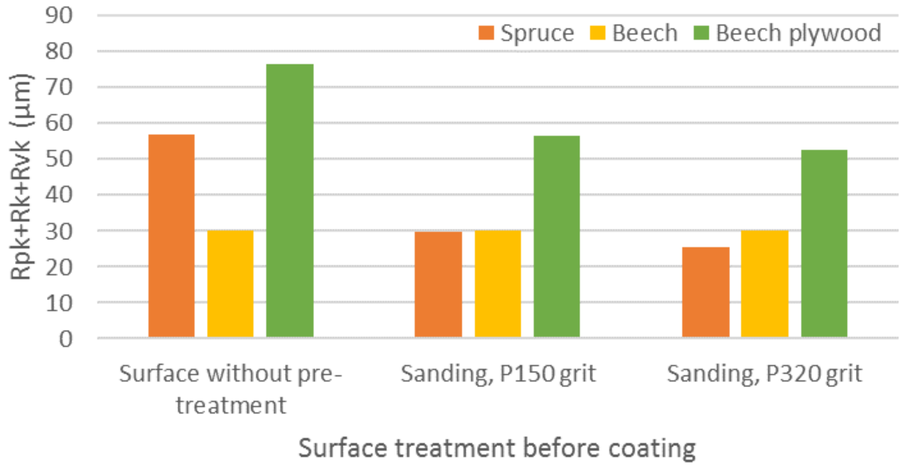


b.

Fig. 3. *Spruce – effect of the direction of wood grains when dipping: a. the wood surface treatment before coating; b. the dipping time on the amount of varnish applied*



a.



b.

Fig. 4. *Changes of the roughness parameters: a. graphical solution of equations S3, Bp3; b. graphical solution of equations S4, B4, and Bp4*

In beech, the *Qα* was influenced by all the factors studied. A graphical solution is presented in Figure 5. In tangential dipping, the wood characteristics that limit the liquid penetration are decisive: density (a small number of pores with a small diameter) and hardness. Further, the amount of varnish applied is greater than recommended by the manufacturer.

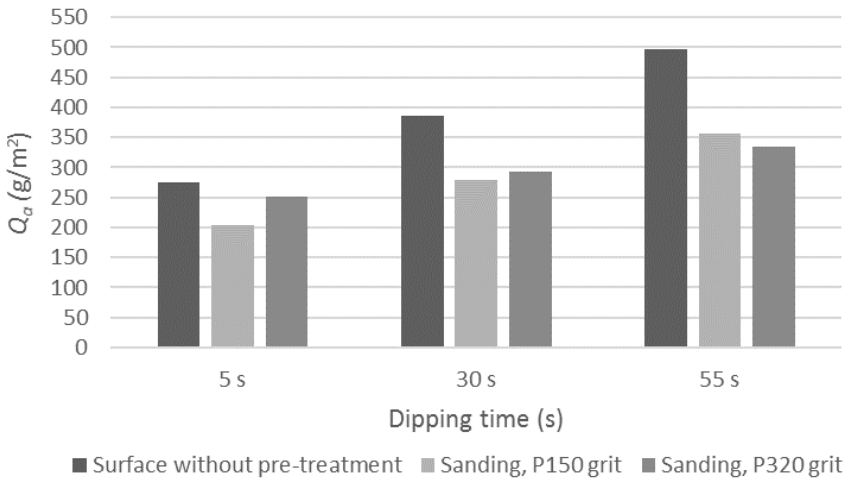


Fig. 5. *Beech – effect of the wood surface treatment before coating and the dipping time on the amount of varnish applied after axial dipping (Qa)*

The arithmetic mean deviation of the evaluated profile is complexly influenced by the two investigated factors (model *B3*). The graphical solution (Figure 6) shows the same values of the parameters for the untreated surfaces and the surfaces sanded with *P320* grit.

