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# The Effects of Surface Roughness on Adhesion Strength of Coated Ash (*Fraxinus excelsior L.*) and Birch (*Betula L.*) Wood

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For the evaluation of surface roughness impact on adhesion properties, the samples of dried ash (*Fraxinus excelsior L.*) and birch (*Betula L.*) wood were used. Before wood finishing, the surfaces of the samples were sanded. In order to get different surface roughness the abrasive material of P80, P120, P150, P180, P220 and P240 grit was used. The parameters of surface roughness $R_a$, $R_z$ and $R_{max}$ were measured in three directions: along the wood grain, across the grain and in the angle of 45º. Comparison of the results showed the non-linear dependency of roughness parameters. Afterwards the wood surface was coated with three different acrylic-polyurethane coating systems (1 layer of varnish without primer, 1 layer of primer and 1 layer of varnish, and 1 layer of primer and 2 layers of varnish). The adhesion strength was assessed using the pull-off method. Also the nature of the fracture was evaluated. It was determined that the peculiarities of surface roughness, coating system type and wood species signally results the values of the adhesion strength.

*Keywords*: ash wood, birch wood, surface roughness, acrylic-polyurethane coating, adhesion strength, pull-off testing.

## INTRODUCTION

Interface and interphase adhesion in wood surface coatings has a great influence on coating performance. In many cases, the surface coating fails due to de-bonding from the surface of the wood. The chemistry of the wood surface and the chemistry of the coating system needs to be understood to determine the important factors governing surface coating performance. The properties of the wood surface, its texture, anatomy, species all affect surface coating performance [1].

As known, wood is not a homogeneous material. For coating adhesion strength it is particularly important early- and latewood ratio in the wood growth-ring. Earlywood is more porous than latewood, thus coating penetration into the earlywood zone is higher, as coating penetration is mainly subjected to its ability to flow into capillaries of wood [2, 3]. Also penetration is influenced by coating binder type, solid content, pigmentation and drying speed. In this work hybrid acrylic-polyurethane coatings were used. These coatings are expected to provide the advantages of polyurethanes such as toughness, durability, good adhesion, fast drying and curing and also the advantages of acrylic polymers such as resistance to chemical exposure, gloss, hardness, and weatherability [4, 5].

Another important factor affecting adhesion is wood surface roughness [6]. In order to accurately characterize the surface roughness of wood, it is important properly to select suitable roughness measurement devices and methodology [7]. Wood surface roughness can be measured by means of contact and non contact methods. The first type includes contact stylus tip, tactile sensation and pneumatic methods. One of the most popular methods is to register the profile of the surface using a stylus drawn along the surface to be measured. The diamond stylus is the main component of the profilometer. This method makes it possible to evaluate the main parameters of the surface roughness in different directions of wood grain [8 – 10].

Adhesion strength of coating film can be measured in several methods – using cross-cut, tape-peel or pull-off tests. Using these techniques a number of adhesion strength researches were carried out. The adhesion strength of bleached, stained and treated with preservative samples of spruce (*Picea orientalis L.*), yellow pine (*Pinus sylvestris L.*), beech (*Fagus orientalis L.*) and chestnut (*Castanae sativa L.*) was measured [11]. Also the surface roughness was evaluated. It was found that wood bleaching had the greatest influence on surface quality, and stained wood samples showed the highest adhesion strength. In the other research samples of Scots pine, Eastern beech and oak (*Quercus petraea L.*) wood were coated with nitrocellulose, two-part polyurethane and waterborne polyurethane varnishes in order to evaluate the influence of moisture content on adhesion strength [12]. The highest adhesion strength showed oak wood with moisture content of 8 % coated with two-part polyurethane varnish. Turkish scientists determined, that increase of wood equilibrium moisture content from 7.5 % to 14.5 % significantly reduces adhesion strength and surface quality. Studying wet adhesion of several types of waterborne acrylic, waterborne alkyd-emulsion, high solid alkyd and solvent alkyd coatings it was obtained that waterborne coatings had lower wet adhesion than solventborne coatings [13]. Also it was determined that the highest adhesion strength was in the zones of earlywood of pine wood. In the other work the influence of beech wood surface roughness and wetting properties on adhesion strength after aging were evaluated [14]. For the research two different processing methods were chosen (helical planning and face milling) as well as different feed speeds and cutting depths were used. It was

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obtained that the highest impact on surface quality and herewith on wetting properties had feed speed.

