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ROUGHNESS PARAMETERS OF BIO-BASED COATING APPLIED TO WOOD SURFACES

Krasimira Atanasova – Dimitar Angelski

ABSTRACT

This research is part of a study to determine the properties of a multilayer waterborne bio-based coating. The liquid system was applied to spruce (*Picea abies* Karst.), beech (*Fagus sylvatica* L.), and beech plywood by brush. The influences of the wood substrate structure and the surface characteristics before coating, the surface treatment before coating, the amount of varnish recommended by the manufacturer, and the number of applied layers on the appearance and roughness of the resulting surfaces were analyzed. The roughness was evaluated by the profile amplitude parameters and the material ratio curve parameters for each of the film formation process phases. It was necessary to apply a two-layer coating on all test surfaces to obtain a good appearance. It was also found that the amount of varnish recommended by the manufacturer is inappropriate when applied to beech and beech plywood. The wood substrate structure and its surface characteristics before coating had a determining influence on the roughness parameters in the last phase of the film formation and on the appearance of the varnished surfaces. The treatment before coating had little effect on the final coating parameters. Roughness parameters suitable for evaluating changes in surface profiles for each of the processing phases were proposed.

Keywords: roughness; waterborne coating; bio-based coating; beech; spruce.

INTRODUCTION

Fossil resources are the main raw materials for manufacturing chemical products for coating formulation (https://www.covestro.com). With the global energy crisis deepening, it is necessary to replace them with alternative raw materials. At the same time, due to the ongoing pollution of the environment, it is essential to use products that do not disturb the ecological balance. A solution to both problems is to replace products made from raw fossil materials with bio-based products manufactured in an eco-friendly manner. This enables the health, safety and environmental risks of each product to be minimized over its entire lifespan, from research and production to disposal. In addition, plant-derived components impart additional anticorrosion, antifouling, antimicrobial, self-healing or ultraviolet (UV) shielding properties to the systems in which they are incorporated (Hamidi *et al.*, 2022).

In furniture industry of Bulgaria, the use of bio-based products in the formation of protective and decorative coatings on wooden surfaces is insignificant. The reasons for this are their higher price and the lack of knowledge of film formation modes and the properties of the resulting coatings. In this regard, in the Furniture Production department of the University of Forestry, Sofia, a complex study of the properties of a multi-layer coating formed by a one-component waterborne bio-based varnish system was conducted. Some properties of the coating, such as water permeability, adhesion strength, and UV resistance, as well as the influence of the process conditions on the coating's performance, were investigated. The object of the present research was to study the performance of a coating applied by brush.

Roughness is a complex indicator that changes in the processing phases and can serve for their technological and quality assessment (Sandak *et al.*, 2005). It depends on the wood's anatomical structure and the previous processing (Kavalov and Angelski, 2015; Cota *et al.*, 2017; Kúdela *et al.*, 2018). When forming coatings, the surface roughness also depends on the liquid system formulation (Landry *et al.*, 2013), the coating formation technology (Salcă *et al.*, 2016), and the coating thickness (Slabejova *et al.*, 2017). Roughness is described by a group of roughness parameters that are selected depending on the objectives of the respective study (Sandak *et al.*, 2005; Magoss *et al.*, 2019).

In this regard, the present study aims to establish the influences of the wood substrate structure and the characteristics of its surface before coating, the surface treatment before coating, the amount of varnish recommended by the manufacturer, and the number of applied layers on the appearance and roughness of the resulting surfaces, as well as to propose roughness parameters suitable for evaluating the variation of the profiles of the treated surfaces in the film formation phases and for the entire coating process.

MATERIALS AND METHODS

The product being researched is called „Bio-based wood stain". It is used for outdoor applications and is produced by Industrias Químicas Masquelack, S. A., Spain. According to the specifications of the manufacturer (https://www.masquelack.com) the varnish system is one-component and waterborne, with a deficient volatile organic compounds (VOC) content. It can be applied by brush, roller, dipping, or spraying. It is fast-drying and creates a water-resistant, breathable, flexible, open-pore film. The finished coating feels like an unvarnished natural wood surface to the touch. It has high outdoor durability and provides reliable protection from the damaging effects of sunlight on timber. It also protects against mold and algae. The coating is safe for children. The recommended amount for a one-layer coating is 70–87 g/m^2.