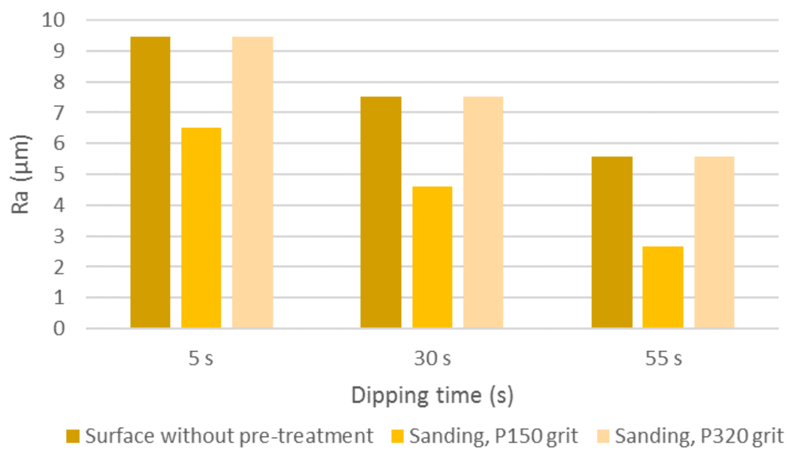


Fig. 6. *Beech – effect of the wood surface treatment before coating and the dipping time on Ra*

Unlike the spruce models, *B4* and *B6* are constant values. In this aspect, the *Rk* (B5) and *Rvk* (B7) models in beech are interesting. A strong inversely linear dependence on the dipping time is observed (Figure 7). While in spruce, the liquid system passes through the zones of *Rk* and *Rpk* and affects *Rvk*, in beech, the influence expands, covering the zone of *Rk*.

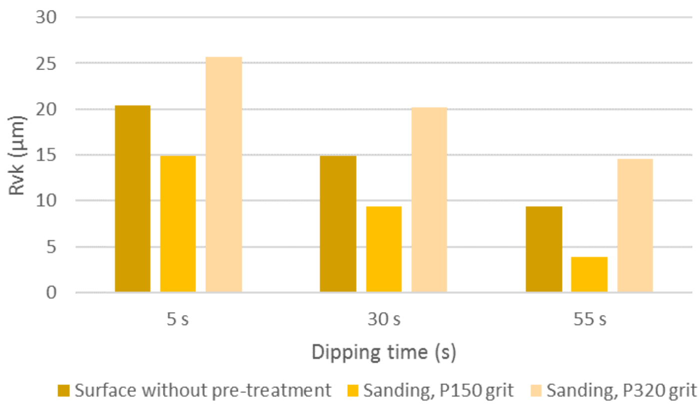


Fig. 7. *Beech – effect of the wood surface treatment before coating and the dipping time on Rvk*

Plywood surfaces are characterised by micro cracks [7], which favour the entry of liquid systems into them. High pressing pressure, the adhesive presence, and crossed wood grains increase density and limit penetration in this direction. The two presented models show a linear, directly proportional dependence on dipping time and an insignificant influence of the processing at close values of the free coefficients (Figure 8). All measured *Q* values are greater than those recommended by the manufacturer.

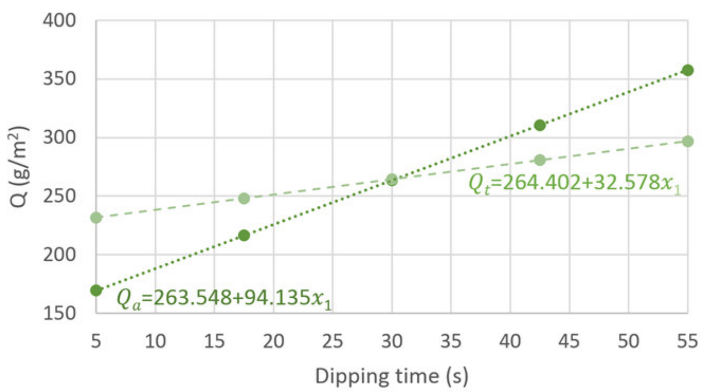


Fig. 8. *Beech plywood – graphical solutions of models Bp1 (Qa) and Bp2 (Qt)*

The larger plywood values compared to the *Qt* values for beech can be explained by the larger actual surface area of the plywood due to factory sanding. The treatment is decisive in the roughness models Bp3 and Bp4 (Figure 4). The change in the number of sandpaper from *P150* to *P320* has a greater but insignificant influence on the values of the investigated parameters compared to the spruce and beech surfaces. In the composite parameter *Rk+Rpk+Rvk*, the effect of *Rk* prevails. The constant value of *Rpk* can be explained by the beech substrate characteristics (models *B2*, *B6*) and *Rvk* - by the adhesive presence and pressing when obtaining plywood. A graphical solution of the *Bp5* model is presented in Figure 9.

