Adhesion of Coating Films on Laser Engraved Wood Surface

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GRAPHICAL ABSTRACT

Adhesion of Coating Films on Laser Engraved Wood Surface

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The adhesion of two coating systems – hard wax oil (oil-based) and PAM lak (water-based) – were evaluated on laser-engraved wood surfaces of Norway spruce (*Picea abies* (L.) Karst.), European beech (*Fagus sylvatica* L.), and pedunculate oak (*Quercus robur* L.). Laser engraving was performed at two laser powers (8% = 11 W; 16% = 22 W) and three raster densities (10, 20, and 30 lines·mm⁻¹) for each power level. Adhesion was assessed using the pull-off test. The oil-based coating generally showed lower adhesion to the wood surface compared to the water-based coating. In contrast, several combinations of engraving parameters on spruce (8 × 20) and oak wood (8 × 10, 16 × 10) increased oil-based adhesion but tended to reduce water-based adhesion. On the other hand, the adhesion of the water-based coating was significantly reduced on beech wood (16 × 30) and oak wood (8 × 30, 16 × 20 and 16 × 30). In some cases, adhesion of the water-based coating exceeded the cohesive strength of the modified wood surface layers, leading to cohesive failure within the wood.

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Keywords: Adhesion; Laser; Beech wood; Oak wood; Spruce wood; Oil-based; Water-based

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INTRODUCTION

Laser-treated wood has become increasingly recognized as an accessible and versatile design material. Lasers are a promising technology in wood science for architectural essence and furniture making to toys and fine crafts (Islam *et al.* 2023). Numerous studies have demonstrated that various technological parameters of laser treatment, as well as the operating conditions applied during processing, result in different surface qualities and visual outcomes depending on the intended aesthetic effect (Chernykh *et al.* 2022; Kúdela *et al.* 2023; Nguyen-Thi-Ngoc and Dang 2023; Jurek *et al.* 2025). Laser modification of wood surfaces can lead to chemical transformations within the surface layer (Dolan *et al.* 2015; Kúdela *et al.* 2020, 2023, 2024; Li *et al.* 2022a,b), distinctive surface characteristics, unconventional coloration (Açık 2023), and tactile surface textures (Gurău *et al.* 2017; Gurău and Petru 2018; Gurău *et al.* 2021; Kúdela *et al.* 2022). This technique is also gaining ground in the context of wooden buildings and architectural applications (Li *et al.* 2014). Furthermore, research has investigated how pre-treatment of furniture parts by laser affects laser processing performance during computer numerical controlled (CNC) machining (Açık 2024).

In practice, laser-textured wood surfaces are most frequently utilized in furniture production and interior design elements (Lungu *et al.* 2022). These surfaces, like untreated wood, usually require protective finishing to preserve their appearance and prevent damage from liquids and mechanical wear. Recently, protection against UV radiation has also been frequently used to maintain the color stability of the treated wood surface (Kúdela and Kubovský 2016). Traditional finishing methods involve the application of coatings that form a hardened film to protect the substrate. However, to ensure proper performance of such coatings, it is crucial to understand the adhesion behaviour between the coating film and laser-treated surfaces (Li *et al.* 2022a). Parameters such as surface roughness and wettability – both significantly affected by laser processing – play a vital role in coating adhesion (Li *et al.* 2021a). Moreover, the mechanical properties of the coatings themselves are important contributors to adhesive performance (Pavlič *et al.* 2021). While surface characteristics influence wettability to a certain extent, it is often the intrinsic properties of the coating that determine the final interaction (Žigon *et al.* 2022).

Laser-textured wood surfaces can also be applied in exterior furniture design, where additional protection is necessary due to exposure to weathering factors. Traditional wood coatings are increasingly restricted due to environmental concerns, prompting a search for eco-friendly alternatives (Varganici *et al.* 2021). Among these, coatings based on natural or synthetic oils and waxes – sometimes combined with water-based dispersions – belong to the class of “green” or ecological coatings. Oils penetrate the wood and enhance its natural grain and appearance. However, because oils fill the lumens and voids without forming chemical bonds with the wood cell walls, they often exhibit certain performance limitations, such as low hardness, poor resistance to detergents and chemicals, and limited photostability (Bulian and Graystone 2009; Vidholdova *et al.* 2021).

Recent advancements have focused on modifying wax-oil coatings to improve their performance. For example, promising results have been achieved with nanocomposite wax-oil coatings incorporating stearoyl chloride-grafted cellulose nanocrystals (SCNCs) (Wang *et al.* 2024). Similarly, hybrid formulations have been prepared using nanoparticles, embedded in linseed oil nanoemulsions (Bansal *et al.* 2022). Likewise, Kabasakal *et al.* (2023) reported promising results from bio-based epoxide-amine nanocoatings.

Another class of environmentally friendly finishes includes water-based coatings. Extensive research has been devoted to improving their performance, particularly by incorporating nanoparticles (Li *et al.* 2021b; Wang *et al.* 2023; Zou *et al.* 2023, 2024) or other functional additives (Henn *et al.* 2021; Calovi and Rossi 2023; Zou *et al.* 2025). Among the key quality parameters for such coatings is their adhesion to the wood surface – a property that has been extensively studied across various formulations and application scenarios (Vidholdova *et al.* 2017; Slabejová *et al.* 2019; Vidholdova *et al.* 2021; Liu and Xu 2022; Karaman *et al.* 2023; Angelski and Atanasova 2024; Hubbe and Laleicke 2025).

The present study investigates the influence of raster density at two power levels (8% and 16% of P_{max} = 137.5 W) during engraving on the adhesion of two different types environmentally friendly of coatings (oil-based and water-based) applied to surfaces of three wood species (spruce (*Picea abies* (L.) Karst.), beech (*Fagus sylvatica* L.), and oak (*Quercus robur* L.)), which are often used to make furniture. The findings are expected to contribute to optimizing the use of environmentally friendly oil- and water-based coatings on laser-engraved surfaces of different wood species.

EXPERIMENTAL

Materials and Sample Preparation

Test samples were prepared from spruce wood (*Picea abies* (L.) Karst.), beech wood (*Fagus sylvatica* L.), and oak wood (*Quercus robur* L.) logs, cut approximately 1.3 m above the ground. From each log, a single plank with final dimensions 1000 × 70 × 15 mm^3 was selected. These planks were then used to prepare eighty-four test specimens from each wood species with either radial even radial-tangential orientation and dimensions of 115 × 70 × 15 mm^3. Six specimens were randomly selected for each combination (Wood × Laser Power × Raster Density) from each plank samples without macroscopic wood defects, and with all samples were and subsequently conditioned to 6% moisture content before sanding the surfaces with coarse and finally fine P180-grit abrasive paper.

Both laser-treated and untreated boards from all three wood species were. The test specimens were divided into two groups:

1. Untreated wood – natural (non-engraved) reference samples.
2. Laser-modified wood – samples treated by surface engraving.

Laser Engraving

Laser engraving was performed according to the methodology described in (Kúdela *et al.* 2022). Each sample was positioned under the lens of a CO_2 laser system (CM-1309, Shenzhen Reliable Laser Tech, Shenzhen, China), with a fixed distance of 17 mm between the lens and the wood surface used (Fig. 1a, b). The laser head moved along the wood grain direction at a constant speed of 350 mm·s^{-1}. The maximum output power of the laser system was P_{max} = 137.5 W, which was measured at the resonator output as described in Kúdela *et al.* (2024).

a) b)

Fig. 1. The laser engraving: a) The sample positioned under the lens of a CO_2 laser system; and b) the laser-treated three wood species (spruce, beech and oak wood)

Laser treatment was conducted at two power levels: 8% = 11 W and 16% = 22 W of P_{max}. For each wood species, samples were engraved using three raster densities: 10, 20, and 30 lines·mm^{-1}, resulting in a total of seven treatment combinations per species (six laser treatments plus one reference (untreated control)). The engraving was executed parallel to the grain.

