The Effect of Weathering on Color and Glossiness Properties of Polyurethane-Modified Water-Based Varnish Layers Applied to Thermally Treated Ash Wood

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The effects of artificial weathering (168, 336, and 504 h) on the glossiness values and color parameters of varnished, polyurethane-modified ash wood were investigated. Samples included control samples without treatment and thermally treated samples under two different conditions (190 °C for 1.5 h and 212 °C for 2 h), all coated with a polyurethane-modified water-based varnish. In non-thermally treated and varnished samples, decreases in L^* values were observed after weathering, while increases were noted in h^o, C^*, b^*, and glossiness at 60° in both perpendicular and parallel directions to the fibers. After weathering, for samples thermally treated at 190 °C for 1.5 h and varnished, increases were observed in glossiness values at 20° and 60° in both directions, as well as in L^*, b^*, and h^o values. Conversely, decreases were noted in a^* and C^* values. In samples thermally treated at 212 °C for 2 h and varnished, increases in a^*, L^*, h^o, b^*, and C^* values were detected after weathering, whereas decreases were observed in glossiness at all angles (20° and 60°) in both directions. The ΔE^* values showed a decreasing trend in non-thermally treated varnished samples after weathering, while an increase was observed in samples thermally treated at 212 °C for 2 h and varnished.

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INTRODUCTION

Most wooden items, in typical applications, are covered with a protective layer. Untreated wood quickly becomes dirty, scratched, cracked, warped, deformed, and worn. Its color deteriorates and turns yellow. A significant benefit of these protective coverings is that they also enhance the natural beauty of the wood (Şanıvar 1978).

Water-based varnish uses water as its medium, making it environmentally friendly, and it is considered a "green" alternative to other varnishes (Zhao *et al*. 2011a,b). Varnishes are widely used in daily life, as well as for technical, cosmetic, and medical purposes; their versatile applications make them indispensable. Depending on their composition and additives, varnishes are generally designed for surface protection or decoration. However, as functional coatings, they can also demonstrate specialized properties (Hirt 2016). A varnish coating serves as a barrier between the material and its environment, with its effectiveness being best assessed through natural environmental exposure and artificial aging tests in the laboratory (Schmidt 1988).

In modern applications, water-based coating systems are available in transparent, semi-transparent, and fully pigmented forms, depending on the functional requirements and desired coating quality. The most commonly used water-based coatings for industrial finishing of furniture and doors are as follows (Prieto and Kiene 2018):

a) Single-component water-based coatings, which cure mainly by evaporation but may also include minor self-crosslinking reactions in certain formulations.

b) Two-component polyurethane water-based coatings, requiring the addition of polyisocyanate as a hardener and involving a covalent reaction during curing

A wooden surface exposed to external environmental conditions without the protection of paint or other finishes typically experiences surface roughening and deterioration, a process commonly known as weathering (Shmulsky and Jones 2011).

Water-borne coating formulations for wood have water as the main suspending fluid medium (typically at least 80% of the volatile content), which distributes the other components within the system (Pathak and Khanna 2008).

Physical drying refers to the process where liquids, including water and solvents, turn into a solid state as they evaporate. This evaporation process is influenced by several factors, such as temperature, air movement, and the concentration of solvents or water, in the surrounding air. In contrast, chemical drying involves a chemical reaction that increases the molecular mass as the substance solidifies. The rate and effectiveness of such reactions depend on factors including temperature and the quantity of reactants. If the reaction is not fully completed, especially in two-component systems, the coating will remain incompletely dried, leading to poor coating performance. Furthermore, when using radiation drying, careful control over the adjustments of all components is required (Winkelaar 2009).

When wood is thermally treated at temperatures above 150 °C, it impacts both physical and chemical characteristics. At temperatures exceeding 200 °C, the changes become more pronounced, including reduced shrinkage and swelling, improved decay resistance, a darker color, the loss of extractives, a lower equilibrium moisture content, and enhanced thermal insulation properties (Viitaniemi and Jämsä 1994).

Several studies have investigated various weathering tests applied to varnished materials, both with and without heat treatment (Çakıcıer 2007; Ayata 2014; Kesik and Akyildiz 2015; Moya *et al*. 2017; Yalcin and Ceylan 2017; Yalcin *et al*. 2017; Gündüz 2018; Gürleyen 2018; Ulay 2018, 2023; Herrera *et al*. 2018; Akter *et al*. 2019; Gunduz *et al*. 2019; Karamanoğlu 2020; Orgenc 2020; Can *et al*. 2021; Aytin *et al*. 2021, 2022; Aytin and Çakıcıer 2022).

Among the wide range of surface protection products available for wood, the reason for selecting polyurethane-based varnish is its superior protective properties, especially against outdoor conditions. Polyurethane-based varnishes stand out with their high color stability, resistance to UV radiation, and ability to maintain surface gloss. Additionally, these varnishes increase abrasion resistance and enhance the wood’s water resistance. There are also various published studies related to this topic in which polyurethane-based varnish was applied to different thermally treated wood species (Çakıcıer *et al*. 2011; Saha *et al*. 2013; Pelit 2017; Aytin *et al*. 2022).

Thermally modified wood is increasingly used in outdoor applications due to its enhanced dimensional stability and resistance to biological degradation. However, this treatment may lead to reduced photostability and surface integrity over time, especially under weathering conditions. Polyurethane-based waterborne varnishes are an effective solution to mitigate these issues, offering improved color stability, gloss retention, and reduced surface dulling. These varnishes provide an eco-friendly alternative to other coatings, as they utilize water as a medium, which reduces environmental impact compared to solvent-based varnishes.

The combination of thermal modification and polyurethane-based varnish aims to address the long-term performance of wood exposed to harsh environmental conditions. While heat treatment improves the wood's physical properties, it can alter the chemical composition, leading to color changes and surface degradation. By applying polyurethane-based varnish, it is hypothesized that the wood's aesthetic properties, such as color and gloss, can be better preserved during weathering processes. This study focuses on the interaction between thermal treatment and polyurethane-modified water-based varnish, specifically on ash wood, which is commonly used for outdoor decking and cladding. The research seeks to evaluate how these treatments affect the wood's color stability and glossiness under artificial weathering conditions. By investigating this interaction, the study aims to fill existing gaps in the literature regarding the combined effect of heat treatment and varnish on the weathering behavior of thermally treated wood.