The Bio-based wood stain is produced using renewable energy and contains DSM Decovery plant-based resins. Decovery® (Covestro Coating Resins B.V.) is a plant-based alternative to acrylic technology. Decovery® SP-7450 XP is a 39% solids bio-based copolymer emulsion (WB acrylics) designed for fast drying and fast blocking resistant coatings for industrial exterior wood applications (https://www.covestro.com).

The flow time of Bio-based wood stain is 21 s using a 4-mm flow cup. According to the calculations the solid content of the coating system is 17.34%. (Angelski and Atanasova, 2023). The dry coating is extremely thin using the selected application stain amounts (according to the manufacturer's recommendations).

For the purposes of this study, specimens of spruce (*Picea abies* Karst.), beech (*Fagus sylvatica* L.) and beech plywood are selected. The beech and spruce surfaces are plane-milled. The plywood surface is sanded with a P80-120 grain size sandpaper by the manufacturer (S.C. Cildro Plywood, Romania).

The specimens, with dimensions of 340 x 70 x 20 mm and tangential wood grain orientation, were conditioned for a month at 20 ± 2°C and 65 ±5 % R.H. They were sanded with *P150*-grain sandpaper, and the first layer of the coating was applied by brush. After drying, the surfaces were treated manually with abrasive steel wool (Scotch-brite®) and a second layer was applied.

The coating was applied and left to dry at 20 ± 2°C and 60 ±5 % R.H.

The stain amounts for the two layers were Q_1 = 80 g/m^2 and Q_2 = 30 g/m^2, respectively. To determine the surface roughness changes, the measurements were made at the same evaluation lengths after each treatment, which made it possible to analyze both the values of the studied parameters and their change after each phase *ΔR*. This methodology provides, to a large extent, that the influence of the initial surface be ignored. It also allows for the variance of the parameter values to be analyzed.

The roughness parameters were measured with a Mitutoyo SJ-210 surface roughness tester with a tip radius of the diamond stylus R = 5 μm, according to ISO 3274, at the following settings:

- profile – R, profile filter – Gauss;
- number of sampling lengths n = 6;
- evaluation length ln =15 mm;
- cut-off length (sampling length) λc = 2.5 mm,
- λs = 8 μm;
- measuring speed 0.25 mm/s.

The measurements were made perpendicular to the wood grains. The following parameters were selected for analysis and evaluation:

- arithmetic mean deviation of the assessed profile (*Ra*), maximum height of the profile (*Rz*), total height of the profile (*Rt*), and mean width of the profile elements (*RSm*) according to ISO 4287;
- core roughness depth (*Rk*), reduced peak height (*Rpk*), reduced valley depths (*Rvk*), and the material portions *Mr1* and *Mr2* according to ISO 13565-2.

Due to the specifics of the material ratio curve parameters for wooden surfaces, the change in composite parameters *Rpk+Rk+Rvk*, *Rpk+Rk*, and *Rk+Rvk* were also of interest.

In the statistical processing of the data, the variance, the coefficient of variation *V* (in percent), and the accuracy index *p* (in percent) were calculated. For all measurements presented, $p < 5\%$. The measured values of the roughness parameters were statistically and graphically evaluated using the Excel program.

The comparison graphs (Fig. 2) illustrate the change in surface profiles as a result of film formation. They were constructed according to the principles set forth by Atanasova in previous publications (Atanasova 2022).

RESULTS AND DISCUSSION

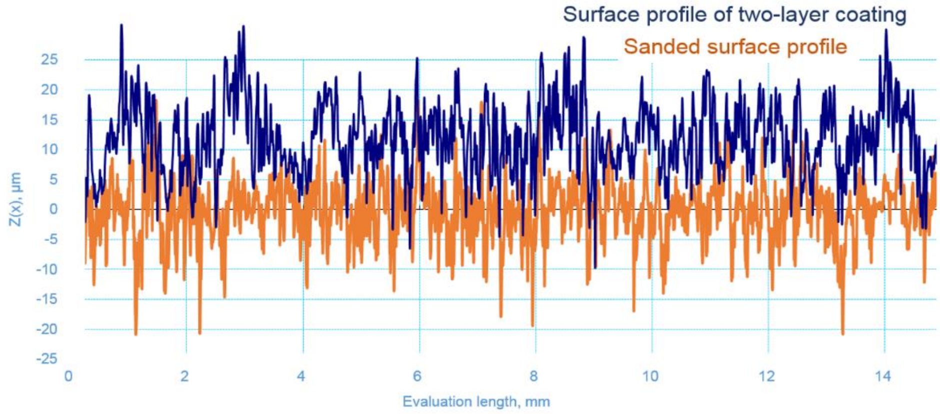
After the solidification of the first coating layer on spruce wood, the treated surfaces had a visible, clearly defined texture and the uniform, rich tobacco coloring of the early wood, without gloss. Wood grain raising was weak. When applied with a brush, the varnish system was distributed evenly, which indicates that the selected varnish amount was appropriate.