The main purpose of this research is to evaluate the dependence of ash and birch wood surface roughness on the adhesion strength of three different acrylic-polyurethane coating systems.

## MATERIALS AND METHODOLOGY

Tangential planed defect free kiln-dried ash (*Fraxinus excelsior L.*) and birch (*Betula L.*) wood samples (270×215×15 mm) were used for this research. The density of ash wood was 649 kg/m$^3$, whereas the density of birch wood – 614 kg/m$^3$. Growth-ring width was around 2.6 mm for ash and 2.9 mm for birch. Moisture content of the samples was 101 % ±1 %. Then samples were sanded with random-orbit sander (eccentric motion speed 6800 min$^{-1}$, sanding stroke 5 mm, sanding time 1 min.) using standard, commercially manufactured, open-type abrasive material with different-sized grits P80, P120, P150, P180, P220 and P240 (grading system by FEPA).

Surface roughness parameters roughness average $R_a$, average maximum height of the profile $R_z$ and maximum roughness depth $R_{max}$ were measured using contact stylus profilometer Mahr Marsurf PS1, whose a diamond stylus tip radius is 2 µm, measurement angle 90º, and evaluation length 17.5 mm. All measurement results were processed using a digital Gaussian filter. The measurement error of unevenness did not exceed ±10 %.

The samples were coated with commercially available clear acrylic-polyurethane varnish (viscosity – 28 – 34 (Ford viscosity cup, 4 mm), density – 0.92 kg/l ±0.03 kg/l, solid content – 24 % ±1 %, hardener – 20 %, diluent – 20 % – 30 % by weight) using an industrial low-pressure spray gun at a spread rate of 120 g/m$^2$ and cured in the convection drying chamber. Three different coating systems were used in evaluation of the strength of wood coating adhesion: type A – 1 layer of varnish, type B – primer (thinned varnish) and 1 layer of varnish, type C – primer and 2 layers of varnish. Subsequently finished wood was cut into samples of (50×50×15) mm. In total 720 wood samples were used for the experiments (20 samples for one wood surface roughness and coating system type).

Adhesion strength of the coating was evaluated carrying out the pull-off test [15]. For the tests aluminium-faced dollies with a rigid, flat faces with nominal diameter of 20 mm were used. The dollies were glued perpendicular to the coating surface of the dry coating film by means of fast-hardening cyanoacrylate adhesive. When the adhesive cured, 20 mm hole saw was used to cut around the circle of the dolly through to the wood substrate. All of the samples were initially conditioned at temperature 23 ºC ±2 ºC and relative humidity of 50 % ±5 % for 20 hours.

Adhesion strength was tested in the universal testing machine P-05 with across-head speed of 30 mm/min. The tensile strength was applied perpendicularly to the plane of the coated substrate. After each test the nature of the fracture was evaluated visually.

## RESULTS AND DISCUSSION

Wood surface roughness ($R_a$, $R_z$ and $R_{max}$) was evaluated in three directions: along the grain, across the grain and in the angle of 45º. The results of surface roughness measurements of ash and birch wood are shown in Table 1.

Table 1 shows that compared to the parameters obtained along the grain, the surface roughness parameters of ash wood across the grain are higher (depending on the grit size of the abrasive paper) $R_a$ – up to 2.8, $R_z$ – up to 3.6, $R_{max}$ up to 5.2 times, and in the angle of 45º – up to 2.7, 3.0 and 3.9 times respectively.