EXPERIMENTAL

Materials

In this study, logs of ash wood (*Fraxinus angustifolia* Vahl.) were collected, measuring 8 to 10 cm in thickness, 20 to 25 cm in width, and 2 to 2.5 m in length. The logs were processed into experimental samples with dimensions of 75 mm × 320 mm × 16 mm.

The selection of the wood was based on a visual inspection to ensure the absence of defects such as knots, cracks, and other imperfections. Only sapwood specimens were used in the study, as identified during the selection process.

Ash wood was chosen for this study due to its high mechanical strength, visual appeal, and widespread use in exterior applications such as decking, cladding, and outdoor furniture. Furthermore, this species is well-suited for thermal modification, and after heat treatment, it exhibits enhanced dimensional stability and improved resistance to biological degradation, making it an ideal candidate for evaluating weathering behavior in coated and uncoated states. The experimental setup consisted of three treatment groups:

Control group: Non-heat-treated ash wood samples coated with polyurethane-modified water-based varnish,

First heat-treated group: Ash wood samples thermally treated at 190 °C for 1.5 h, followed by varnish application,

Second heat-treated group: Ash wood samples thermally treated at 212 °C for 2 h, followed by varnish application.

Each group included 10 replicate specimens, and for each specimen, 10 repeated measurements were taken during the artificial weathering process to ensure statistical validity and data reliability.

The thermal modification of the samples was performed using the ThermoWood process at Nova Forest Products Industry Trade Inc.'s facility in Gerede, Bolu, Turkey.

After thermal treatment, the samples were conditioned for 4 weeks at 20 ± 2 °C and 65 ± 5% relative humidity until their equilibrium moisture content reached between 6% and 8%.

The polyurethane-modified water-based varnish used in this study was supplied by Dual Paint Company. Application amounts were determined based on solid content ratio and manufacturer recommendations (Table 1).

Table 1. Some Key Information Regarding Varnishes and Their Applications

Technical Information of the Varnishes Used					
Varnish Type	pH Level	Solid Matter Ratio (%)	Applied Varnish Amount (g/m^2)	Sample Surface (g/m^2)	Number of Layers
Primer varnish	9.12	22.0	110	2.64	1
Topcoat varnish	9.30	39.0	150	3.60	2

Water-based Single-component Varnish Application			
Varnish properties	Number of Layers	Application Amount (g/m^2)	Amount of Solid Matter (g/m^2)
Primer varnish 10 s immersion method (22%)	1 time application	110	24.2
Polyurethane modified Water-based varnish with spray gun Solid Matter (39%)	first layer application	150	58.5
	second layer application	150	58.5
	Total Solids Content = 141.2 g/m^2		

A 2.0-mm nozzle spray gun with a top-feed system was used, operating 20 to 25 cm away from the sample surface in a cross-pattern (perpendicular then parallel to the wood grain), under 2 bar pressure. After the first coat dried for 3 h at room temperature (20 °C), the surface was lightly sanded first with 400 grit and then with 600 grit sandpaper before applying the second coat. All varnish applications followed the ASTM D3023-98 (2017) standard, and after application, the coated samples were conditioned under controlled conditions (20 ± 2 °C, 65 ± 3% RH) for 4 weeks according to TS 642 ISO 554 (1997).

The amount of varnish applied was calculated based on the solid content specified by the manufacturer, and uniform coating was ensured across all samples using a controlled spray method. The amount of varnish applied was controlled based on the solid content recommended by the manufacturer. All specimens were coated using a spray gun under identical application parameters (nozzle diameter, distance from the surface, and spray pressure) to ensure uniform film thickness across samples. This approach minimized variation in coating thickness and helped maintain consistency in weathering performance.

The fully cured varnish layers were subjected to artificial weathering under modified ISO 11507-A (2007) conditions using a QUV accelerated weathering tester with UV-B 313 EL fluorescent lamps. The cycle consisted of 15 minutes of water spray, followed by 4 h of UV exposure at 0.67 light intensity and a chamber temperature of 50 °C. Samples were exposed to artificial weathering for durations of 0, 168, 336, and 504 h.

The color changes in the samples were assessed using a spectrophotometer cm-2500d (Konica Minolta, Japan), following the CIE 10° standard observer and CIE D65 light source, with an 8/d (8°/diffuse illumination) setup as per ASTM D 2244-3 (2007) standard. The analysis was conducted using the CIELAB color system, and the total color variations were quantified using Eqs. 1 through 8:

$$\Delta a^* = [a^*_{\text{Weathered test sample}}] - [a^*_{\text{Non-weathered test sample}}] \quad (1)$$

$$\Delta L^* = [L^*_{\text{Weathered test sample}}] - [L^*_{\text{Non-weathered test sample}}] \quad (2)$$

$$\Delta b^* = [b^*_{\text{Weathered test sample}}] - [b^*_{\text{Non-weathered test sample}}] \quad (3)$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2]^{1/2} \quad (4)$$

$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \quad (5)$$

$$\Delta C^* = [C^*_{\text{Weathered test sample}}] - [C^*_{\text{Non-weathered test sample}}] \quad (6)$$

$$h^{\circ} = \arctan\,[b^*/a^*] \quad (7)$$

$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2} \quad (8)$$

ΔL^* Positive samples indicate a lighter shade than the reference, while negative samples indicate a darker shade.

ΔH^*: Signifies variations in hue angle or shading.

Δa^*: Positive samples lean towards a more pronounced red tone than the reference, whereas negative samples lean towards a greener hue.

ΔC^*: Represents changes in chroma or saturation. For positive samples, ΔC^* indicates increased vibrancy and luminance compared to the reference, while negative samples display reduced vividness and distinctiveness relative to the reference.

Δb^*: Positive samples shift towards increased yellowness compared to the reference, while negative samples shift towards heightened blueness (Lange 1999).

h° is a hue parameter calculated based on the CIELAB color system. This parameter, used to determine the color tone, is calculated based on the ratio of the a^* and b^* color components. The h° parameter helps to determine the direction and tone of color changes on a surface.