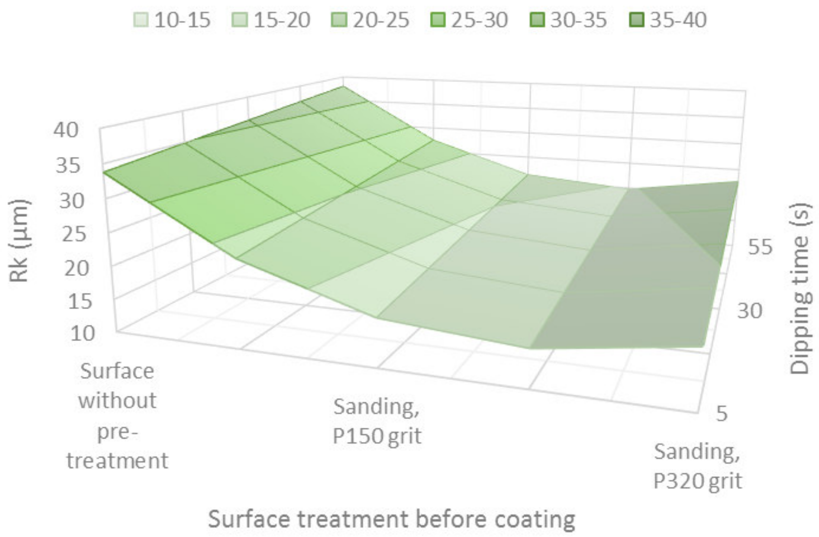


Fig. 9. *Beech plywood – graphical solution of model Bp5*

3.3. Changes in the Profiles of the Investigated Surfaces as a Result of Dipping

Figures 10, 11, and 14 show the surface profiles before and after axial dipping. Spruce showed the most significant grain raising (Figure 10). It is more pronounced in earlywood in beech, the grain raising is smaller and evenly distributed (Figure 11).

The influence of the wood structure is expressed in the preservation of the type of surface profile.

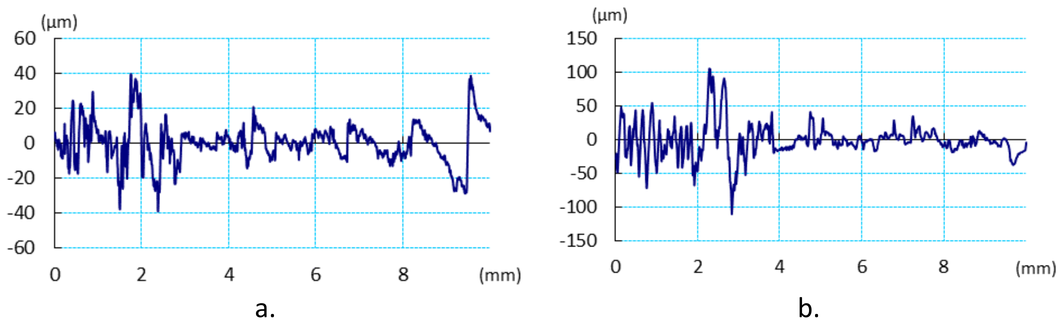


Fig. 10. *Spruce – surface profile change after axial dipping:*
a. surface profile without pre-treatment; b. surface profile after dipping

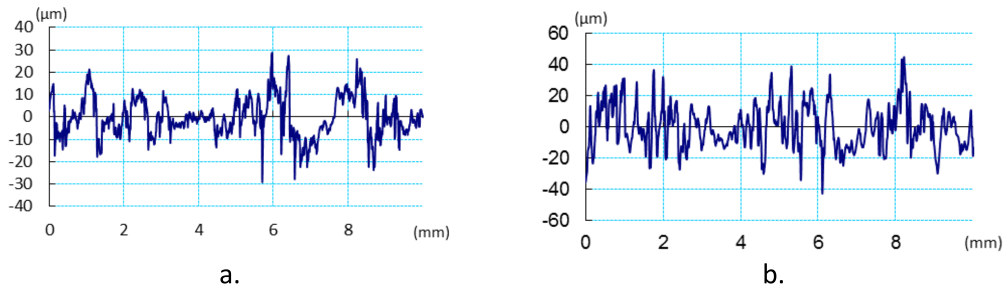


Fig. 11. *Beech – surface profile change after axial dipping:*
a. surface profile without pre-treatment; b. surface profile after dipping

Figures 12 and 13 show the spruce and beech surface profile changes in the tangential dipping processing phases. The grain raising is less pronounced. A significant similarity was observed between the profiles of the surfaces without pre-treatment and those of the surfaces after dipping compared to the profiles after sanding and the profiles after dipping.