Surface Finishing

Two types of coating materials (Table 1) were used for surface finishing:

1. Oil-based finish – Hard wax oil Osmo Original 3032, Osmo Holz und Color GmbH & Co. KG, Warendorf, Germany), a high-solids coating based on natural oils and waxes (Osmoshop 2025).
2. Water-based finish – PAM lak (PAM-lak, Čierna Voda – Triblavina, Slovakia). It was composed of aqueous acrylic dispersions, coalescing agents, and special additives (PAM 2020).

Table 1. Characteristics of Coating Materials and their Applications

Finish Product	Oil-based finish	Water-based finish
Commercial name	Hard wax oil Osmo Original 3032	PAM lak
Components	One-component	One-component
Film former	Sunflower oil, Soybean oil, Thistle oil, Carnauba wax and Candelilla wax	Acrylic dispersions
Gloss	Semi-matte	Semi-matt
Solid content (%)	50	30
Density at 20 °C ($g \cdot cm^{-3}$)	0.88 to 0.95	1.05
Finish product drying parameters	Max. 8 to 10 hours at 23˚C, RVV 50%	Max. 24 hours at 23˚C, RVV 55%
Spread rate ($mL \cdot m^{-2}$)	35 to 45	100 to 140
VOC content ($g \cdot L^{-1}$) *	<500	<130
Solvent	Dearomatized white spirit (benzene-free)	Water
Sand grit	For floors P120 to 150, for furniture P180 to 240	P180 to 220
Application/Coat number	Flat brush/2	Flat brush/2
* as per the Decopaint Directive 2004/42/EG		

All coating applications were carried out in accordance with the manufacturers' technical data sheets. The finishes were applied to all test specimens after laser treatment and prior to adhesion testing. After application of the coating materials, the surface treatment cured under the same conditions (at 23˚C, RVV 55%) for 21 days.

Thickness of the Coating Film

To document the visual changes of the coated wood surfaces after laser engraving, high-resolution images were acquired using a Color Laser Jet Pro MFP M477fdw (Fig. 2a).

The non-destructive method was chosen to measure the film thickness (μm) using the ultrasonic instrument PosiTector 200 (DeFelsko Corporation, Ogdensburg, NY, USA). Thickness measurements were conducted with surface of 100 × 50 mm² at 12 points per specimen across the top surface (Fig. 2b).

a) b)

Fig. 2. The instruments: a) multifunction printer Color Laser Jet Pro M477fdw; and b) the PosiTector 200 non-destructively measures the film thickness

Adhesion

The adhesion of the coating films on both laser-modified and unmodified wood surfaces was evaluated using the pull-off test in accordance with the STN EN ISO 4624 (2024) standard (Slovak Technical Standard adopted as European Standard, which adopted the International ISO Standard). For each wood species and coating material, seven combinations of laser treatment (including untreated) were tested. In each combination, six replicates were tested, as specified by the STN EN ISO 4624 (2024) standard.

Adhesion was measured using a PosiTest® AT-A Pull-Off Adhesion Tester (DeFelsko Corporation, Ogdensburg, NY, USA). Circular metal dollies (20 mm in diameter) were bonded to the coated surfaces using a two-component epoxy adhesive (Pattex® Repair Epoxy, Henkel AG & Co. KGaA, Düsseldorf, Germany). The adhesive was allowed to cure for 72 h at 20 °C and 60% relative humidity. Prior to testing, the edges of the bonded dollies were carefully incised with a blade to localize the failure within the test area and avoid propagation outside the bonded zone (Fig. 3a).

The pull-off force was applied at a rate of 1 mm·min^{-1} until detachment occurred. Each failure was then visually assessed using both a table magnifier and a VHX-7000 digital microscope (Keyence Corporation, Osaka, Japan) (Fig. 3b).

a) b)

Fig. 3. The adhesion of the coating films was evaluated using the pull-off test: a) the PosiTest AT-A Pull-off Adhesion Tester measures adhesion of coatings; and b) the digital microscope Keyence VHX-7000

The failure modes were classified based on their location: within the wood substrate, the coating film, the adhesive joint, or at the interface with the metal dolly. Microscope inspection of the fracture surfaces was carried out to determine the nature of the failure as follows:

A – Cohesive failure within the substrate (wood).

A/B – Adhesive failure between the substrate and the first coating layer.

Y/Z – Adhesive failure between the adhesive and the dolly.

The area of each type of fracture was calculated according to the content of the circular sector (Fig. 4a) and segment (Fig. 4b):

$$A1 = \pi r2.\ \alpha / 360° \quad (1)$$

$$A2 = r2/2\ .\ (\text{arc}\ \alpha - \sin \alpha) \quad (2)$$

In these equations, $A1$ and $A2$ represent the content (m^2), C represents the centre of the circle, π represents pi (Archimedes' constant), r represents the circle radius (m), and α represents the central angle (°). The area of each type of fracture was a percentage of the total fracture area, rounded to the nearest 10%.

a) b)

Fig. 4. The area of type of fracture was calculated according to the content of: a) the circular sector and b) the circular segment

RESULTS AND DISCUSSION

Statistical Analysis

In the statistical processing of data, a three-way Analysis of Variance was applied to examine the effects of three independent factors – wood, number of lines and laser power on the response variable - adhesion. This approach made it possible to assess both main effects and interaction effects among the factors. Duncan's post-hoc test was applied as part of the pairwise simultaneous comparison. To complement the ANOVA results, confidence intervals were constructed for the mean values of adhesion for each group, providing an 95% estimate of the population mean values. All analyses were performed under the assumption of normality and homogeneity of variances. As a decision rule in hypothesis testing, the commonly accepted 5% significance level was applied. All calculations were performed using the statistical software STATISTICA 14.

Dry Film Thickness and Surface Wood after Laser Engraving

Table 2 presents the visual documentation (scans) of the engraved surfaces of spruce, beech, and oak wood with coating films.

Table 2. The Surface Change after Laser Engraving with Surface Finishes (Oil-based and Water-based) on Spruce, Beech, and Oak Wood

Wood	Laser Power *	Oil-based				Water-based			
		Raster Density (lines·mm⁻¹)							
		Control	10	20	30	Control	10	20	30
Spruce	8								
	16								
Beech	8								
	16								
Oak	8								
	16								

*Laser treatment was conducted at two power levels: 8% and 16% of P_{max} = 137.5 W

Engraving altered the colour of the wood surface (Kúdela *et al.* 2022, 2023, 2024) and transformed the originally flat surfaces into wavy ones. The undulation was caused by the uneven loss of material during engraving. These same samples were analysed in detail in previous studies by Kúdela *et al.* (2020, 2021), where roughness parameters both parallel and perpendicular to the grain were quantified. The present article therefore builds directly on this published research by the project team, highlighting the most relevant characteristics to explain adhesion behaviour. The results of Kúdela *et al.* (2020, 2021) showed that increases in roughness and waviness were significant already at 8% laser power. Across the entire raster density range, increasing raster density produced higher roughness parameters both parallel and perpendicular to the grain, with significantly greater variance recorded perpendicular to the grain. The most pronounced changes were observed in spruce, whereas beech exhibited the lowest variance.