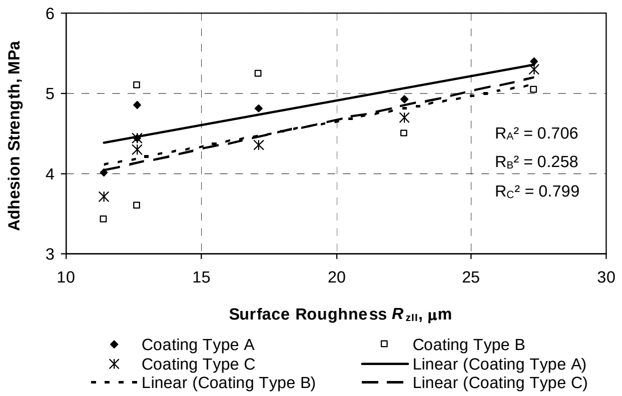
**Table 1.** Mean values of ash and birch wood surface roughness

| Grit Size (FEPA) | Parameters of Roughness, µm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Along the Grain | | | Across the Grain | | | In the angle of 45º | | |
| | $R_{a\parallel}$ | $R_{z\parallel}$ | $R_{max\parallel}$ | $R_{a\perp}$ | $R_{z\perp}$ | $R_{max\perp}$ | $R_{a45}$ | $R_{z45}$ | $R_{max45}$ |
| Ash wood | | | | | | | | | |
| P80 | 3.92 | 27.33 | 37.34 | 6.04 | 51.39 | 76.48 | 5.82 | 46.87 | 66.77 |
| P120 | 3.13 | 22.54 | 33.53 | 8.64 | 77.45 | 107.66 | 8.04 | 63.27 | 96.14 |
| P150 | 2.34 | 17.12 | 26.35 | 4.59 | 43.29 | 68.97 | 4.97 | 40.77 | 68.03 |
| P180 | 1.67 | 12.65 | 15.85 | 4.73 | 46.03 | 82.13 | 4.19 | 34.76 | 53.00 |
| P220 | 1.63 | 12.63 | 17.42 | 4.06 | 41.59 | 71.16 | 4.43 | 37.85 | 67.53 |
| P240 | 1.53 | 11.42 | 18.24 | 3.88 | 38.71 | 58.49 | 3.69 | 34.11 | 55.34 |
| Birch wood | | | | | | | | | |
| P80 | 7.77 | 49.46 | 61.08 | 8.43 | 59.67 | 74.90 | 8.47 | 57.65 | 69.35 |
| P120 | 4.18 | 28.67 | 36.78 | 5.14 | 39.74 | 51.86 | 5.45 | 40.71 | 51.92 |
| P150 | 3.38 | 23.33 | 32.02 | 4.34 | 38.98 | 49.70 | 4.32 | 35.31 | 45.97 |
| P180 | 3.52 | 25.82 | 35.61 | 4.40 | 43.59 | 54.43 | 4.32 | 37.37 | 47.37 |
| P220 | 3.09 | 22.95 | 33.91 | 3.68 | 38.31 | 48.36 | 3.47 | 33.41 | 44.95 |
| P240 | 3.03 | 21.95 | 31.87 | 3.87 | 39.54 | 48.77 | 3.88 | 35.75 | 45.57 |

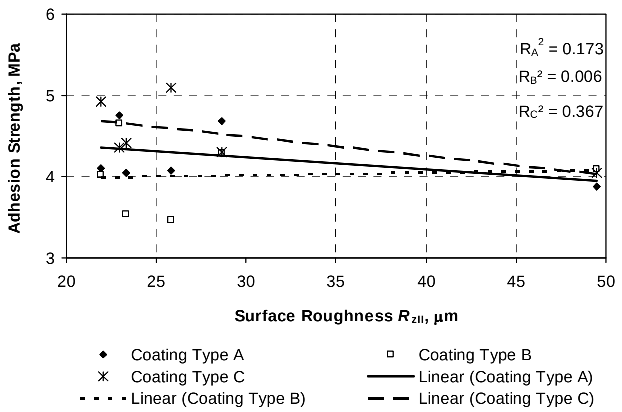
$R_a$ – arithmetic average of the absoliute values of the roughness profile ordinates; $R_z$ – arithmetic mean value of the single roughness depths of consecutive sampling lengths; $R_{max}$ – the largest single roughness depth with the evaluation length.