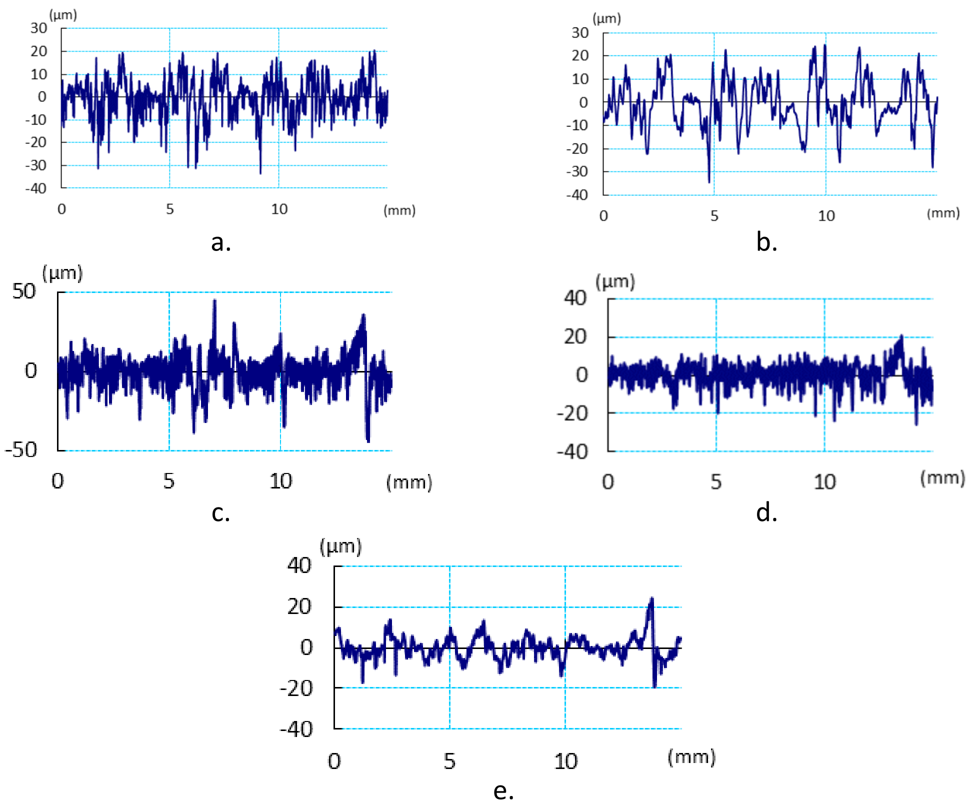


Fig. 12. *Spruce – surface profile change after tangential dipping: a. surface profile without pre-treatment; b. surface profile without pre-treatment after dipping;*
c. surface profile without pre-treatment; d. sanded surface profile;
e. sanded surface profile after dipping