Treatment of the wood surface with a CO_2 laser caused changes in the physical, mechanical, and chemical properties of the wood. Dolan *et al.* (2015) reported that the transition from translucent wood to dark discolorations, concentrated at the top 25 microns of the surface, provided evidence of laser penetration and surface modification. Ablation and wood penetration are known to depend strongly on wood cellular structure. Although laser modification altered native morphology, nearly two-thirds of the surface still consisted of cellulose, which ensures mechanical performance and contributes to adhesion.

This finding indicate that laser engraving, similarly to steaming, as reported by Adamčík *et al.* (2022), influences the quality of semi-finished and finished wood surfaces. Heat treatments (laser, steaming, *etc.*) thus represent an important tool for improving adhesion of coatings.

Based on the analysis of published knowledge, it can be stated that heat treatments of wood (laser engraving, steaming, *etc.*) affect the quality of the wood surface. It was necessary to verify how laser engraving affects the adhesion of coating films on three different types of wood. The following articles (Dolan *et al.* 2015; Kúdela *et al.* 2022, 2023, 2024) present the results of chemical analysis of the wood surface after laser treatment.

After compositional analysis, Dolan *et al.* (2015) reported that the isolated solids portion of the laser modified material contained an increased amount of lignin due to laser treatment. Hemicelluloses were less thermally stable compared to other wood components and were susceptible to degradation and potentially volatilization during laser modification dependent upon the degree of degradation. Residual hemicellulose monosaccharides are known to create sticky surfaces and may provide initial tack for adhesion. Kúdela *et al.* 2022, 2023, 2024) present the chemical analysis of wood surfaces after laser engraving and subsequently the discolouration of surface due to the laser action on spruce, beech, and oak wood, on which adhesion was determined by using the Pull-off test.

For the untreated reference samples of all the wood species, the penetration of both coating materials (oil-based and water-based) into the wood was the lowest compared with the laser-engraved surfaces. Measurements of film thickness using the non-destructive ultrasonic method showed that the coatings on untreated samples remained mostly on the surface, forming a thicker continuous film. In contrast, the coatings on engraved surfaces formed thinner films, as the surface layers of the charred wood after engraving were more impregnated (Table 3).

Table 3. Thickness of the Coating Film of the Oil-based and Water-based Surface Finishes on Spruce, Beech, and Oak Wood After Laser Engraving

Wood	Laser Power *	Raster Density (lines·mm⁻¹)	Dry Film Thickness (µm)			
			Oil-based		Water-based	
			Mean	SD/CV (%)	Mean	SD/CV (%)
Spruce	8	10	40	3/7.5	36	1/2.8
		20	38	3/7.9	40	4/10.0
		30	37	2/5.4	43	1/2.3
	16	10	36	2/5.6	43	3/7.0
		20	41	1/2.4	42	1/2.4
		30	51	4/7.8	44	3/6.8
	Control	–	98	8/8.2	108	5/4.6
Beech	8	10	36	1/2.8	37	1/2.7
		20	36	2/5.6	37	2/5.4
		30	36	1/2.8	36	1/2.8
	16	10	36	1/2.8	36	2/5.6
		20	37	1/2.7	37	3/8.1
		30	37	1/2.7	37	3/8.1
	Control	–	131	6/4.6	124	12/9.7
Oak	8	10	37	4/10.8	34	2/5.9
		20	35	2/5.7	34	2/5.9
		30	36	3/8.3	37	1/2.7
	16	10	37	1/2.7	35	5/14.3
		20	37	3/8.1	36	1/2.8
		30	44	9/20.5	37	1/2.7
	Control	–	133	22/16.5	111	22/19.8

* Laser treatment was conducted at two power levels: 8% and 16% of P_{max} = 137.5 W

Coating Adhesion Strength on Oil-based Surface Finish

Table 4 presents the results of three-factor analysis of variance for the oil-based coating film. The factors monitored were wood (spruce, beech, oak); laser power (8% and 16% of P_{max}); and raster density (10, 20, and 30 lines·mm⁻¹). At significance level of α = 0.05, the differences in mean adhesion values were found to be significant. The interaction effect of the investigated factors on adhesion was also significant (p = 0.020).

Table 4. Results of Three-factor ANOVA – Influence of the Interaction of the Investigated Factors (Wood × Laser Power × Raster Density) on Adhesion

Three-factor ANOVA (Wood × Laser Power × Raster Density)	SS*	df	MS	F-test	p-level
Model	31.61	4	7.90	3.06	0.020
Error	30.67	90	0.34		

* SS-sum of squares, df – degree of freedom, MS-mean square

For the oil-based coating film, the basic descriptive statistics and 95% interval estimates for the mean adhesion values for each combinations of experimental factors are presented in Table 5.

Table 5. Descriptive Statistics and 95% Confidence Intervals of Adhesion of Oil-based Coating Film Means for Individual Combinations of Experimental Factors (Wood × Laser Power × Raster Density)

Wood	Laser Power *	Raster Density (lines·mm⁻¹)	Mean	Standard Deviation	95% Confidence Interval	
					Lower limit	Upper limit
Spruce	8	10	1.74	0.48	1.24	2.24
		20	2.16	0.34	1.81	2.51
		30	1.56	0.40	1.14	1.98
	16	10	1.41	0.28	1.11	1.71
		20	1.61	0.33	1.26	1.96
		30	1.87	0.44	1.40	2.33
	Control	–	1.37	0.55	0.80	1.95
Beech	8	10	2.51	0.41	2.07	2.94
		20	3.05	0.63	2.39	3.71
		30	3.05	0.92	2.08	4.02
	16	10	3.64	1.03	2.56	4.71
		20	2.66	0.72	1.90	3.41
		30	2.65	0.74	1.87	3.43
	Control	–	1.83	0.27	1.55	2.11
Oak	8	10	2.92	0.66	2.22	3.61
		20	2.41	0.66	1.71	3.10
		30	2.60	0.61	1.96	3.25
	16	10	2.92	0.32	2.59	3.25
		20	2.44	0.49	1.92	2.95
		30	2.26	0.33	1.91	2.60
	Control	–	1.95	0.62	1.30	2.60

* Laser treatment was conducted at two power levels: 8% and 16% of P_{max} = 137.5 W

The sample means and 95% confidence intervals are illustrated as box plots in Fig. 5. For spruce, the combination 8 × 20 showed a significant increase compared to the reference sample (p = 0.017). For beech, all tested factor combinations differed significantly from the reference ($p < 0.05$). For oak, significant differences were observed for combinations 8 × 10 (p = 0.027) and 16 × 10 (p = 0.011).

Dolan *et al.* (2015) reported that laser modification creates a surface phenomenon that physically and chemically alters the natural biopolymer organization of lignocelluloses materials in a way that promotes adhesion. The present results confirmed the conclusions in Dolan *et al.* (2015); thus, the adhesion of oil-based coating film to laser engraved wood surfaces increased. In Table 4, it is apparent that the lowest adhesion was on spruce surfaces with laser engraving 16 × 10 (1.41 MPa) and the highest on beech surfaces with laser engraving 16 × 10 (3.64 MPa).