In addition, the color alteration benchmarks outlined in Table 2 by Barański *et al.* (2017) have been compared with the results presented in Table 13.

Table 2. Color Change Criteria by Barański *et al.* (2017)

Color Change Criteria	ΔE^* value
Invisible color change	$\Delta E^* < 0.2$
Slight change of color	$2.0 > \Delta E^* > 0.2$
Color change visible in high filter	$3.0 > \Delta E^* > 2.0$
Color change visible with average quality of filter	$6.0 > \Delta E^* > 3.0$
High color change	$12.0 > \Delta E^* > 6.0$
Different color	$\Delta E^* > 12.0$

Glossiness measurements were carried out at 20°, 60°, and 85° angles to the wood fibers using the ETB-0833 glossmeter device from Vetus Electronic Technology Co., Ltd., China. These measurements followed the guidelines specified in ISO 2813 (1994).

Statistical analysis

In this study, SPSS software was used to calculate various parameters, including the identification of groups with similar characteristics, minimum and maximum values, percentage fluctuations (%), standard deviations, multivariate coefficients of variation, and average results. A significance level of 0.05 was adopted for the statistical analyses.

RESULTS AND DISCUSSION

Table 3 provides the results of the variance analysis for the *L** parameter, indicating that all factors and their interactions had a significant impact on the *L** parameter (Table 3).

Table 3. Analysis of Variance Results for *L** Parameter

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
Heat Treatment (A)	23684.803	2	11842.401	10558.944	0.000*
Weathering Period (B)	234.367	3	78.122	69.656	0.000*
Interaction (AB)	182.930	6	30.488	27.184	0.000*
Error	121.128	108	1.122		
Total	311317.103	120			
Corrected Total	24223.228	119			

Table 4 displays the results for the *L** parameter. In thermally untreated samples, the *L** values exhibited a decrease following the weathering process, with reductions of 9.85% after 168 h, 4.13% after 336 h, and 4.15% after 504 h. Conversely, in materials varnished after being thermally treated at 190 °C for 1.5 h, decreases of 2.89% and 0.31% were observed after 168 and 336 h of weathering, respectively, while an increase of 6.24% was recorded after 504 h. In contrast, for samples thermally treated at 212 °C for 2 h and coated with varnish, increases in *L** values were observed after weathering, with gains of 0.39% after 168 h, 6.81% after 336 h, and 10.75% after 504 h (Table 4).

Table 4. Results for *L** Parameter

Heat Treatment	Weathering Period	Mean	Change (%)	Homogeneity Group	Standard Deviation	Minimum	Maximum	COV
Control (non-heat treatment)	Non-weathered	69.33	-	A*	1.53	67.61	72.31	2.20
	168 h	62.50	↓9.85	C	1.67	60.50	64.84	2.67
	336 h	66.47	↓4.13	B	1.20	64.46	68.65	1.81
	504 h	66.45	↓4.15	B	1.05	65.24	68.47	1.58
190 °C for 1.5 h	Non-weathered	48.41	-	E	1.32	46.26	51.29	2.72
	168 h	47.01	↓2.89	F	0.94	45.13	48.23	2.00
	336 h	48.26	↓0.31	E	1.09	46.58	50.24	2.26
	504 h	51.43	↑6.24	D	0.53	50.73	52.20	1.03
212 °C for 2 h	Non-weathered	30.41	-	I**	0.43	29.67	30.83	1.42
	168 h	30.53	↑0.39	I	0.64	29.40	31.45	2.11
	336 h	32.48	↑6.81	H	0.89	30.96	34.16	2.75
	504 h	33.68	↑10.75	G	0.55	32.63	34.42	1.63
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation								

Aytin and Çakıcıer (2022) found that weathering resulted in a reduction of *L** values in ash, spruce, and poplar wood coated with parquet varnishes without thermal treatment. In contrast, after thermal treatment at 212 °C and 190 °C for 1 h, an increase in *L** values was observed in the parquet varnish-coated samples during weathering. Çakıcıer (2007) stated in their study that xenon weathering resulted in decreases in the *L** parameter for Scots pine and iroko wood samples treated with double-component acrylic-modified and single-component water-based varnishes, while increases were observed in chestnut wood. Söğütlü and Sönmez (2006) explained in their study that reductions in gloss values might reflect a shift toward a darker color tone, whereas increases could signify a transition to a lighter appearance. Real *et al*. (2005) reported in their study that polymeric materials subjected to natural and water-cycle artificial weathering experienced notable color changes, including a decline in gloss and intense yellowing. They further noted the formation of localized white patches on the surface during weathering, with surface glossiness diminishing further as a result of volumetric surface wear.

Table 5 shows the variance analysis results for *a** parameter, revealing that all factors and their interactions had a significant effect on *a** parameter (Table 5).

Table 5. Analysis of Variance Results for *a** Parameter

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
Heat Treatment (A)	286.962	2	143.481	657.487	0.000*
Weathering Period (B)	2.045	3	0.682	3.123	0.029*
Interaction (AB)	39.199	6	6.533	29.937	0.000*
Error	23.568	108	0.218		
Total	13512.146	120			
Corrected Total	351.774	119			

The *a** parameter results are shown in Table 6. In thermally untreated and varnished samples, decreases in *a** values were observed after the weathering process, with reductions of 0.85% at 336 h and 2.82% at 504 h. Samples treated at 190 °C for 1.5 h and coated with varnish showed reductions in *a** values after the weathering process, with decreases of 6.80% at 168 h, 9.30% at 336 h, and 11.19% at 504 h. In samples thermally treated at 212 °C for 2 h and coated with varnish, increases in *a** values were observed following the weathering process, with rises of 0.91% after 168 h, 16.34% after 336 h, and 25.81% after 504 h (Table 6).