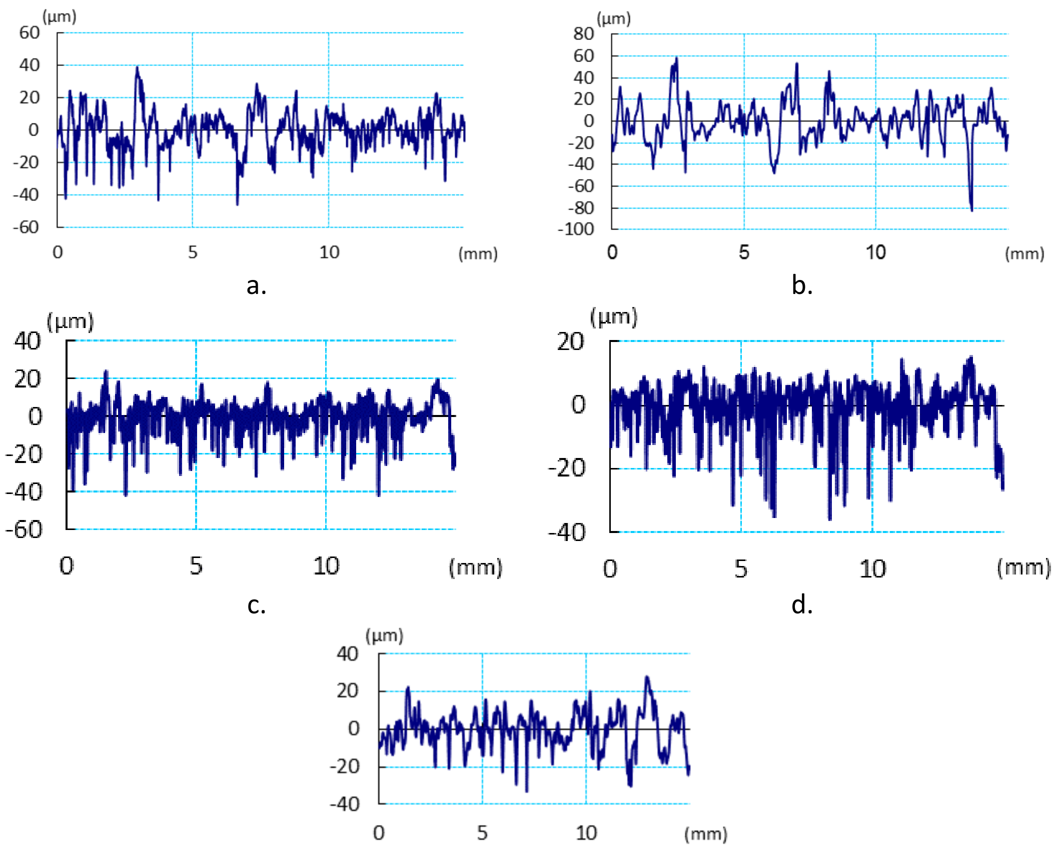


Fig. 13. *Beech – surface profile change after tangential dipping: a. surface profile without pre-treatment; b. surface profile without pre-treatment after dipping; c. surface profile without pre-treatment; d. sanded surface profile; e. sanded surface profile after dipping*

Under the conditions of the current experiment the amount of varnish applied, the wood structure, and sanding had a mixed effect and were partially balanced. As a result, the surface profile parameters approach the surface parameters after dipping without pre-treatment.

It is fair to note that dipping affects the profile type of beech surface to a greater extent than the spruce surface (Figure 13). The established significant changes below the median line are reflected in models *B5* and *B7* by the presence of the significant coefficients b_1. Due to limited grain raising, the surface profile changes are minor when axially dipping beech plywood (Figure 14).

When tangentially dipping a plywood surface, grain raising cannot be detected (Figure 15). The densification of the beech wood can explain that during pressing. Upon dipping, the liquid fills the micro irregularities, which causes the surface profile to change.

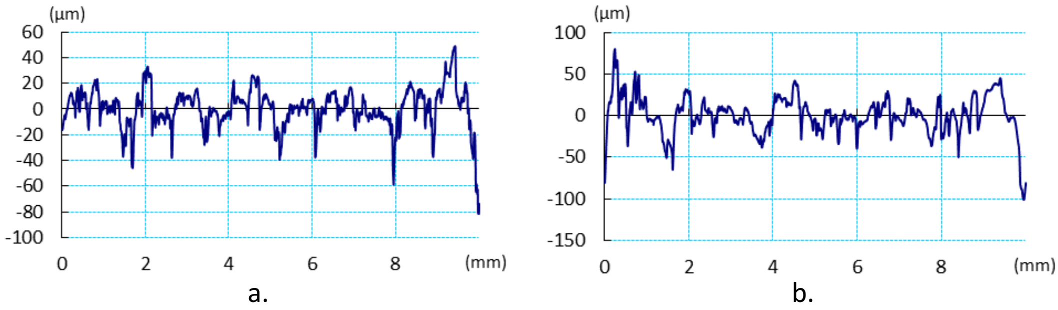


Fig. 14. *Beech plywood – surface profile change after axial dipping:*
a. surface profile without pre-treatment; b. surface profile after dipping