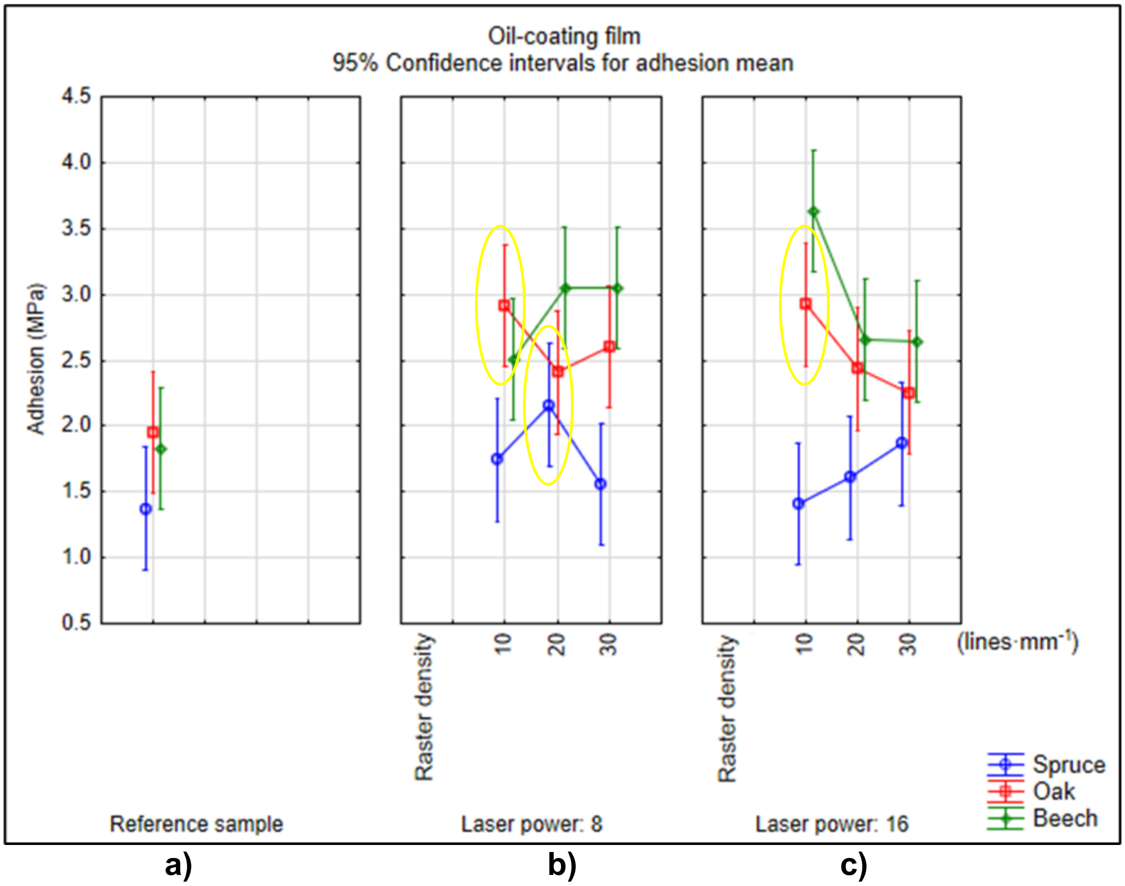

Fig. 5. Confidence intervals (95%) for means of adhesion of oil-based coating film at three raster densities (10, 20, and 30 lines·mm⁻¹). a) reference sample; b) laser power 8%; c) laser power 16%

Coating Adhesion Strength on Water-based Surface Finish

The results of the three-factor ANOVA for the adhesion strength of the water-based coating layer are shown in Table 6. The factors monitored were: wood (spruce, beech, oak); laser power (8% and 16% of P_{max}); and raster density (10, 20, and 30 lines·mm^{-1}). At $\alpha = 0.05$, the interaction effect of the investigated factors on adhesion was significant ($p = 0.013$), indicating that the mean adhesion values differed significantly across factor combinations.

Table 6. Results of Three-factor ANOVA –Influence of the Interaction of the Investigated Factors (Wood × Laser Power × Raster Density) on Adhesion

Three-factor ANOVA (Wood × Laser Power × Raster Density)	SS*	df	MS	F-test	p-level
Model	4.53	4	1.13	3.32	0.013
Error	30.67	90	0.34		
* SS-sum of squares, df – degree of freedom, MS-mean square					

For the water-based coating film, the descriptive statistics and 95% confidence intervals of the mean adhesion values for each combination of experimental factors are presented in Table 7.

Table 7. Descriptive Statistics and 95% Confidence Intervals of Adhesion Means of Water-based Coating Film for Individual Combinations of Experimental Factors

Wood	Laser Power *	Raster Density (lines·mm⁻¹)	Mean	Standard Deviation	95% Confidence Interval	
					Lower limit	Upper limit
Spruce	8	10	3.16	0.49	2.65	3.68
		20	3.16	0.30	2.84	3.47
		30	3.16	0.72	2.41	3.92
	16	10	2.84	1.03	1.76	3.92
		20	3.36	0.81	2.50	4.21
		30	3.37	0.67	2.67	4.06
	Control	–	3.27	0.63	2.61	3.93
Beech	8	10	7.64	2.17	5.36	9.92
		20	7.79	2.81	4.84	10.74
		30	8.36	2.56	5.67	11.05
	16	10	9.60	2.98	6.47	12.72
		20	8.39	2.53	5.73	11.05
		30	6.09	1.31	4.71	7.47
	Control	–	8.07	1.44	6.55	9.58
Oak	8	10	7.03	1.16	5.81	8.25
		20	6.43	1.64	4.71	8.15
		30	4.59	0.68	3.88	5.31
	16	10	6.24	1.38	4.79	7.68
		20	4.08	0.82	3.21	4.94
		30	4.51	0.39	4.10	4.92
	Control	–	7.15	0.84	6.26	8.03

* Laser treatment was conducted at two power levels: 8% and 16% of P_{max} = 137.5 W

The sample means and 95% confidence intervals are illustrated in Fig. 6. Reference samples are shown on the left, and factor combinations on the right. For spruce, no significant differences from the reference were observed. For beech, the combination 16 (laser power) × 30 (raster density) differed significantly from the reference ($p = 0.002$). For oak, the combinations 8 × 30, 16 × 20, and 16 × 30 showed significant differences ($p < 0.05$).

The present results on the adhesion of water-based coating film to laser engraved wood surface did not confirm the conclusions in the work of Dolan *et al.* (2015). The laser engraved wood surface did not promote adhesion of water-based coating film on spruce wood. Adhesion on beech wood was both increased and decreased, and on oak wood it was reduced. In Table 6, it can be seen that the lowest adhesion was on spruce surfaces with laser engraving 16 × 10 (2.84 MPa) and the highest on beech surfaces with laser engraving 16 × 10 (9.60 MPa).