Table 6. Results for *a** Parameter

Heat Treatment	Weathering Period	Mean	Change (%)	Homogeneity Group	Standard Deviation	Minimum	Maximum	COV
Control (non-heat treatment)	Non-weathered	10.65	-	D	0.69	9.46	11.49	6.43
	168 h	10.65	0.00	D	0.63	9.54	11.83	5.91
	336 h	10.56	↓0.85	D	0.62	9.41	11.34	5.84
	504 h	10.35	↓2.82	D	0.38	9.62	10.76	3.66
190°C for 1.5 h	Non-weathered	13.23	-	A*	0.20	13.00	13.67	1.54
	168 h	12.33	↓6.80	B	0.22	11.93	12.68	1.79
	336 h	12.00	↓9.30	BC	0.44	11.02	12.78	3.68
	504 h	11.75	↓11.19	C	0.21	11.50	12.07	1.76
212°C for 2 h	Non-weathered	7.71	-	G**	0.34	7.21	8.15	4.36
	168 h	7.78	↑0.91	G	0.55	6.81	8.56	7.05
	336 h	8.97	↑16.34	F	0.64	7.71	9.88	7.12
	504 h	9.70	↑25.81	E	0.29	9.28	10.17	2.94
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation								

Çakıcıer (2007) indicated in their study that xenon weathering (144 and 288 h) resulted in increases in the *a** parameter for chestnut, Scots pine, and iroko wood samples treated with double-component acrylic-modified and single-component water-based varnishes. In the study conducted by Ayata (2014), it was determined that *a** values decreased during weathering in Scots pine and beech wood subjected to thermal treatment at 190 °C for 2 h and coated with single- and double-component water-based varnishes. However, in oak wood treated under the same conditions and varnish applications, an increase in *a** values was reported with weathering. In the research conducted by Aytin and Çakıcıer (2022), it was stated that weathering caused an increase in the *a** values of ash, spruce, and poplar wood that had been coated with parquet varnishes without thermal treatment. Furthermore, after thermal treatment at 190 °C for 1 h, the samples coated with parquet varnish showed a decrease in *a** values during weathering, while samples thermally treated at 212 °C for 1 h and coated with parquet varnish experienced an increase in a value during weathering.

The variance analysis results for the *b** parameter are shown in Table 7, with all factors and interactions found to be significant for the *b** parameter (Table 7).

Table 7. Analysis of Variance Results for *b** Parameter

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
Heat Treatment (A)	11467.850	2	5733.925	7499.921	0.000*
Weathering Period (B)	126.347	3	42.116	55.087	0.000*
Interaction (AB)	113.879	6	18.980	24.826	0.000*
Error	82.569	108	0.765		
Total	71772.241	120			
Corrected Total	11790.646	119			

The *b** parameter results are provided in Table 8. In thermally untreated and varnished samples, the *b** values decreased 10.8% after 168 h, 3.05% after 336 h, and 4.5% after 504 h of weathering. For samples thermally treated at 190 °C for 1.5 h and varnished with a water-based varnish, reductions of 6.9% and 5.1% were observed after 168 and 336 h of weathering, respectively, while an increase of 0.5% was noted after 504 h. In samples treated at 212 °C for 2 h and coated with water-based varnish, the *b** values increased by 37.4% after 336 h and 59.3% after 504 h of weathering (Table 8).

Table 8. Results for *b** Parameter

Heat Treatment	Weathering Period	Mean	Change (%)	Homogeneity Group	Standard Deviation	Mini-mum	Maxi-mum	COV
Control (non-heat treatment)	Non-weathered	34.12	-	A*	0.91	32.96	35.45	2.68
	168 h	30.44	↓10.79	C	1.62	28.49	34.27	5.32
	336 h	33.08	↓3.05	B	1.08	30.57	34.43	3.25
	504 h	32.57	↓4.54	B	0.59	31.65	33.73	1.83
190 °C for 1.5 h	Non-weathered	26.10	-	D	0.78	25.41	28.03	2.97
	168 h	24.29	↓6.93	E	0.67	22.62	25.00	2.77
	336 h	24.78	↓5.06	E	0.50	23.94	25.51	2.02
	504 h	26.22	↑0.46	D	0.44	25.58	26.75	1.69
212 °C for 2 h	Non-weathered	7.39	-	H**	0.52	6.59	8.13	7.05
	168 h	7.39	0.00	H**	0.86	6.07	8.83	11.63
	336 h	10.15	↑37.35	G	1.14	8.08	12.09	11.22
	504 h	11.77	↑59.27	F	0.63	10.54	12.76	5.36
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation								

Aytin and Çakıcıer (2022) reported that weathering resulted in an increase in the *b** values of ash, spruce, and poplar wood coated with parquet varnishes without thermal treatment. Additionally, after thermal treatment at 212 °C and 190 °C for 1 h, the samples coated with parquet varnish showed increases in *b** values during weathering. In the study by Ayata (2014), it was stated that weathering treatments (144, 288, and 432 h) led to a decrease in *b** values in samples thermally treated at 190 °C for 1 h and coated with water-based varnishes. Additionally, for the same wood species, increases in *b** values were observed in samples thermally treated at 212 °C for 2 h and coated with the same varnish, subjected to the same weathering treatment. Çakıcıer (2007) found in their study that after applying xenon weathering, the *b** parameter increased for Scots pine and chestnut wood treated with double-component acrylic-modified and single-component water-based varnishes, while a decrease was observed in iroko wood.

Table 9 displays the variance analysis results for the *C** parameter, with all factors and interactions found to be significant for the *C** parameter (Table 9).

Table 9. Analysis of Variance Results for *C** Parameter

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
Heat Treatment (A)	9992.097	2	4996.048	5558.170	0.000*
Weathering Period (B)	107.865	3	35.955	40.001	0.000*
Interaction (AB)	133.454	6	22.242	24.745	0.000*
Error	97.077	108	0.899		
Total	85141.114	120			
Corrected Total	10330.494	119			

Table 10 provides the results for the *C** parameter. The highest results for the *C** parameter were obtained in the unaged group of thermally untreated samples and those thermally treated at 190 °C for 1.5 h. In contrast, the highest results in the 212 °C for 2 h thermally treated samples were found in the group aged for 504 h. In samples that were thermally untreated and varnished, the *C** values showed decreases of 9.8% at 168 h, 2.8% at 336 h, and 4.4% at 504 h of weathering. In samples thermally treated at 190 °C for 1.5 h and varnished with a water-based finish, the *C** values decreased by 6.9%, 5.9%, and 2.7% after 168, 336, and 504 h of weathering, respectively. For samples thermally treated at 212 °C for 2 h and coated with water-based varnish, the *C** values increased 0.5% at 168 h, 26.9% at 336 h, and 42.9% at 504 h of weathering (Table 10).