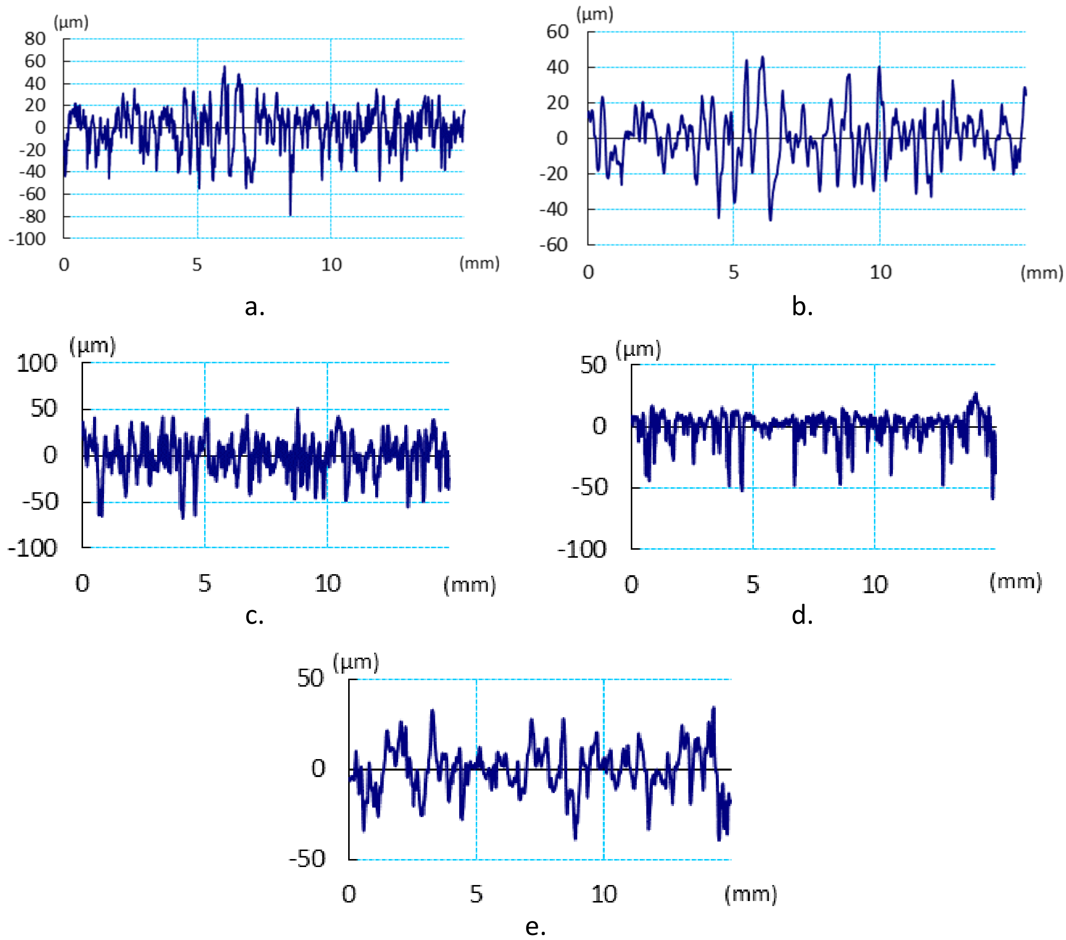


Fig. 15. *Beech plywood – surface profile change after tangential dipping:*
a. surface profile without pre-treatment; b. surface profile without pre-treatment after dipping; c. surface profile without pre-treatment; d. sanded surface profile;
e. sanded surface profile after dipping

3.4. Penetration
3.4.1. Axial Dipping

Spruce

Under the experiment conditions, due to the significant difference in the liquid system intensity of penetration in the early and late wood, it is difficult to derive a regression model (Figure 16). While the liquid system penetration to 1.5 mm in depth was found in the early-wood, penetration was minimal in the latewood. The largest penetration depth was observed for the sample without a pre-treated surface and a dipping time of 55 seconds. There are no data for scientifically based conclusions regarding the correlations between the amount of varnish applied and the extent of its penetration into the wood.