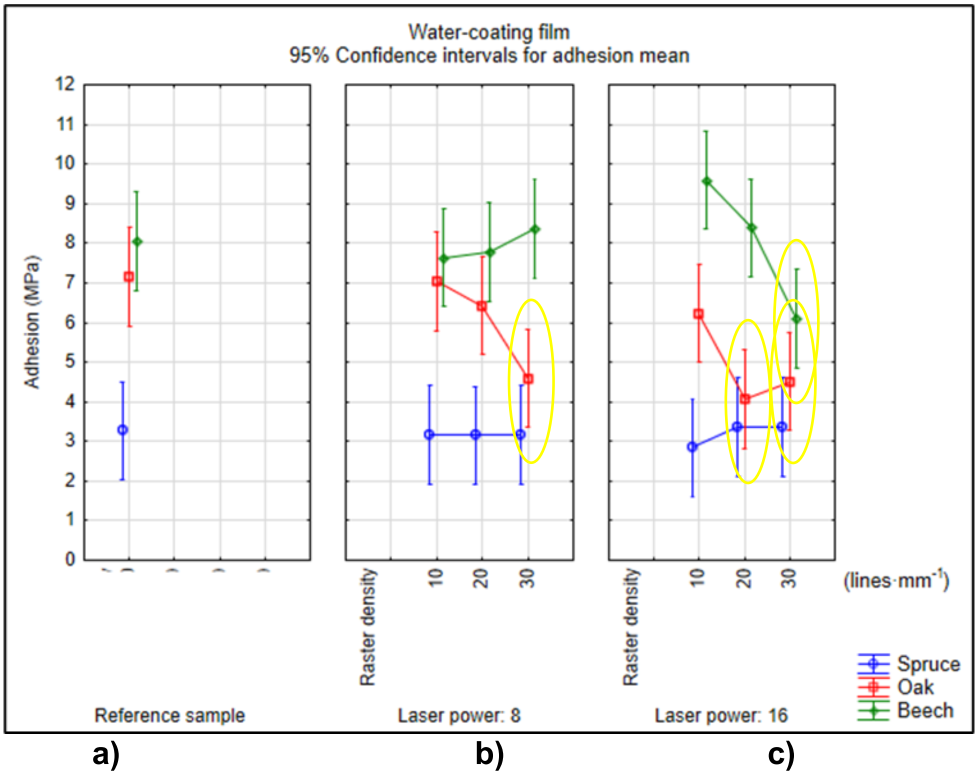

Fig. 6. Confidence intervals (95%) for means of adhesion of water-based coating film at three raster densities (10, 20, and 30 lines·mm^{-1}). a) reference sample; b) laser power 8%; c) laser power 16%

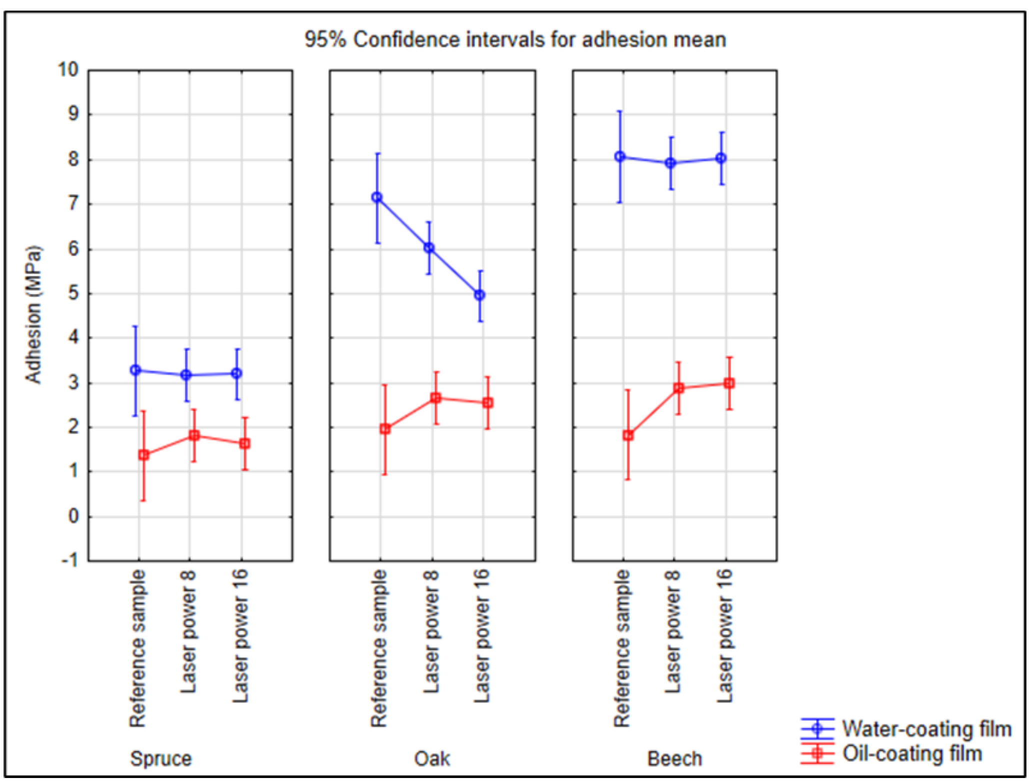

Fig. 7. Confidence intervals (95%) for means of adhesion of oil- and water-based coating film at two laser powers (8%; 16% of P_{max} = 137.5 W)

Coating Adhesion Strength on Laser Engraving Surface Wood

The results showed (Fig. 7) that laser engraving power level 8% and 16% without influence of raster density (10, 20, or 30 lines·mm⁻¹) on spruce, beech, and oak wood did not significantly increase the adhesion of the oil-based coating film. The laser engraving power level 8% and 16% on spruce and beech wood did not significantly reduce the adhesion of the water-based coating film. However, the laser engraving power level 16% on oak significantly reduced the adhesion of the water-based coating film.

Coating Adhesion Strength: Fracture Pattern

After the Pull-off test, the dolly surface and the surface of the laser-treated and non-treated wood that were and subsequently coated with coatings were microscopically inspected (Table 8.).

Table 8. Nature of the Fracture, and the Type of Fracture for Oil-based and Water-based Surface Finish on Engraved Spruce, Beech, and Oak Wood

Wood	Laser Power *	Raster Density (lines·mm⁻¹)	Failure (%)					
			Oil-based			Water-based		
			A**	A/B**	Y/Z**	A**	A/B**	Y/Z**
Spruce	8	10	10	90		90	10	
		20	10	80	10	80	20	
		30	10	90		70	30	
	16	10		80	20	80	20	
		20	20	80		60	40	
		30	10	80	10	70	30	
	Control	–		100		70	30	
Beech	8	10		90	10	20	60	20
		20		100		10	80	10
		30		100		10	70	20
	16	10		90	10	30	50	20
		20		90	10	10	60	30
		30		100			80	20
	Control	–		100		10	80	10
Oak	8	10		100		30	70	
		20		100		30	60	10
		30		100		10	80	10
	16	10		90	10	20	70	10
		20		100		10	90	
		30		100		20	70	10
	Control	–		100		20	70	10

* Laser treatment was conducted at two power levels: 8% and 16% of P_{max} = 137.5 W
** A – Cohesive failure within the substrate (wood).
A/B – Adhesive failure between the substrate and the first coating layer.
Y/Z – Adhesive failure between the adhesive and the dolly.

On the spruce wood surface without laser treatment, the type of fracture was 100% adhesive failure between the substrate and the first coating layer (Fig. 8a). The oil-based system on surfaces of the laser-treated spruce exhibited combination adhesive failure (Fig. 5a) and cohesive failure within the substrate (Fig. 8c).