Table 10. Results for *C** Parameter

Heat Treatment	Weathering Period	Mean	Change (%)	Homogeneity Group	Standard Deviation	Minimum	Maximum	COV
Control (non-heat treatment)	Non-weathered	35.74	-	A*	1.04	34.29	37.09	2.90
	168 h	32.25	↓9.76	C	1.67	30.04	36.25	5.19
	336 h	34.73	↓2.83	B	1.19	31.99	36.25	3.44
	504 h	34.18	↓4.36	B	0.65	33.15	35.39	1.89
190 °C for 1.5 h	Non-weathered	29.27	-	D	0.66	28.64	30.90	2.25
	168 h	27.24	↓6.94	E	0.65	25.57	27.95	2.40
	336 h	27.54	↓5.91	E	0.57	26.35	28.27	2.09
	504 h	28.47	↓2.73	D	0.73	26.75	29.35	2.55
212 °C for 2 h	Non-weathered	10.68	-	H**	0.59	9.77	11.51	5.56
	168 h	10.73	↑0.47	H	0.98	9.12	12.30	9.14
	336 h	13.55	↑26.87	G	1.27	11.17	15.61	9.36
	504 h	15.26	↑42.88	F	0.65	14.04	16.22	4.27
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation								

According to Ayata (2014), *b** values showed a decrease during weathering in Scots pine and beech wood that underwent thermal treatment at 190 °C for 2 h and were coated with single- and double-component water-based varnishes. Furthermore, it was observed that artificial weathering caused an increase in *b** values for samples that had been thermally treated at 212 °C for 2 h and coated with the same varnishes.

Table 11 outlines the variance analysis results for the h^o parameter, with all factors and interactions found to be significant for the h^o parameter (Table 11).

Table 11. Analysis of Variance Results for h^o Parameter

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
Heat Treatment (A)	13627.363	2	6813.682	8926.462	0.000*
Weathering Period (B)	270.596	3	90.199	118.167	0.000*
Interaction (AB)	169.835	6	28.306	37.083	0.000*
Error	82.438	108	0.763		
Total	458643.677	120			
Corrected Total	14150.232	119			

The h^o parameter results are shown in Table 12. In the samples without thermal treatment and varnished, weathering treatments led to decreases in h^o values (168 h: 2.7%, 336 h: 0.5%, and 504 h: 0.4%). For the varnished samples that underwent thermal treatment at 190 °C for 1.5 h and 212 °C for 2 h, weathering for 168 h resulted in slight reductions in h^o values (0.05% and 0.8%, respectively). In contrast, weathering for 336 and 504 h caused increases in h^o values (ranging from 1.7% to 4.4% and 10.6% to 15.3%, respectively). The highest h^o values were observed in the unweathered varnished samples without thermal treatment, whereas for the thermally treated samples, the highest h^o values were found after 504 h of weathering (Table 12). The h^o parameter is an important indicator for measuring the color tone changes of wood, and in this study, it has been used to evaluate the effect of varnishes applied under different thermal treatment conditions on the weathering process. Artificial weathering tests conducted on non-thermally treated and varnished samples have shown a decrease in h^o values over time. The change in the h^o parameter clearly demonstrates that the combination of thermal treatment and varnish applications helps to maintain the color stability of the wood and increases its resistance to external factors.

Table 12. Results for h^o Parameter

Heat Treatment	Weathering Period	Mean	Change (%)	Homogeneity Group	Standard Deviation	Minimum	Maximum	COV
Control (non-heat treatment)	Non-weathered	72.69	-	A*	0.77	71.91	73.99	1.07
	168 h	70.71	↓2.72	B	0.82	69.62	72.22	1.16
	336 h	72.31	↓0.52	A	0.56	71.49	73.12	0.77
	504 h	72.38	↓0.43	A	0.47	71.93	73.47	0.65
190 °C for 1.5 h	Non-weathered	63.11	-	E	0.89	61.72	65.12	1.40
	168 h	63.08	↓0.05	E	0.57	62.19	64.02	0.91
	336 h	64.17	↑1.68	D	0.71	62.91	65.28	1.10
	504 h	65.87	↑4.37	C	0.36	65.29	66.28	0.55
212 °C for 2 h	Non-weathered	43.76	-	H	0.97	42.15	44.93	2.22
	168 h	43.40	↓0.82	H**	1.50	40.82	45.89	3.46
	336 h	48.42	↑10.65	G	1.28	46.34	50.74	2.65
	504 h	50.46	↑15.31	F	0.88	48.64	51.86	1.74
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation								

The results for total color differences are given in Table 13. According to these results, after weathering, the Δ*b**, Δ*L**, and Δ*C** values in the thermally untreated and 190 °C for 1.5 h thermally treated and varnished samples were found to be negative (*i.e.*, bluer, darker, and more dull/matte compared to the reference, respectively). When examining the Δ*b**, Δ*L**, Δ*a**, and Δ*C** values, it was found that in the samples thermally treated at 212 °C for 2 h and varnished, the parameters after weathering were positive (*i.e.*, more yellow, lighter, more red, clearer, and more glossy compared to the reference, respectively) (Table 13).