After applying and solidifying a second coating layer, the surface acquired a darker color and a faint pearl-like shine (Figure 1). The coating was open-pored. The surface felt like unvarnished natural wood to the touch. The texture was visible.

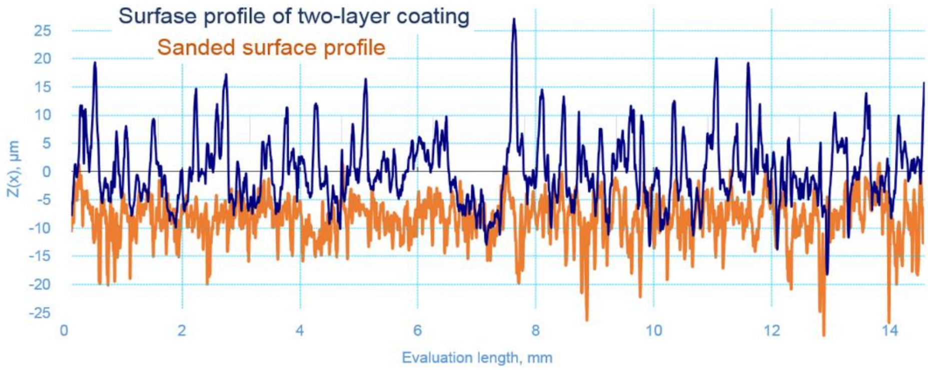
Spruce (*Picea abies* Karst.) Beech (*Fagus sylvatica* L.) Beech plywood

Fig. 1 Wood surfaces with two-layer coatings.

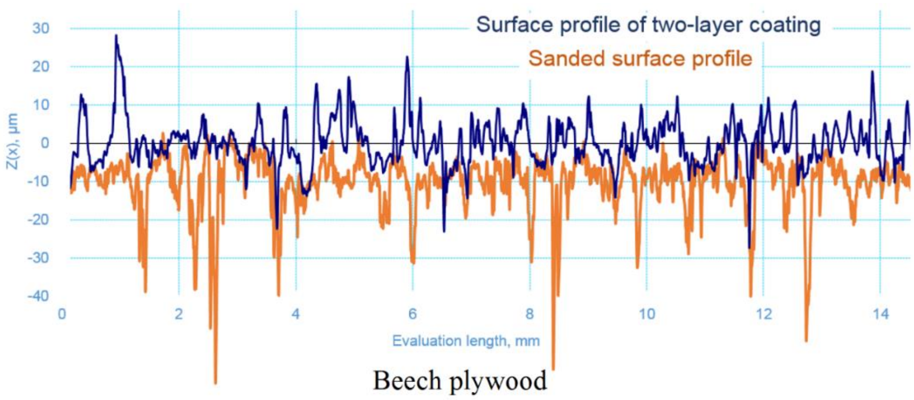
The change of the surface profiles as a result of a two-layer coating formation on spruce (*Picea abies* Karst.), beech (*Fagus sylvatica* L.) and beech plywood is presented in Fig. 2.



Spruce (*Picea abies* Karst.)



Beech (Fagus sylvatica L.)



Beech plywood

Fig. 2 Substrate surface profiles change as a result of two-layer coating formation.

The average values of the roughness parameters and their change after each film formation phase, as well as the initial surface parameters for the three types of wood surfaces, are presented in Tables 1–3. The presented data shows that in each phase of the processing, the parameters change to a different extent, which means that the parameters whose values change most significantly in the specific phase are its characteristics. Similarly, the parameters that have changed most significantly at the end of the film formation process are process characteristics. It can also be seen that different parameter values are obtained for different wood substrates, despite the same treatment before coating. This means that the wood substrate structure affects the parameters of the treated surfaces to a greater extent than the treatment before coating.