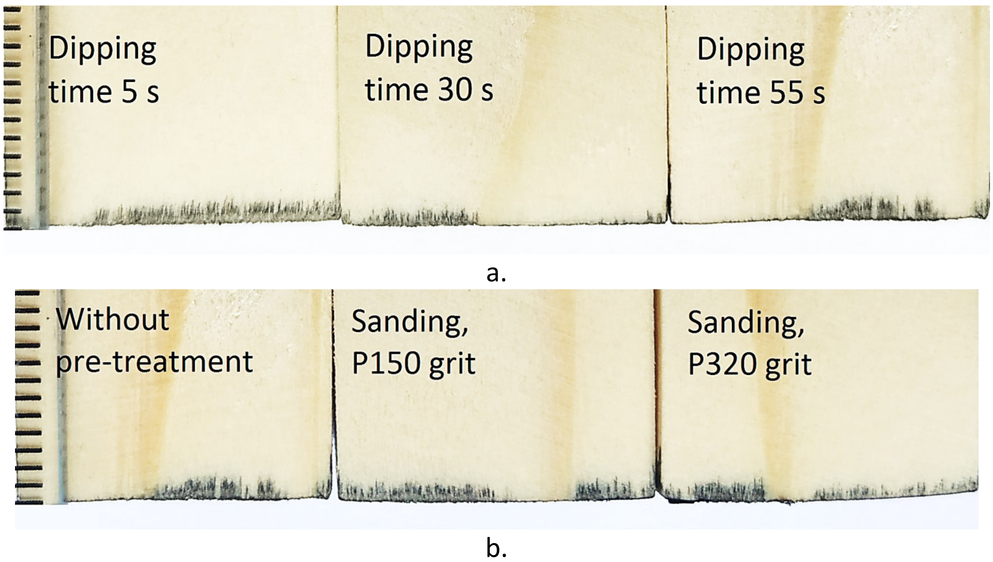


Fig. 16. *Spruce – penetration after axial dipping:*
a. specimens without pre-treatment; b. dipping time 55 seconds

Beech

Significant liquid system penetration was found in the specimens without pre-treatment. The maximum depth reaches 3 mm (Figure 17). The penetration intensity depends on the dipping time. The intensity decreases significantly in the sanded surfaces and the maximum depth reaches 2 mm. Penetration is the least when sanding with *P150* grit.

Plywood

Maximum depth penetration of the stain was found in the central part of the internal axially oriented layers (4 mm) and significantly less (1 mm) in the tangentially oriented layers (Figure 18). The dependence on dipping time is seen, which is consistent with the regression model. Treatment dependence is also clearly visible. In the case of surfaces without pre-treatment, penetration is mainly in the axial layers. In the sanded samples, the penetration in the axial direction reaches 2.5 mm but is less intense. Penetration to 1 mm was observed in the tangentially oriented layers when the surface was sanded with *P320* grit. The discrepancy with the regression model can be explained by the more significant relative proportion of the tangentially oriented layers in the studied section and the inverse ratio between the amount of Bio-based wood stain penetrated in the differently oriented layers when changing the "surface treatment" factor levels.

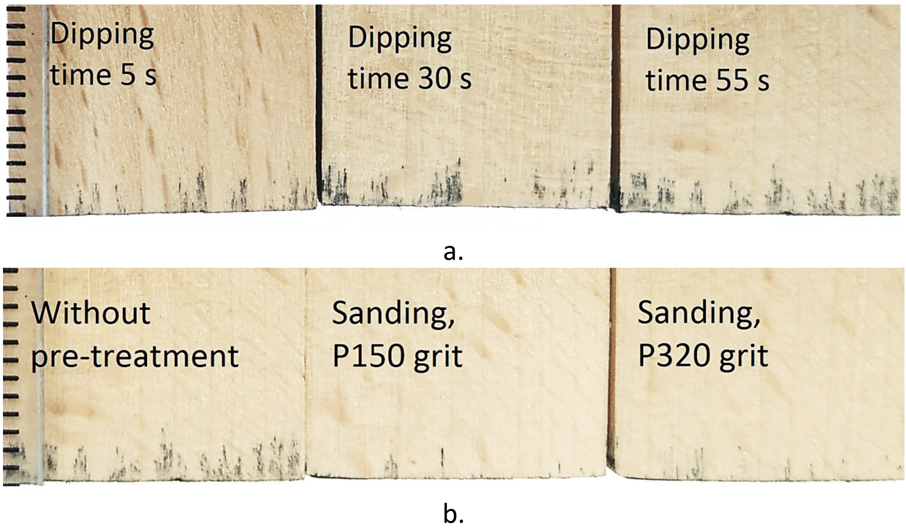


Fig. 17. *Beech – penetration after axial dipping:*
a. specimens without pre-treatment; b. dipping time 55 seconds