Table 13. Results of Total Color Differences

Heat Treatment	Weathering Period	Δ*L**	Δ*a**	Δ*b**	Δ*C**	Δ*H**
Control (non-heat treatment)	168 h	-6.82	0.00	-3.68	-3.50	1.16
	336 h	-2.86	-0.09	-1.04	-1.02	0.22
	504 h	-2.88	-0.30	-1.55	-1.57	0.16
190 °C for 1.5 h	168 h	-1.39	-0.90	-1.81	-2.02	X
	336 h	-0.15	-1.23	-1.32	-1.73	0.51
	504 h	3.03	-1.48	0.12	-0.79	1.26
212 °C for 2 h	168 h	0.12	0.07	0.00	0.05	0.05
	336 h	2.07	1.26	2.76	2.86	0.99
	504 h	3.28	2.00	4.38	4.57	1.49
Heat Treatment	**Weathering Period**	**Δ*E***	Baranski *et al*. (2017) according to color change criteria			
Control (non-heat treatment)	168 h	7.76	High color change (12 > Δ*E** > 6)			
	336 h	3.05	Color change visible with average quality of filter (6 > Δ*E** > 3)			
	504 h	3.29				
190 °C for 1.5 h	168 h	2.45	Color change visible in high filter (3 > Δ*E** > 2)			
	336 h	1.81	Slight change of color (2 > Δ*E** > 0.2)			
	504 h	3.37	Color change visible with average quality of filter (6 > Δ*E** > 3)			
212 °C for 2 h	168 h	0.14	Invisible color change (Δ*E** < 0.2)			
	336 h	3.67	Color change visible with average quality of filter (6 > Δ*E** > 3)			
	504 h	5.82				
X: A negative result cannot be square-rooted mathematically						

The samples that were thermally untreated and varnished with 336 and 504 h of weathering, as well as the samples thermally treated at 190 °C for 1.5 h and varnished with 504 h of weathering, and the samples thermally treated at 200 °C for 2 h and varnished with 336 and 504 h of weathering, all yielded a color change result of "color change visible with average quality of filter (6 > Δ*E** > 3)." The samples that were thermally treated at 200 °C for 2 h and varnished, after undergoing 168 h of weathering, displayed an "invisible color change (Δ*E** < 0.2)" result. For the samples treated at 190 °C for 1.5 h and varnished, a "slight color change (2 > Δ*E** > 0.2)" was observed after 336 h of weathering. The samples treated at 190 °C for 1.5 h and varnished, when aged for 168 h, showed a "visible color change in high filter (3 > Δ*E** > 2)" criterion. Finally, the thermally untreated and varnished samples, after 168 h of weathering, resulted in a "high color change (12 > Δ*E** > 6)" classification (Table 13).

In the study by Aytin and Çakıcıer (2022), after weathering for 720 h, the Δ*E** values were found to be 5.15 for untreated poplar, 10.50 for poplar treated thermally at 190 °C for 1 h, and 11.9 for poplar treated thermally at 212 °C for 1 h. Additionally, for ash, the Δ*E** values were 9.43, 6.82, and 12.00, while for spruce, the Δ*E** values were 17.20, 3.04, and 8.27, corresponding to untreated, 190 °C for 1 h, and 212 °C for 1 h thermal treatments, respectively, with varnish applied (these values include varnished materials).

The graphical representation of the total color difference (Δ*E**) results is presented in Fig. 1.

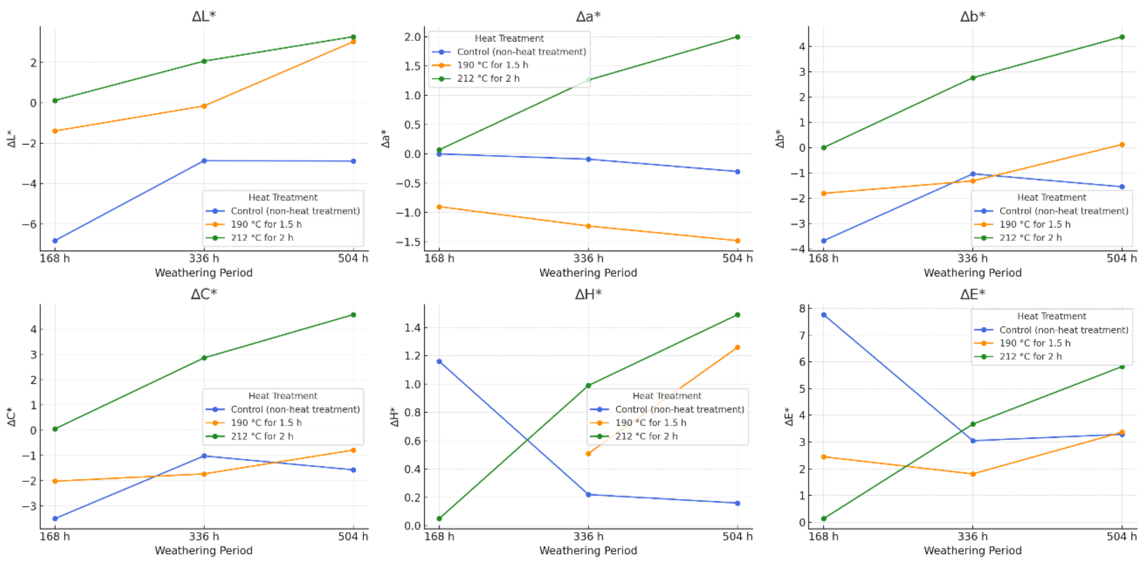

Fig. 1. Graphical representation of the total color difference (Δ*E**) results

The variance analysis results for the glossiness values measured in both directions at 20° are presented in Table 14. All factors and interactions were found to be significant (Table 14).

Table 14. Analysis of Variance Results for 20° Glossiness

Test	Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
⊥	Heat Treatment (A)	5052.465	2	2526.232	1188.153	0.000*
	Weathering Period (B)	374.660	3	124.887	58.737	0.000*
	Interaction (AB)	453.439	6	75.573	35.544	0.000*
	Error	229.628	108	2.126		
	Total	57736.200	120			
	Corrected Total	6110.192	119			
∥	Heat Treatment (A)	717.956	2	358.978	113.089	0.000*
	Weathering Period (B)	713.426	3	237.809	74.917	0.000*
	Interaction (AB)	1444.309	6	240.718	75.833	0.000*
	Error	342.825	108	3.174		
	Total	46793.490	120			
	Corrected Total	3218.516	119			

Table 15 shows the glossiness values measured at 20° for both the perpendicular and parallel directions to the fibers. For varnished materials without thermal treatment, a reduction in the 20° glossiness values was found after 168 h of weathering in both directions, followed by increases after 336 and 504 h. In samples treated thermally at 190 °C for 1.5 h and then varnished, the glossiness values increased in the perpendicular direction to the fibers, while a decrease was observed in the parallel direction, showing an opposite result. In samples treated thermally at 212 °C for 2 h and varnished, decreases in the 20° glossiness values were recorded after weathering in both directions (Table 15).