From the data presented in Table 1, it can be seen that after the film formation on a spruce surface, the values of the parameters *RSm*, *Mr1*, *Rpk*, and *Rk+Rpk* changed to the greatest extent. The first processing phase is surface preparation for coating by sanding. Sanding affects the wood substrate's top layer, creating a new surface (Gochev, 2018). *Rpk*, *RSm*, *Ra*, and *Rk*, as well as the three composite parameters, were most suitable for evaluation. As a result of sanding, the parameter values decreased. The sanded surface is the starting surface for the film formation process.

Tab. 1 Average values of the roughness parameters of the initial surface and of the sanded surface, as well as of the single-layer and two-layer coatings on spruce wood. Change in roughness parameter values after each processing phase and for the entire film formation process.

Roughness parameter	Average values				Change after each phase of processing			Change for the entire film forming process ΔR, %
	Initial surface	Sanded surface	Single layer coating	Two-layer coating	Sanding ΔR, %	Single layer coating ΔR, %	Two-layer coating ΔR, %	
$\overline{Ra}$, μm	9.78	4.52	6.15	4.96	-53.83	36.25	-19.33	9.91
$\overline{Rz}$, μm	61.42	36.11	46.94	36.41	-41.21	30.00	-22.44	0.83
$\overline{RSm}$, μm	512.45	199.67	201.31	282.72	-61.04	0.82	40.44	41.59
$\overline{Rt}$, μm	88.07	47.89	59.18	47,14	-45.63	23.58	-20.34	-1.56
$\overline{Rk}$, μm	28.93	14.04	9.08	15.55	-51.48	35.90	-18.47	10.80
$\overline{Rpk}$, μm	18.21	5.64	9.57	7.13	-69.03	69.72	-25.56	26.35
$\overline{Rvk}$, μm	15.88	8.09	9.23	7.76	-49.02	14.10	-15.95	-4.10
$\overline{Mr1}$, %	10.55	7.59	10.95	10.23	-28.05	44.34	-6.63	34.76
$\overline{Mr2}$, %	88.07	87.26	89.69	89.72	-0.91	2.78	0.03	2.81
$\overline{Rk+Rvk}$, μm	44.06	22.13	28.31	23.31	-49.78	27.93	-17.65	5.35
$\overline{Rpk+Rk+Rvk}$, μm	61.09	27.77	37.88	30.44	-54.54	36.42	-19.65	9.61
$\overline{Rpk+Rk}$, μm	47.29	19.68	28.65	22.68	-58.39	45.60	-20.84	15.25

As a result of the application of the coating's first layer, the values of the parameters increased due to the grain raising. Grain raising is a common undesirable phenomenon when wood substrates are treated with waterborne coating systems (Landry *et al.*, 2013; Ramananantoandro *et al.*, 2018; Magoss *et al.*, 2019). The degree of wood grain raising depends on many factors, including the substrate condition (Evans, 2009; Ramananantoandro *et al.*, 2018; Magoss *et al.*, 2019), the coating system formulation (Landry *et al.*, 2013), and the applied varnish amount (Atanasova, 2022). The parameters that changed most significantly were *Rpk*, *Rpk+Rk*, *Mr1*, *Rpk+Rk+Rvk*, and *Ra*. As a result of the application of the coating's first layer, the values of the parameters increased. When the second layer was applied, *RSm* increased to the greatest extent, while *Rpk*, *Rz,* and *Rpk+Rk* decreased the most.

The single-layer coating on beech wood was translucent, without gloss, and had a washed-out, uneven color. The latter is due to uneven coating system spreading. The selected varnish amount was too large to be applied by brush. The surface of the coating was unpleasant to the touch due to the raised wood grain. The raised wood grain was felt to a greater extent in comparison to the treated spruce wood surface due to the greater hardness of the beech wood.

After applying and solidifying a second coating layer, the surface acquired a pronounced tobacco color and a faint pearl-like shine (Fig. 1). The coating was open-pored. The surface felt like unvarnished natural wood to the touch. The texture was visible.