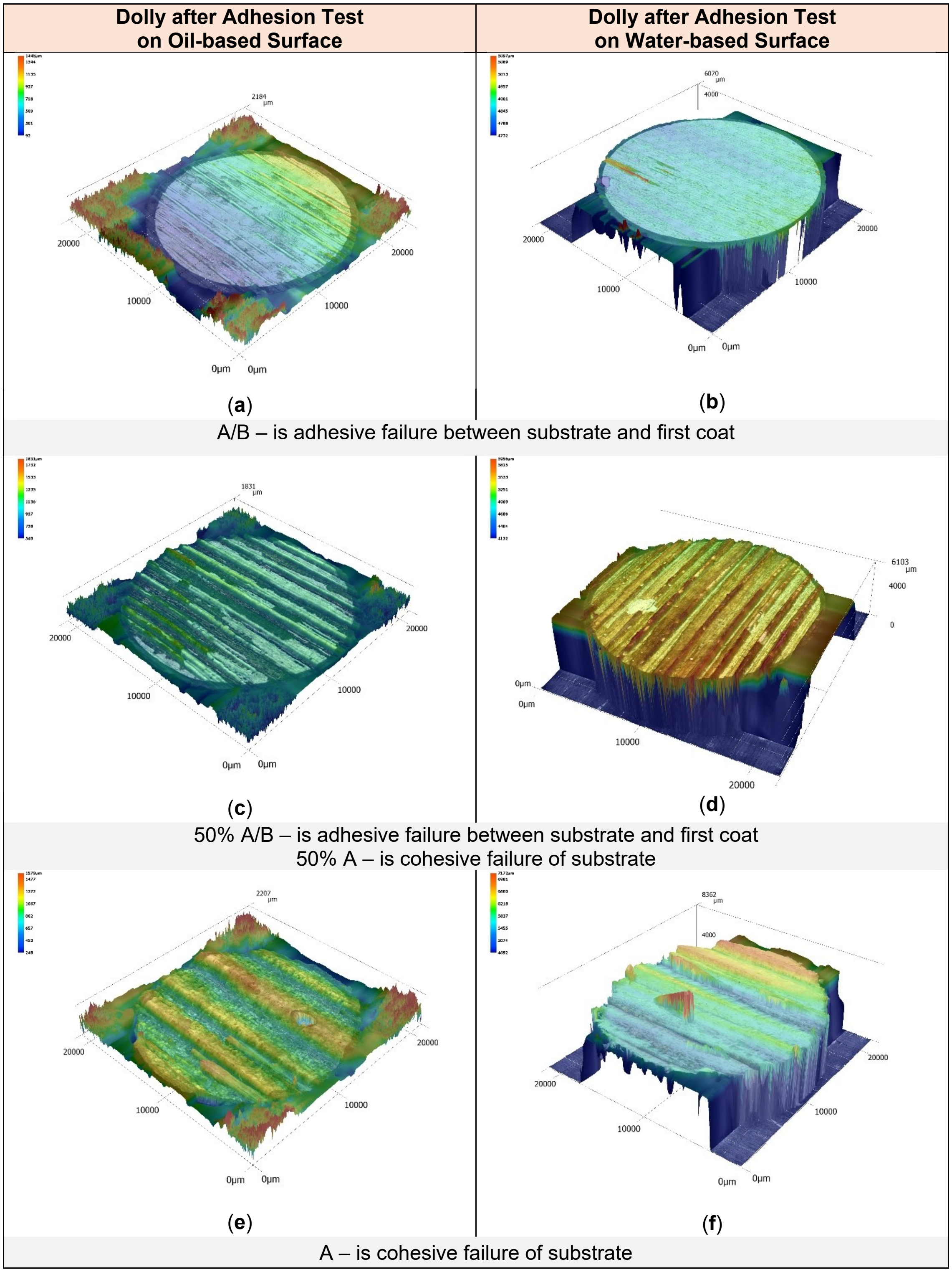

Fig. 8. The nature of the failure of dolly after fracture

It can be stated that the oil-based system on surfaces of the laser-treated spruce exhibited adhesive failure of fracture between the substrate and the first coating layer on 80% to 90% of the surface on dolly. Only 10% to 20% of the surface on dolly fracture that occurred was a fracture in the surface layers of the wood. The adhesion of the oil-based surface finish was less than the cohesion in the surface layers of the wood. The measured adhesion of the oil-based surface finish on spruce surfaces with laser engraving was comparable to the adhesion on spruce wood without engraving, in the range 1.41 to 2.16 MPa.

On the beech wood surface without laser treatment, the type of fracture was 100% adhesive failure between the substrate and the first coating layer, and adhesion was 1.83 MPa. The type of fracture of the beech with laser treatment – oil-based system after the pull-off test was 90% to 100% adhesive failure between the substrate and the first coating layer (Fig. 8a), and there was 10% adhesive failure between the adhesive and the dolly. On the beech wood surface with laser treatment, the adhesion was in range of 2.51 MPa to 3.05 MPa. The current results did not show a reduction in the strength of the surface layers of beech wood due to laser treatment, but rather a slight increase in adhesion.

On the oak wood surface without and with laser treatment, the type of fracture was 100% adhesive failure between the substrate and the first coating layer. Adhesion of coating film oil-based on the oak wood surface without laser treatment was 1.95 MPa and on the wood with laser treatment was 2.26 to 2.92 MPa. The type of fracture of the oak wood – oil-based system after the pull-off test was predominantly 100% adhesive failure between the substrate and the first coating layer (Fig. 8a). Laser modification creates a surface phenomenon that physically and chemically alters the natural biopolymer organization of lignocelluloses materials in a way that promotes adhesion (Kúdela *et al.* 2021). However, for surfaces engraved with higher raster densities, it is necessary to consider an unstable carbonised layer, with weak adhesion, possible to peel off from the substrate easily (Kúdela *et al.* 2022). This could have caused lower adhesion of the coating film on the laser-engraved oak wood.

On the surface of spruce wood without laser treatment, the type of fracture was the same as that on surfaces of the laser-treated in the ratio A70% to A/B30%, and adhesion water-based system was 3.27 MPa. The water-based system on surfaces of the laser-treated spruce exhibited combination adhesive failure (Fig. 8b) and cohesive failure within the substrate (Fig. 8d, f). It can be stated that the water-based system on surfaces of the laser-treated spruce exhibited adhesive failure of fracture between the substrate and the first coating layer on 10% to 40% of the surface on dolly. On 60% to 90% of the surface on dolly fracture that occurred was cohesive failure within the wood. The measured adhesion of the water-based surface finish on spruce surfaces with laser engraving decreased significantly and proportionately compared to spruce wood without engraving, with values in the range of 1.41 to 2.16 MPa.

There was a maximum of 10% adhesive failure between the adhesive and the dolly on the beech wood surface without laser treatment and of 80% cohesive failure within the wood, adhesion water-based system was 8.07 MPa. The water-based system on surfaces of the laser-treated beech exhibited combination adhesive failure (Fig. 8b) and cohesive failure within the substrate (Fig. 8d, f). It can be stated that the water-based system on surfaces of the laser-treated beech exhibited adhesive failure of fracture between the substrate and the first coating layer on 10% to 30% of the surface on dolly. On 50% to 80% of the surface on the dolly fracture that occurred was cohesive failure within the wood. On laser-engraved beech wood, 10% to 30% adhesive failure between the adhesive and the dolly occurred. On the beech wood surface with laser treatment, adhesion was in the range of 6.09 to 9.60 MPa.

On the surface of oak wood with laser treatment, after the pull-off test, the type of fracture was 60% to 90% adhesive failure between the substrate and the first coating layer water-based system. The type of fracture was 10% to 30% cohesive failure within the oak wood (Fig. 8f) and the adhesion was in the range 4.08 to 7.03 MPa. The type of fracture was also similar on oak wood without laser treatment and the adhesion was 7.15 MPa.

Kúdela *et al.* (2022) reported that the results concerning the wetting and the surface free energy values obtained for the laser-engraved oak wood surfaces make it possible to suppose an appropriate spreading of film-forming material on the wood surface, and, correspondingly, appropriate adhesion of film-forming materials to wood. Dolan *et al.* (2015) reported that laser-modified samples had a surface free energy that remained similar to the control wood sample. In addition, the dispersion component of the surface free energy increased due to laser ablation while acid-base components were reduced. In Reinprecht and Vidholdová (2021) it was concluded that the adhesion strength of the phase interface "synthetic polymer-wood", as evaluated by the standard EN ISO 4624 (2024), decreased significantly and proportionately in all the laser modification modes, with higher irradiation doses, leading to a more apparent degradation and carbonization of the wood adherent or the synthetic polymer layer.