While the surface of birch wood is more even and the differences between surface roughness parameters along, across the grain and in the angle of 45º are significantly lower. Roughness parameters along the grain are about 1.3–1.8 times lower than across the grain and in the angle of 45º. Also it can be seen, that with the increasing of grit size of abrasive paper from P80 to P240, the surface roughness parameters of ash and birch wood decrease (for ash wood ($R_z$) – along the grain 2.39 times, across the grain – 1.33 times and in the angle of 45º – 1.37 times, for birch wood ($R_z$) – 2.25, 1.51 and 1.61 times respectively).

Surface roughness parameters of birch wood compared to ash wood along the grain are higher almost 2 times, while across the grain and in the angle of 45º – lower, respectively 0.48 – 0.98 and 0.54 – 0.89 times. The obtained data can be related to the measurement location on the specimen and wood structure. As ash is ring-porous, and birch – diffuse-porous deciduous tree, consequently ash wood vessels are located mainly in the earlywood, whereas in the birch wood – throughout cross-section.




a




b

**Fig. 1.** Dependence of surface roughness (along the grain $R_{z||}$) on the adhesion strength: a – ash wood, b – birch wood

Subsequently, the adhesion strength was evaluated depending on the coating system and substrate surface roughness. Dependencies of surface roughness parameter $R_z$ along and across the grain on the adhesion strength are presented in Fig. 1. In addition, the nature of the failure is given in Tables 2 and 3.

Fig. 1 shows that in the case of ash wood the adhesion strength and surface roughness has quite good positive correlation, i. e. with the decreasing of surface roughness, the adhesion strength tends to decrease also. Rough surface increases the area of physical contact, thus coating better adheres to wood substrate [16 – 18].

When the surface becomes smoother, coating looses mechanical interlocking with the substrate, thus weakens the adhesion. Besides, it may be that surface sanding causes damage to the walls of wood cells, which are particularly weak in the tangential direction and especially in the earlywood area. For wood coating it is much more difficult to penetrate through the layer of crushed cells or capillaries clogged with dust [17, 18]. As a result, this area foremost looses adhesion. As can be seen in Fig. 1, a, adhesion strength of ash wood decreases 25.6 % for coating system A, 31.9 % for coating system B, and 30.0 % for coating system C, when surface roughness increases about 60 %. That can be explained by obtained nature of the failure also (Table 2). Tables 2 and 3 present the nature of the fracture as the percentage of cohesive failure of wood substrate and the percentage of failure between the wood substrate and first coat. All other failure types are not

**Table 2.** Adhesion strength and nature of the failure (ash wood)

| Grit Size | Adhesion Strength σ (MPa) | Coefficient of Variation, % | Cohesive Failure of Wood, % | Failure between Wood and First Coat, % |
|---|---|---|---|---|
| Coating Type A | | | | |
| P80 | 5.4 | 13.5 | 26 | 74 |
| P120 | 4.9 | 10.8 | 53 | 46 |
| P150 | 4.8 | 12.2 | 19 | 80 |
| P180 | 4.9 | 16.6 | 14 | 82 |
| P220 | 4.4 | 25.8 | 23 | 71 |
| P240 | 4.0 | 17.8 | 20 | 76 |
| Coating Type B | | | | |
| P80 | 5.0 | 12.9 | 42 | 56 |
| P120 | 4.5 | 8.5 | 47 | 52 |
| P150 | 5.3 | 16.5 | 33 | 65 |
| P180 | 5.1 | 21.2 | 24 | 69 |
| P220 | 3.6 | 23.8 | 17 | 78 |
| P240 | 3.4 | 20.3 | 17 | 76 |
| Coating Type C | | | | |
| P80 | 5.3 | 9.6 | 43 | 55 |
| P120 | 4.7 | 12.2 | 50 | 47 |
| P150 | 4.4 | 13.9 | 25 | 75 |
| P180 | 4.4 | 8.5 | 30 | 69 |
| P220 | 4.3 | 15.6 | 22 | 77 |
| P240 | 3.7 | 17.7 | 10 | 87 |