It can be seen (Table 2) that in film formation on a beech surface, the values of *Rpk*, *RSm*, *Mr1*, and *Rk+Rpk* have changed to the greatest extent. For sanding evaluation, the most suitable were *Rpk*, *Rpk+Rk*, *Rpk+Rk+Rvk*, *Ra*, and *Rk*. As a result of sanding, the parameter values decreased.

The parameters that changed (increased) most significantly after the first layer of the coating was applied were *Rpk*, *Mr1*, *Rpk+Rk*, *Rpk+Rk+Rvk*, and *Ra*. When the second layer was applied, *RSm* increased to the greatest extent, while *Rpk*, *Rvk*, and *Rz* decreased the most. Of the compositional parameters, the most representative of the change was *Rpk+Rk+Rvk*.

Tab. 2 Average values of the roughness parameters of the initial surface and of the sanded surface, as well as of the single-layer and two-layer coatings on beech wood. Change in roughness parameter values after each processing phase and for the entire film formation process.

Roughness parameter	Average values				Change after each phase of processing			Change for the entire film forming process ΔR, %
	Initial surface	Sanded surface	Single layer coating	Two-layer coating	Sanding ΔR, %	Single layer coating ΔR, %	Two-layer coating ΔR, %	
$\overline{Ra}$, μm	7.05	3.32	5.08	4.62	-52.92	53.12	-9.14	39.13
$\overline{Rz}$, μm	56.64	28.88	43.68	36.30	-49.01	51.23	-16.88	25.70
$\overline{RSm}$, μm	398.26	267.34	344.01	488.25	-32.87	28.68	41.93	82.63
$\overline{Rt}$, μm	77.95	39.70	61.36	53.88	-49.07	54.54	-12.18	35.72
$\overline{Rk}$, μm	19.54	9.60	14.08	13.56	-50.88	46.72	-3.71	41.28
$\overline{Rpk}$, μm	12.18	3.04	11.13	9.30	-75.07	266.48	-16.43	206.28
$\overline{Rvk}$, μm	15.15	8.10	8.72	7.36	-46.56	7.70	-15.55	-9.05
$\overline{Mr1}$, %	9.69	6.49	13.18	11.86	-33.02	103.07	-10.07	82.63
$\overline{Mr2}$, %	85.65	85.21	89.26	89.70	-0.52	4.75	0.49	5.27
$\overline{Rk + Rvk}$, μm	34.69	17.69	22.80	20.92	-48.99	28.86	-8.24	18.25
$\overline{Rpk + Rk + Rvk}$, μm	46.87	20.73	33.93	30.23	-55.77	63.67	-10.92	45.79
$\overline{Rpk + Rk}$, μm	31.60	12.63	25.21	22.86	-60.02	99.55	-9.32	80.94

The changes in the beech wood surface parameter values were larger than in spruce wood.

From the comparison of the orders of importance of the essential parameters characterizing the film formation on beech and spruce wood surfaces, it can be concluded that the significance rating of the parameters is determined by the wood structure. The low-viscosity varnish system penetrated into the pores of the early spruce wood, thereby having less influence on the surface parameters. The same amount of varnish applied to beech remains on the surface, influencing the surface parameters until the film solidifies. The longer contact time of the liquid system with the base caused a greater change in the surface profile and in the investigated parameter values.

The single-layer coated beech plywood was the most unacceptable in appearance. Its visible texture was like that of a beech surface, but the wood grain raising was greater. The coating has no shine. Despite the relatively uniform spread of the varnish system, after its solidification, the coloring agent was distributed unevenly. This indicates that the selected varnish amount was inappropriate.

After applying and solidifying a second coating layer, the surface acquired a pronounced tobacco color and a faint pearl-like shine (Fig. 1). The coating was open-pored. The surface felt like unvarnished natural wood to the touch. The texture was visible.

From the data presented in Table 3, it can be seen that in the case of film formation on beech wood and beech plywood surfaces, the parameters for the process effectiveness evaluation were almost equal, namely:

- *Rpk*, *Rpk+Rk*, *Rvk*, *Rk*, and *Mr1* for the entire process;
- *Rpk*, *Rk*, *Ra*, as well as the three composite parameters, on sanding (their values decreased);
- *Rpk*, *Rpk+Rk*, *Mr1*, *Rk*, *Ra*, and *Rpk+Rk+Rvk*, when applying the coating's first layer (their values increased);
- *Rvk*, *Rpk*, *Rz*, as well as the three composite parameters, when applying a coating's second layer (their values decreased).