The above statements cannot be generalized for all types of wood, nor for all types of coatings. The aim of the present article was to monitor the changes in adhesion due to laser-treated wood on three different types of wood. Two different types of ecological coating materials were selected from the coating materials. For individual coatings and investigated wood species, the following changes in adhesion occurred due to different raster density, at laser power 8% and 16%. The pull-off test results showed that laser engraving power level 8% and 16% on spruce wood did not increase the adhesion of the oil-based coating film. The test results showed that laser engraving power level 8% and raster density 10 lines·mm^{-1} on oak wood increased the adhesion of the oil-based coating film. Laser engraving power level 8% and raster density 20 and 30 lines·mm^{-1} on beech wood increased the adhesion of the oil-based coating film. The test results showed that laser engraving power level 16% and raster density 10 lines·mm^{-1} on beech and oak wood increased the adhesion of the oil-based coating film.

The pull-off test results showed that laser engraving power levels 8% and 16% on spruce wood did not increase nor reduce the adhesion of the water-based coating film. The test results showed that laser engraving power level 8% and raster density 30 lines·mm^{-1} on oak wood reduced the adhesion of the water-based coating film. The test results showed that laser engraving power level 16% and raster density 30 lines·mm^{-1} on beech wood reduced the adhesion of the water-based coating film. Laser engraving power level 16% and raster density 20 and 30 lines·mm^{-1} on oak wood reduce the adhesion of the water-based coating film.

CONCLUSIONS

1. The results demonstrated that laser engraving at power levels of 8% and 16% on spruce wood neither increased the adhesion of the oil-based coating film except for the combination (spruce × 8 × 20) nor reduced the adhesion of the water-based coating film across almost all tested raster density combinations. Therefore, laser-engraved

spruce surfaces were able to be finished with both oil-based and water-based coatings, as adhesion remained comparable to that of unengraved surfaces.

2. For beech wood, laser engraving generally enhanced the adhesion of oil-based coatings. However, in the combination (beech × 16 × 30) cases it reduced the adhesion of water-based coatings.
3. For oak wood, laser engraving generally enhanced the adhesion of oil-based coatings, significantly in the combinations (oak × 8 × 10 and oak × 16 × 10). However, in the combinations (oak × 8 × 30, oak × 16 × 20 and oak × 16 × 30) cases it reduced the adhesion of water-based coatings.
4. Across all three wood species, oil-based coatings exhibited lower adhesion to the wood surface compared with water-based coatings, typically resulting in adhesive failure. In contrast, water-based coatings occasionally failed within the wood itself, indicating that their adhesion strength exceeded the cohesive strength of the laser-modified surface layers. We recommend an oil-based finish on laser-engraved wood surfaces as it has a uniform adhesion.

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Use of Generative AI

Generative artificial intelligence tools were not used to prepare text, images, pictures, graphs, or diagrams.

REFERENCES CITED

Açık, C. (2023). "Modeling of color design on furniture surfaces with CNC laser modification," *Wood Industry* 74(4), 518-526. https://doi.org/10.5552/drvind.2023.0096

Açık, C. (2024). "Studying of the effects of some varnish types used in the furniture industry on woodworking performance of laser," *Eur. J. Wood Wood Prod.* 82(5), 1491-1499. https://doi.org/10.1007/s00107-024-02075-1

Adamčík, L., Kminiak, R., and Banski, A. (2022). "The effect of thermal modification of beech wood on the quality of milled surface," *Acta Fac. Xylolog. Zvo.* 64(2), 57-67. https://doi.org/10.17423/afx.2022.64.2.06

Angelski, D., and Atanasova, K. (2024). "Water permeability and adhesion strength of bio-based coating applied on wood," *Wood Industry* 75(1), 43-48. https://doi.org/10.5552/drvind.2024.0118

Bansal, R., Nair, S., and Pandey, K. K. (2022). "UV resistant wood coating based on zinc oxide and cerium oxide dispersed linseed oil nano-emulsion," *Mater. Today Commun.* 2022(30), article 103177. https://doi.org/10.1016/j.mtcomm.2022.103177

Bulian, F., and Graystone, J. A. (2009). *Wood Coatings-Theory and Practice*, Elsevier, Amsterdam, The Netherlands.

Calovi, M., and Rossi, S. (2023). "From wood waste to wood protection: New application of black bio renewable water-based dispersions as pigment for bio-based wood paint," *Prog. Org. Coat.* 180, article 107577. https://doi.org/10.1016/j.porgcoat.2023.107577

Chernykh, M., Zykova, M., Stollmann, V., and Gilfanov, M. (2022). "Influence effect of wood laser engraving mode on aesthetic perception of images," *Acta Fac. Xylolog. Zvo.* 64(2), 87-96. https://doi.org/10.17423/afx.2022.64.2.09

Dolan, J. A., Sathitsuksanoh, N., Rodriguez, K., Simmons, B. A., Frazier, C. E., and Renneckar, S. (2015). "Biocomposite adhesion without added resin: understanding the chemistry of the direct conversion of wood into adhesives," *RSC Advances* 5(82), 67267-67276. https://doi.org/10.1039/C5RA09676F

Gurău, L., and Petru, A. (2018). "The influence of CO2 laser beam power output and scanning speed on surface quality of Norway maple (*Acer platanoides*)," *BioResources* 13(4), 8168-8183. https://doi.org/10.15376/biores.13.4.8168-8183

Gurău, L., Coşereanu, C., and Paiu, I. (2021). "Comparative surface quality of larch (*Larix decidua* Mill.) fretwork patterns cut through by CNC routing and by laser," *Appl. Sci.* 11(15), article 6875. https://doi.org/10.3390/app11156875

Gurău, L., Petru, A., Varodi, A., and Timar, M. C. (2017). "The influence of CO_2 laser beam power output and scanning speed on surface roughness and colour changes of beech (*Fagus sylvatica*)," *BioResources* 12(4), 7395-7412. https://doi.org/10.15376/biores.12.4.7395-7412

Henn, K. A., Forsman, N., Zou, T., and Österberg, M. (2021). "Colloidal lignin particles and epoxies for bio-based, durable, and multiresistant nanostructured coatings," *ACS Appl. Mater. Interfaces* 13(29), 34793-34806. https://doi.org/10.1021/acsami.1c06087

Hubbe, M. A., and Laleicke, F. (2025). "Chemical and mechanistic aspects of wood finishing: A review encompassing paints and clear coats," *BioResources* 20(2), 4952-5029. https://doi.org/10.15376/biores.20.2.Hubbe

Islam, M. N., Das, A. K., Billah, M. M., Rahman, K. S., Hiziroglu, S., Hattori, N., Agar, D. A., Rudolfsson, M. (2023). "Multifaceted laser applications for wood–a review from properties analysis to advanced products manufacturing," *Laser Manuf. Mater. Process.*, 10(2), 225-250. https://doi.org/10.1007/s40516-023-00204-x

Jurek, M., Wagnerová, R., Šafář, M., and Bidhar, S. (2025). "Crafting pixels in wood: Understanding the interplay of technologies and visual perception in wooden photo engraving," *Eur. J. Wood Wood Prod*. 83(1), 1-15. https://doi.org/10.1007/s00107-024-02172-1

Kabasakal, Y., Baysal, E., Babahan-Bircan, I., Altay, Ç., and Toker, H. (2023). "Investigation of some physical and mechanical properties of wood coated with plant-oil based epoxide nanocomposite materials," *Prog. Org. Coat*. 176, article 107383. https://doi.org/10.1016/j.porgcoat.2022.107383

Karaman, I., Kılıç, K., and Söğütlü, C. (2023). "Prediction of adhesion strength of some varnishes using soft computing models," *Wood Industry* 74(2), 153-166. https://doi.org/10.5552/drvind.2023.0029