**Table 3.** Adhesion strength and nature of the failure (birch wood)

| Grit Size | Adhesion Strength σ (MPa) | Coefficient of Variation, % | Cohesive Failure of Wood, % | Failure between Wood and First Coat, % |
|---|---|---|---|---|
| Coating Type A | | | | |
| P80 | 3.9 | 14.7 | 97 | 2 |
| P120 | 4.7 | 10.6 | 85 | 15 |
| P150 | 4.0 | 18.8 | 46 | 53 |
| P180 | 4.1 | 21.9 | 70 | 27 |
| P220 | 4.7 | 14.5 | 62 | 38 |
| P240 | 4.1 | 17.5 | 86 | 14 |
| Coating Type B | | | | |
| P80 | 4.1 | 18.8 | 65 | 34 |
| P120 | 4.3 | 10.5 | 76 | 24 |
| P150 | 3.5 | 19.5 | 44 | 54 |
| P180 | 3.5 | 18.9 | 21 | 75 |
| P220 | 4.7 | 14.4 | 31 | 69 |
| P240 | 4.0 | 21.8 | 43 | 56 |
| Coating Type C | | | | |
| P80 | 4.0 | 16.7 | 82 | 15 |
| P120 | 4.3 | 12.0 | 77 | 21 |
| P150 | 4.4 | 15.2 | 62 | 38 |
| P180 | 5.1 | 12.9 | 65 | 35 |
| P220 | 4.4 | 12.4 | 62 | 37 |
| P240 | 4.9 | 13.2 | 69 | 31 |

included in the table. Analysis of the data in Table 2 showed that the percentage of cohesive failure in most cases is the highest of rougher ash wood surface (up to 53 %), while becoming smoother the percentage of failure between the wood substrate and first coat increases. For ash wood cohesive failure of wood substrate observed only in the areas of earlywood with big round vessels. Also the earlywood cells have much thinner walls compared to the latewood, consequently coating easier reaches open lumens and penetrates deeper [1].

This tendency is not so well-defined for birch wood. From Fig. 1, b, it can be seen that surface roughness and adhesion strength are not interdependent. When surface roughness decreases, adhesion strength do not changes in the same dependence as well as relation between adhesion strength and the nature of the failure is not clearly expressed (Table 3). However, the percentage of cohesive failure tends to be higher, when the adhesion strength increases and lower, when adhesion strength decreases. The percentage of cohesive failure of wood substrate in the specimen group of birch wood is significantly higher compared to ash wood – about 64 % of all tested specimens total area failed through the wood, while for ash wood – only 29 %. High cohesive failure for birch wood can result from the distinct wood structure. As mentioned before, on the contrary to ash wood, vessels in birch wood are arranged throughout cross-section, besides wood structure is more even, that results good coating penetration into wood capillaries in the whole area.

Comparing the adhesion strength subjected to the chosen coating system and wood species, it was determined, that in the case of one layer of varnish, adhesion strength for ash wood was higher from 4.9 % to 28.1 % than for birch wood, when wood substrate was treated with abrasive material grit size from P80 to P180, however when wood was sanded with the abrasive material grit size P220 and P240 the adhesion strength for birch wood was higher about 2.3 % – 7.0 % compared to ash wood. The same dependence is observed when wood was coated with one layer of primer and one layer of varnish – the adhesion strength of wood treated with abrasive material P80-P180 for ash wood was higher about 4.9 % – 32.7 % than for birch wood, still when treated with paper P220 and P240, the adhesion strength for birch wood was 16.9 % – 29.2 % higher compared to ash wood. However in the case of coating system C, there was observed completely different tendency – higher adhesion strength for ash wood was obtained only for P80 and P120 sanding (about 8.7 % – 23.8 %), later higher adhesion strength for birch wood was observed (about 1.2 % – 32.7 %). These tendencies could be explained by the different wood structure and variation of surface roughness.

## CONCLUSIONS

Examination of adhesion strength showed that the effect of surface roughness to the adhesion properties is significant. With the increasing of surface roughness, increases the area for the mechanical interlocking between coating and wood substrate, consequently the adhesion strength also increases. This tendency is very clear for ash wood, while for the birch wood is not so well-defined – surface roughness and adhesion strength are not interdependent. Due to diffused distribution of vessels in birch wood, significant part of failure has cohesive nature (up to 64 % of all cases of failure), while for ash wood cohesive failure was observed only in the earlywood area (up to 29 % of all cases of failure).

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