Tab. 3 Average values of the roughness parameters of the initial surface and of the sanded surface, as well as of the single-layer and two-layer coatings on beech plywood. Change in roughness parameter values after each processing phase and for the entire film formation process.

Roughness parameter	Average values				Change after each phase of processing			Change for the entire film forming process ΔR, %
	Initial surface	Sanded surface	Single layer coating	Two-layer coating	Sanding ΔR, %	Single layer coating ΔR, %	Two-layer coating ΔR, %	
$\overline{Ra}$, µm	15.90	3.72	7.72	5.29	-76.62	107.83	-28.51	42.24
$\overline{Rz}$, µm	104.24	34.97	58.86	33.98	-66.46	68.33	-35.61	-2.83
$\overline{RSm}$, µm	439.13	310.65	322.65	266.48	-29.26	3.86	-12.01	-14.22
$\overline{Rt}$, µm	134.08	60.18	95.13	55.61	-55.11	58.06	-25.85	-7.61
$\overline{Rk}$, µm	48.74	10.24	22.06	16.63	-78.99	115.41	-22.40	62.45
$\overline{Rpk}$, µm	16.74	3.44	16.65	7.70	-79.48	384.54	-44.43	124.01
$\overline{Rvk}$, µm	26.70	10.42	8.68	2.91	-60.95	-16.74	-60.03	-72.08
$\overline{Mr1}$, %	7.69	6.53	14.22	9.98	-15.08	117.68	-28.99	52.78
$\overline{Mr2}$, %	86.17	85.94	91.49	92.05	-0.27	6.45	-0.09	7.10
$\overline{Rk+Rvk}$, µm	75.44	19.26	29.93	20.31	-74.47	55.37	-32.48	5.45
$\overline{Rpk+Rk+Rvk}$, µm	93.05	22.44	44.88	25.92	-75.89	100.00	-32.48	15.53
$\overline{Rpk+Rk}$, µm	66.35	13.95	37.33	25.97	-78.98	167.61	-26.62	86.15

The essential differences were the absence of the *RSm* parameter, the presence of the *Rk* parameter, and the more pronounced *Rvk* influence. This was due to the wood compression in plywood production. The plywood surface was sanded, and its texture was mainly determined by the sanding conditions. The beech wood structure does not have a significant influence (Atanasova, 2022). In terms of penetration, the plywood surface has beech surface characteristics. The grain raising was more pronounced due to the greater cell wall damage as a result of the two-step sanding (Evans, 2009).

For the three investigated surfaces and for the entire film formation process, *Ra* reflected the surface changes better than the *Rz* parameter.

The parameters *Rpk* and *Mr1* are related (ISO 13565-2). Their calculated dispersion values were close. Therefore, there is no reason to calculate and analyze them simultaneously. Due to the more complete information that can be obtained from the composite parameters, it is recommended to measure *Rpk*.

The graphs in Figs. 3 and 4 are based on the data presented in Tables 1–3. They compare the change in the main parameter values for the different wood bases during two-layer coating formation.

Figure 3B shows the change in the most dynamic roughness parameter -*Rp*. It affected considerably the values of the composite parameters in which it was included and determined the nature of their change. It cannot be claimed to be a film formation parameter, as the environment affects the outermost coating layer (Müller and Poth, 2011). This is the reason for the large variance in its values, which makes it difficult to work with. When the environmental conditions vary widely, it is recommended to replace it with *Rpk+Rk* (Fig. 3C) or *Rk* (Fig. 3D).