Kúdela, J., and Kubovský, I. (2016). "Accelerated-ageing-induced photo-degradation of beech wood surface treated with selected coating materials," *Acta Fac. Xylolog. Zvo.* 58(2), 27-36. https://doi.org/10.17423/afx.2016.58.2.03

Kúdela, J., Andrejko, M., and Kubovský, I. (2023). “The effect of CO_2 laser engraving on the surface structure and properties of spruce wood,” *Coat.* 13(12), article 2006. https://doi.org/10.3390/coatings13122006

Kúdela, J., Andrejko, M., and Mišíková, O. (2021). “Wood surface morphology alteration induced by engraving with CO_2 laser under different raster density values,” *Acta Fac. Xylolog. Zvo.* 63(1), 35-47. https://doi.org/10.17423/afx.2021.63.1.04

Kúdela, J., Kubovský, I., and Andrejko, M. (2020). “Surface properties of beech wood after CO_2 laser engraving,” *Coat.* 10(1), article 77. https://doi.org/10.3390/coatings10010077

Kúdela, J., Kubovský, I., and Andrejko, M. (2022). “Influence of irradiation parameters on structure and properties of oak wood surface engraved with a CO_2 laser,” *Materials* 15(23), article 8384. https://doi.org/10.3390/ma15238384

Kúdela, J., Kubovský, I., and Andrejko, M. (2024). “Discolouration and chemical changes of beech wood after CO2 laser engraving,” *Forests* 15(12), article 2211. https://doi.org/10.3390/f15122211

Li, R., He, C., and Wang, X. (2022a). “Effects of processing parameters on mass loss and coating properties of poplar plywood during CO_2 laser modification,” *Eur. J. Wood Wood Prod.* 4, 899-906. https://doi.org/10.1007/s00107-022-01802-w

Li, R., He, C., Chen, Y., and Wang, X. (2021a). “Effects of laser parameters on the width of color change area of poplar wood surface during a single irradiation,” *Eur. J. Wood Wood Prod.* 79(5), 1109-1116. https://doi.org/10.1007/s00107-021-01706-1

Li, R., He, C., Xu, W., and Wang, X. A. (2022b). “Prediction of surface roughness of CO_2 laser modified poplar wood *via* response surface methodology,” *Maderas. Ciencia y Tecnología* 24, 1-12. https://doi.org/10.4067/s0718-221x2022000100442

Li, X., Wang, D., Zhao, L., Hou, X., Liu, L., Feng, B., Li, M., Zheng, P., Zhao, X., and Wei, S. (2021b). “UV LED curable epoxy soybean-oil-based waterborne PUA resin for wood coatings,” *Prog. Org. Coat.* 151, article 105942. https://doi.org/10.1016/j.porgcoat.2020.105942

Li, Z., Zhang, J., Lin, L., Zhang, X., Liu, Q., and Shi, J. (2024). “Layered laser-engraved wood-based composite capable of photothermal conversion and energy storage for indoor thermal management in buildings,” *Energy Build.* 318, article 114425. https://doi.org/10.1016/j.enbuild.2024.114425

Liu, C., and Xu, W. (2022). “Effect of coating process on properties of two-component waterborne polyurethane coatings for wood,” *Coat.* 12(12), article 1857. https://doi.org/10.3390/coatings12121857

Lungu, A., Timar, M. C., Beldean, E. C., Georgescu, S. V., and Coşereanu, C. (2022). “Adding value to maple (*Acer Pseudoplatanus*) wood furniture surfaces by different methods of transposing motifs from textile heritage,” *Coat.* 12(10), article 1393. https://doi.org/10.3390/coatings12101393

Nguyen-Thi-Ngoc, H. U. Y. E. N., and Dang, T. V. (2023). “Optimization of process parameters for wood laser engraving based on Taguchi method approach,” *MM Sci. J.* 3, 6723-6729. https://doi.org/10.17973/MMSJ.2023_10_2023053

Osmoshop (2025). “OSMO Hardwax-oil original,” Available online: https://www.osmoshop.com/en/osmo-hardwax-oil-original/3032-375, Accessed 11 July 2025.

PAM (2020). “Pam lacquer,” Available online: https://www.pam.sk/pam-lak/1189, Accessed 11 July 2025.

Pavlič, M., Petrič, M., and Žigon, J. (2021). "Interactions of coating and wood flooring surface system properties," *Coat.* 11(1), article 91. https://doi.org/10.3390/coatings11010091
Reinprecht, L., and Vidholdová, Z. (2021). "The impact of a CO_2 laser on the adhesion and mold resistance of a synthetic polymer layer on a wood surface," *Forests* 12(2), article 242. https://doi.org/10.3390/f12020242
Slabejová, G., Vidholdová, Z., and Šmidriaková, M. (2019). "Surface finishes for thermally modified beech wood," *Acta Fac. Xylolog. Zvo.* 61(2), 41-50. https://doi.org/10.17423/afx.2019.61.2.04
STN EN ISO 4624 (2024). "Paints and varnishes - Pull-off test for adhesion," Slovak Office of Standards, Metrology and Testing, Bratislava, Slovakia.
Varganici, C. D., Rosu, L., Rosu, D., Mustata, F., and Rusu, T. (2021). "Sustainable wood coatings made of epoxidized vegetable oils for ultraviolet protection," *Environ. Chem. Lett.* 19, 307-328.
Vidholdová, Z., Slabejová, G., and Kaloč, J. (2017). "Influence of wood pre-weathering on selected surface properties of the system wood–coating film," *Acta Fac. Xylolog. Zvo.* 59(2), 67-77. https://doi.org/10.17423/afx.2017.59.2.07
Vidholdova, Z., Slabejová, G., and Šmidriaková, M. (2021). "Quality of oil-and wax-based surface finishes on thermally modified oak wood," *Coat.* 11(2), article ID 143. https://doi.org/10.3390/coatings11020143
Wang, X., Shen, J., Chen, Y., and Li, L. (2024). "A wood wax oil-based nanocomposite coating with excellent durability, ultraviolet and water resistance for wood finishing," *Prog. Org. Coat.* 2024(190), article 108408. https://doi.org/10.1016/j.porgcoat.2024.108408
Wang, Y., Ge-Zhang, S., Mu, P., Wang, X., Li, S., Qiao, L., and Mu, H. (2023). "Advances in sol-gel-based superhydrophobic coatings for wood: A review," *Int. J. Mol. Sci.* 24(11), article 9675. https://doi.org/10.3390/ijms24119675
Žigon, J., Kovač, J., and Petrič, M. (2022). "The influence of mechanical, physical and chemical pre-treatment processes of wood surface on the relationships of wood with a waterborne opaque coating," *Prog. Org. Coat.* 162, article 106574. https://doi.org/10.1016/j.porgcoat.2021.106574
Zou, Y., Pan, P., and Yan, X. (2023). "Comparative analysis of performance of water-based coatings prepared by two kinds of anti-bacterial microcapsules and nano-silver solution on the surface of Andoung wood," *Coat.* 13(9), article 1518. https://doi.org/10.3390/coatings13091518
Zou, Y., Pan, P., Zhang, N., and Yan, X. (2024). "Effect of nano-silver solution microcapsules mixed with rosin-modified shellac micro-capsules on the performance of water-based coating on Andoung wood (*Monopetalanthus* spp.)," *Coat.* 14(3), article 286. https://doi.org/10.3390/coatings14030286
Zou, Y., Zhang, Y., Li, P., Qiao, J., Wu, Y., Li, X., and Zuo, Y. (2025). "Water-resistant, transparent, and highly efficient flame-retardant wood coating," *Ind. Crop. Prod.* 223, article 120061. https://doi.org/10.1016/j.indcrop.2024.120061

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