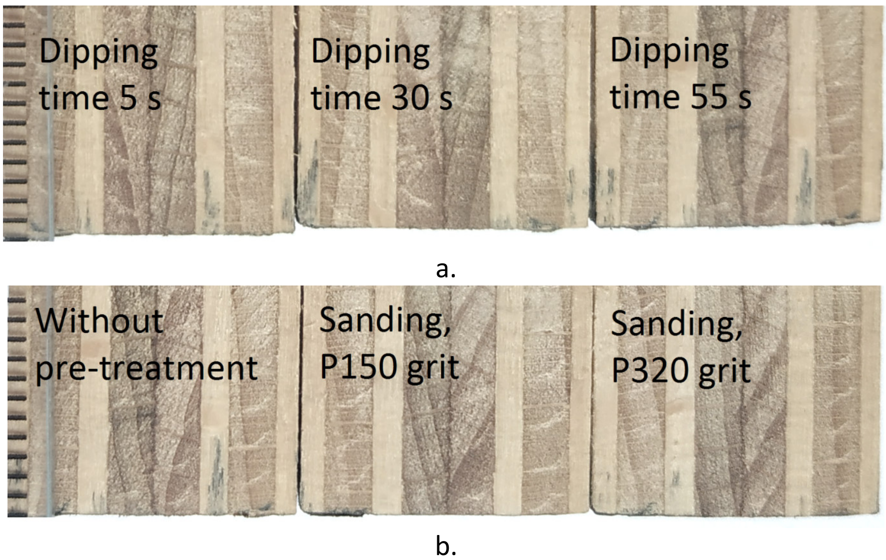


Fig. 18. *Beech plywood – penetration after axial dipping:*
a. specimens without pre-treatment; b. dipping time 55 seconds

3.4.2. Tangential Dipping

Spruce

A low degree of Bio-based wood stain penetration in the tangential direction of the wood grains was found. The maximum penetration depth (below 0.5 mm) was observed with a dipping time of 55 s and sanding of the substrate with *P150* grit, corresponding to model *S2*. A change in flatness was found on a surface without pre-treatment and a dipping time of *30 s* (Figure 19). This is due to the higher initial roughness of the specimen surface (influence of wood structure).

Beech

The penetration depth is below 0.5 mm (Figure 20). At this scale, the only dependence that can be found is that the penetration in the "tangential direction" is times less than the penetration in the "axial direction".

Plywood

The penetration found is much less than the "axial direction" penetration. At this scale, no other dependence can be established.

Fig. 19. *Spruce – penetration and grain raising after tangential dipping*

Fig. 20. *Beech – penetration after tangential dipping*

4. Conclusions

The presented study evaluated a bio-based waterborne coating applied by dipping on spruce, beech, and beech plywood surfaces. The studied parameters, i.e. amount of varnish applied, varnish penetration into the wood, and roughness of the surfaces after coating drying, were influenced differently by the variable conditions: dipping orientation to the grain direction in the wood specimens, wood surface treatment before coating, and dipping time. To obtain coatings with a good appearance, it was sufficient to dip the surfaces once for 5 seconds. Under these conditions, the amount of varnish applied exceeded the manufacturer's recommended norms several times in both dipping directions. This means that the appearance of the coating and the amount of varnish applied cannot be controlled by the dipping time. When axially dipping spruce and beech specimens, the varnish amount was the least when the surfaces were sanded with *P150* grit. For the plywood specimens, the treatment had no effect. In tangential dipping, the characteristics of the wood species determine the varnish amount and the roughness parameter values. The sanding process has a more significant influence than the sandpaper grit size. It is necessary to continue the research in order to specify the choice of the most suitable grit size, depending on the wood surface type. The maximum depth and the intensity of the penetration depend on the wood species, the wood surface treatment before coating, and the dipping time. In axial dipping, the penetration is times greater than in tangential dipping. Before dipping cross-cut grain surfaces, it may be recommended that they be treated with bio-based stain applied by brush or with another compatible primer.

The information provided in this study may be useful to optimise the conditions of the film-forming process for the investigated coating system, which will lead to an increase in its consumption.

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