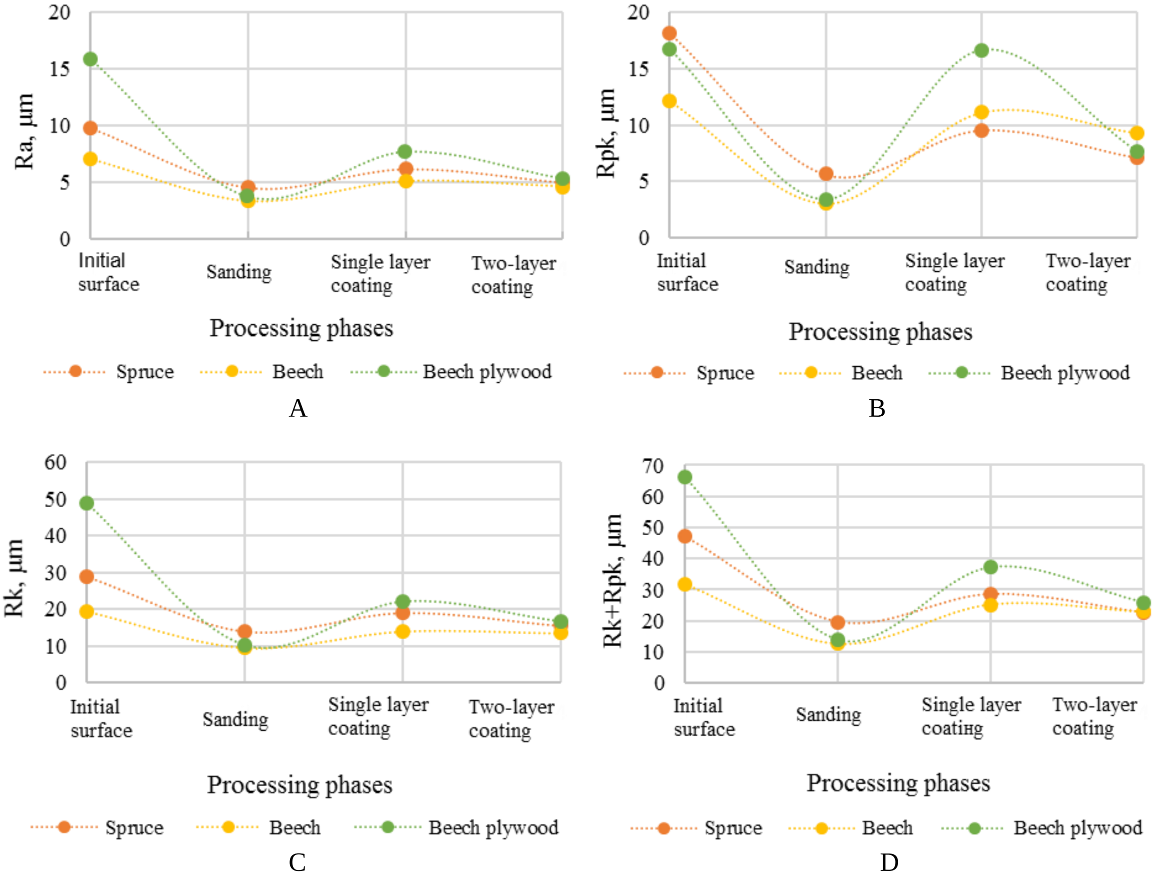


Fig. 3 Changes in *Ra, Rpk, Rk,* and *Rpk+Rk* for the different wood surfaces after each phase of the two-layer coating formation.

Fig. 4 shows that the deformations induced in the treated wood when creating wood materials were the cause of the qualitatively different behavior of the substrate surface during film formation.

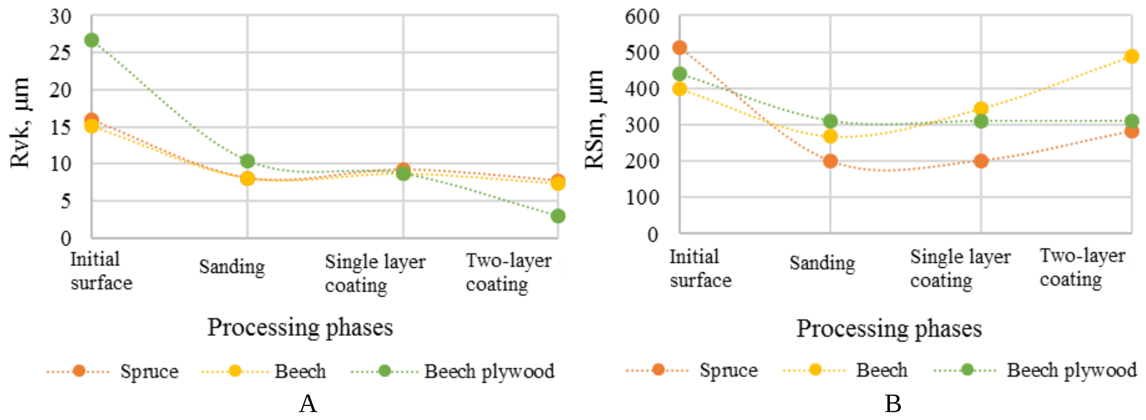


Fig. 4 Changes in *Rvk* and *RSm* for the different wood surfaces after each phase of the two-layer coating formation.