Table 15. Results for 20° Glossiness

Test	Heat Treatment	Weathering Period	Mean	Change (%)	Homo-geneity Group	Standard Deviation	Mini-mum	Maxi-mum	COV
⊥	Control (non-heat treatment)	Non-weathered	17.62	-	F	2.09	14.60	19.40	11.87
		168 h	16.86	↓4.31	FG	1.16	15.80	18.90	6.88
		336 h	24.48	↑38.93	D	2.07	21.50	25.90	8.44
		504 h	20.98	↑19.07	E	1.89	19.00	23.30	9.01
	190 °C for 1.5 h	Non-weathered	26.00	-	C	1.73	24.10	28.30	6.65
		168 h	27.10	↑4.23	C	1.48	25.80	28.80	5.45
		336 h	30.00	↑15.38	B	2.08	28.00	32.40	6.93
		504 h	33.06	↑27.15	A*	0.39	32.70	33.60	1.19
	212 °C for 2 h	Non-weathered	15.58	-	GH	0.57	15.00	16.20	3.64
		168 h	11.32	↓27.34	I	0.41	10.90	11.90	3.65
		336 h	11.10	↓28.75	I**	0.72	10.30	11.90	6.47
		504 h	14.80	↓5.01	H	1.14	13.70	16.70	7.71
ǁ	Control (non-heat treatment)	Non-weathered	15.47	-	FG	2.31	13.00	18.20	14.90
		168 h	13.91	↓10.08	GH	2.35	12.40	20.30	16.88
		336 h	18.30	↑18.29	E	1.42	15.00	20.70	7.77
		504 h	23.46	↑51.65	C	0.77	22.60	24.80	3.30
	190 °C for 1.5 h	Non-weathered	25.24	-	B	3.56	20.60	29.60	14.11
		168 h	19.57	↓22.46	DE	2.09	17.20	21.70	10.67
		336 h	21.11	↓16.36	D	0.86	20.30	23.10	4.06
		504 h	23.99	↓4.95	BC	1.17	22.30	24.80	4.87
	212 °C for 2 h	Non-weathered	27.00	-	A*	0.43	26.70	27.80	1.60
		168 h	15.66	↓42.00	F	1.16	14.40	17.00	7.40
		336 h	12.30	↓54.44	H**	1.40	10.40	14.10	11.42
		504 h	12.66	↓53.11	H	1.41	11.60	15.30	11.14
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation									

Table 16 presents the variance analysis results for the glossiness values measured in both directions at 60°. It was determined that all factors and interactions were significant (Table 16).

Table 16. Analysis of variance results for 60° glossiness

Test	Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
⊥	Heat Treatment (A)	7115.293	2	3557.647	735.932	0.000*
	Weathering Period (B)	1265.894	3	421.965	87.287	0.000*
	Interaction (AB)	1049.184	6	174.864	36.172	0.000*
	Error	522.094	108	4.834		
	Total	315074.140	120			
	Corrected Total	9952.465	119			
ǁ	Heat Treatment (A)	1442.844	2	721.422	70.819	0.000*
	Weathering Period (B)	812.630	3	270.877	26.591	0.000*
	Interaction (AB)	3000.398	6	500.066	49.089	0.000*
	Error	1100.180	108	10.187		
	Total	438572.080	120			
	Corrected Total	6356.053	119			

The results of the glossiness measurements taken at 60° in the perpendicular and parallel directions to the fibers are presented in Table 17. In glossiness measurements taken at 60° in the perpendicular and parallel directions to the fibers, a regular increase in gloss values was observed in the control group as the weathering period increased. This suggests that as the weathering period was extended, the chemical and physical changes on the varnished surface may have contributed to an increase in surface glossiness. Varnished materials treated at 190 °C for 1.5 h showed a decrease in the 60° glossiness values in both directions after 168 and 336 h of weathering, but an increase was observed after 504 h of weathering. Furthermore, increases in the 60° glossiness values were also found in both directions for varnished materials weathered at 212°C for 2 h (Table 17).

Gunduz *et al*. (2019) found in their study that, for Scots pine wood coated with water-based varnish, the glossiness values at a 60° angle decreased compared to the control after 250 and 500 h of accelerated weathering, but increased after 750 and 1000 h of weathering. Çakıcıer (2007) noted in their study that xenon weathering (144 and 288 h) resulted in a decrease in glossiness values at 60°, both perpendicular and parallel to the fibers, for Scots pine, chestnut, and iroko wood samples treated with double-component acrylic-modified and single-component water-based varnishes.

Table 17. Results for 60° Glossiness

Test	Heat Treatment	Weathering Period	Mean	Change (%)	Homo-geneity Group	Standard Deviation	Mini-mum	Maxi-mum	COV
⊥	Control (non-heat treatment)	Non-weathered	47.87	-	E	1.43	46.20	49.50	2.98
		168 h	48.40	↑1.11	E	2.82	45.30	52.20	5.83
		336 h	55.36	↑15.65	C	4.81	48.80	59.80	8.69
		504 h	56.54	↑18.11	C	1.64	54.20	57.80	2.89
	190 °C for 1.5 h	Non-weathered	59.04	-	B	1.26	56.80	60.40	2.13
		168 h	53.40	↓9.55	D	2.86	50.60	56.60	5.36
		336 h	58.92	↓0.20	B	1.46	57.40	60.60	2.49
		504 h	64.41	↑9.10	A*	0.38	63.90	64.80	0.58
	212 °C for 2 h	Non-weathered	47.76	-	E	2.83	44.70	51.60	5.93
		168 h	34.68	↓27.39	G**	0.59	33.70	35.10	1.70
		336 h	36.20	↓24.20	G	0.51	35.40	36.80	1.41
		504 h	42.52	↓10.97	F	1.23	41.70	44.80	2.89
‖	Control (non-heat treatment)	Non-weathered	50.07	-	E**	1.90	48.70	53.30	3.79
		168 h	51.88	↑3.61	E	3.25	48.30	58.80	6.26
		336 h	61.64	↑23.11	C	4.26	54.80	65.60	6.90
		504 h	66.00	↑31.82	B	2.89	63.00	70.20	4.38
	190 °C for 1.5 h	Non-weathered	65.82	-	B	2.34	62.00	68.80	3.55
		168 h	62.20	↓5.50	C	2.26	59.10	64.50	3.64
		336 h	62.45	↓5.12	C	3.30	59.90	68.50	5.29
		504 h	69.19	↑5.12	A*	5.26	63.60	75.10	7.61
	212 °C for 2 h	Non-weathered	68.36	-	AB	3.54	64.30	72.00	5.17
		168 h	56.75	↓16.98	D	0.84	56.00	57.90	1.47
		336 h	50.44	↓26.21	E	3.10	47.50	55.30	6.14
		504 h	55.38	↓18.99	D	3.11	52.20	60.50	5.61

Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation

The variance analysis results for the glossiness values measured in both directions at 85° are shown in Table 18, where all factors and interactions were found to be significant (Table 20).