The change of parameter *Rpk+Rk+Rvk*, as well as the change of its component parameters (in percent) during film formation, is presented in Fig. 5.

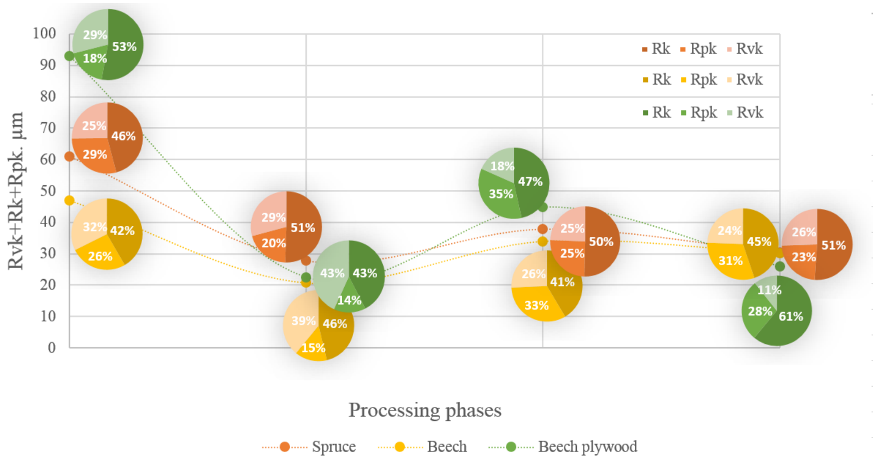


Fig. 5 Composite parameter *Rpk+Rk+Rvk* change and the change of the base parameters for the different wood surfaces after each phase of the two-layer coating formation.

It is impressive that the small variation of the *Rk* parameter for solid wood surfaces is less than 5%. In the statistical processing of the data, *Rk* is distinguished by its low accuracy index ($p < 2.25\%$) and correlation coefficient ($V < 19\%$). These results extend Gurau's conclusion (Gurau, 2022) that *Rk* is the most stable parameter of the parameters calculated from the Abbott curve for the film formation process as well.

CONCLUSION

The presented research investigated the effect of wood substrate structure and surface characteristics prior to coating, the surface treatment before coating, the manufacturer's recommended amount of varnish, and the number of applied layers on the appearance and roughness of surfaces obtained by film-forming a multilayer waterborne bio-based coating. The liquid system was applied by brush to spruce, beech, and beech plywood. The roughness was evaluated by 12 roughness parameters after each phase of the film formation process. The results obtained showed that:

- It is necessary to apply a two-layer coating on all test surfaces.
- The amount of varnish recommended by the manufacturer is inappropriate when applied with a brush on beech and beech plywood.
- The wood substrate structure and the characteristics of its surface before coating have a determining influence on the roughness parameters in the last phase of the film-building process, as well as on the appearance of the varnished surfaces. The treatment before coating had little effect on the final coating parameters.
- Reduced peak height *Rpk*, core roughness depth *Rk*, reduced valley depths *Rvk*, arithmetic mean deviation of the assessed profile *Ra*, mean width of the profile elements *RSm* and the composite parameter *Rpk+Rk+Rvk* can be proposed as universal parameters for technological control. Reduced peak height can be replaced with sufficient accuracy by the composite parameter *Rpk+Rk* when environmental conditions vary widely.

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

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AUTHORS' ADDRESSES

Assist. Prof. Krasimira Atanasova, PhD
Prof. Dimitar Angelski, PhD
University of Forestry, Sofia
Faculty of Forest Industry
10 Kliment Ohridski Blvd.
1797 Sofia
Bulgaria
k_atanasova@ltu.bg
d.angelski@ltu.bg