Table 18. Analysis of Variance Results for 85° Glossiness

Test	Source	Sum of Squares	Degrees of Freedom	Mean Square	F Values	α ≤ 0.05 (*: Significant)
⊥	Heat Treatment (A)	2370.558	2	1185.279	64.248	0.000*
	Weathering Period (B)	45788.579	3	15262.860	827.317	0.000*
	Interaction (AB)	754.477	6	125.746	6.816	0.000*
	Error	1992.452	108	18.449		
	Total	1434398.580	120			
	Corrected Total	50906.065	119			
‖	Heat Treatment (A)	1477.630	2	738.815	53.420	0.000*
	Weathering Period (B)	55776.808	3	18592.269	1344.314	0.000*
	Interaction (AB)	622.249	6	103.708	7.499	0.000*
	Error	1493.672	108	13.830		
	Total	1774735.938	120			
	Corrected Total	59370.359	119			

Table 19. Results for 85° Glossiness

Test	Heat Treatment	Weathering Period	Mean	Change (%)	Homo-geneity Group	Standard Deviation	Mini-mum	Maxi-mum	COV
⊥	Control (non-heat-treatment)	Non-weathered	119.88	-	C	0.87	119.00	121.30	0.72
		168 h	91.40	↓23.76	F	9.80	80.20	104.80	10.72
		336 h	81.13	↓32.32	H	7.44	70.60	86.90	9.17
		504 h	127.33	↑6.21	B	6.72	117.60	131.51	5.28
	190 °C for 1.5 h	Non-weathered	128.18	-	B	1.54	126.30	129.50	1.20
		168 h	104.60	↓18.40	D	0.46	104.10	105.20	0.44
		336 h	86.56	↓32.47	G	0.27	86.30	87.00	0.31
		504 h	135.10	↑5.40	A*	0.36	134.80	135.60	0.26
	212 °C for 2 h	Non-weathered	123.36	-	C	3.49	119.60	127.00	2.83
		168 h	96.68	↓21.63	E	1.26	94.90	98.00	1.30
		336 h	72.94	↓40.87	H**	2.45	68.30	74.20	3.35
		504 h	121.32	↓1.65	C	1.28	120.10	123.20	1.05
‖	Control (non-heat treatment)	Non-weathered	128.75	-	D	4.10	121.60	133.50	3.19
		168 h	105.89	↓17.76	F	3.71	98.10	110.70	3.51
		336 h	86.38	↓32.91	H	4.49	77.80	93.70	5.20
		504 h	138.80	↑7.81	BC	6.50	130.70	146.10	4.68
	190 °C for 1.5 h	Non-weathered	135.54	-	C	2.30	132.70	138.70	1.69
		168 h	117.76	↓13.12	E	1.23	116.30	119.30	1.04
		336 h	91.22	↓32.70	G	2.79	86.70	94.20	3.06
		504 h	149.34	↑10.18	A*	0.26	149.10	149.70	0.18
	212 °C for 2 h	Non-weathered	139.16	-	B	2.88	135.90	141.90	2.07
		168 h	114.61	↓17.64	E	2.45	111.10	116.50	2.14
		336 h	85.20	↓38.78	H**	5.25	75.30	88.60	6.16
		504 h	142.08	↑2.10	B	4.06	134.60	145.70	2.86
Number of measurements: 10, *: Highest result, **: Lowest result, COV: Coefficient of variation									

The results of glossiness measurements at 85°, conducted in both parallel and perpendicular orientations to the fibers, are provided in Table 19. In varnished materials without thermal treatment and treated at 190 °C for 1.5 h, a decrease in the 85° glossiness values was observed in both directions after 168 and 336 h of weathering, whereas an increase was noted after 504 h of weathering. Moreover, weathering varnished and thermally treated samples at 212 °C for 2 h resulted in a decrease in 85° glossiness values in the perpendicular direction. In the parallel direction, decreases were observed after 168 and 336 h of weathering, with an increase found after 504 h (Table 19).

CONCLUSIONS

1. Based on the weathering results of the control (non-thermally treated) samples, it was observed that as the weathering time increased, there were reductions in color parameters and fluctuations in glossiness values. In the initial stages, color fading and loss of glossiness on the surface were observed, while in the later stages, especially during weathering at 336 and 504 h, increases in some glossiness values were noted.
2. According to the results of the heat treatment and weathering, for the samples heat-treated at 190 °C for 1.5 h, in general, as the weathering period increased, color changes (a^* and C^*) and glossiness loss were observed in the heat-treated samples. However, at certain periods (especially after 504 h of weathering), increases in glossiness values as well as in L^*, b^*, and h^o parameters were observed.
3. Based on the results of the heat treatment and weathering, in the samples treated at 212 °C for 2 h, noticeable increases in h^o, L^*, a^*, b^*, and C^* parameters were observed after 504 h of weathering. While a slight improvement in glossiness values was detected in the 85° parallel measurement, glossiness loss persisted in the perpendicular measurements.
4. This study has introduced a new dimension to the interactions between heat treatment, varnish, weathering, and wood species. Furthermore, it has led to different results and contributed valuable insights to the literature.

Based on the results obtained, it is recommended to increase the number of layers or use more durable coating formulations to provide more effective and long-lasting protection on the surface after heat treatment.

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