Application of Electrostatic Powder Coating on Wood Composite Panels Using a Cooling Method. Part 1: Investigation of Water Intake, Abrasion, Scratch Resistance, and Adhesion Strength

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Powder coating is environmentally friendly and safe in terms of human health and is used especially on home appliances and in the automotive sector. Because of these advantages, recent studies have expanded work on the application of powder coating on non-conductive surfaces. Within the scope of this research, low temperature curing (120 °C to 130 °C) was applied on wood-based composite panels of medium-density fiberboard (MDF), particleboard, and plywood to facilitate conductivity. Epoxy, polyester, and hybrid (epoxy-polyester) types of powder paint and water-based liquid paint (control group) were applied to the surface of materials. Panels coated with the powder coatings were compared to the panels coated with the water-soluble acrylic resin coating. The prepared samples were analyzed for performance properties. The best results for thickness swelling, water absorption, adhesive strength, abrasion, and scratch resistance were found for the plywood coated with water-based liquid paint, MDF coated with polyester-based powder paint, plywood coated with hybrid powder paint, particleboard coated with hybrid powder paint, and plywood coated with epoxy powder paint, respectively.

Keywords: Electrostatic powder coatings; Wood-based panels; Water-based coating

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INTRODUCTION

Great care must be taken with solvent-based paints that are used during the production of furniture. Both the coating operation and the dust that is released during the sanding process are harmful to the health of the workers. Solvent-based coatings cause serious damage to the lungs when inhaled, and these toxic substances can cause asthma, bronchitis, and even lung cancer. Solvents pose a hazard, as they are flammable, volatile, evaporate easily, and are prone to form explosive mixtures. Consequently, solvents can be the cause of fires and explosions in painting plants. During their application, 30% to 50% of solvent-based paints go to waste, and these are classified as hazardous wastes having toxic effects that substantially threaten human health and the environment (Akkuş 2018).

Due to solvent emission rules and increased ecological awareness of consumers and producers, the use of economic and ecologically sound coatings is becoming increasingly popular (Prieto and Kiene 2007). Coatings that do not harm the environment or human health have started to replace acid-based or double-component polyurethane-based paints containing high amounts of solvent-based nitrocellulose. Recently, powder paints, water-based paint systems, and UV-based paints have become the preferred coatings for medium-density fiberboard (MDF) surfaces. In terms of the furniture industry, powder coating technology presents great potential. Research and development studies in this field have been conducted for the last 10 years (Lin 2008). For example, new powder coating formulations suitable for temperature-sensitive materials and low-temperature curing have been developed, and special surface treatments to increase electrical conductivity have been performed (Jocham *et al*. 2011).

Resins, curing agents, fillers, and additives used in powder paints determine the film properties of the paint. The properties are particularly affected by the surface smoothness performance of the paint (leveling) and the viscosity and curing reactivity of the resin. The film formation behavior of powder paint was examined in three stages during curing (Han and Wu 2003). In the first stage, when the powders begin to melt, the viscosity of the coating is increased. In the second stage, the powder coating begins to flow, and the viscosity decreases. In the third stage, the viscosity increases rapidly when the powder coating undergoes cross-linking. According to the curing mechanism of the powder coating, the leveling performance of the film depended on the rheological behavior in the second and third stages (Li *et al.* 2016).

In recent years, the international powder coating/paint sector has accelerated research for development of powder coating applications on surfaces of non-metal, plastic, and wood materials. However, there are some difficulties in applying powder coating to plastic and wood material surfaces. One of these is the low conductivity of these products and thus, it is difficult to apply electrostatic coatings on these products using the traditional powder coating application techniques. However, with recent changes in powder coating formulations and some modifications to the materials, attempts have been made to overcome these difficulties. Generally, the home appliance, automobile, and metal industries are currently continuing their intense research and development activities on the application of electrostatic powder coatings/paints on wood-based panels.

Studies in the literature (Jocham *et al.* 2011; Schmidt and Jocham 2009; Jocham 2009) have stated that the moisture content of MDF has a significant effect on the powder coating of MDF panel surfaces. However, the conductivity values need not be as high as with metal materials, and in light of new developments on this subject, wood-based panel surfaces can be made suitable for powder coating applications either by using electrical conductivity-increasing additives in the MDF or by modifying processes in the powder-coating formulations. In general, in order to apply an electrostatic powder coating, the electrical resistance of MDF surfaces should be less than 10^{11} ohms (Schmidt *et al*. 2013).

Badila *et al.* (2014) conducted their study on particleboard covered with wood veneers of Norway maple (*Acer platanoides*), bamboo (*Phyllostachys pubescens*), beech (*Fagus sylvatica*), walnut (*Juglans regia*), oak (*Quercus robur*), and wenge (*Millettia laurentii*). Afterwards, transparent, highly reactive epoxy/polyester-based powder coating (Drylac series 530) was pressed on the surfaces for 8 min at pressures of 64 N / cm^2 and cured at 130 °C. The adhesion strength of the transparent electrostatic powder-coating varnish on the wood-veneered particleboard was determined using the cross-cut method and rated “very good” for all types of wood veneers, with the paint film thickness ranging from 37 to 286 μm.

Mazumder *et al*. (1997) determined the properties of powder paint including particle size, chemical structure, tribo and corona application structure, electrical resistivity, hygroscopicity (moisture uptake), fluidity and particle form, and the effects of the paint on application efficiency, film thickness, adhesion strength, and appearance properties.

Gheno *et al*. (2016) reported that resin selection had a significant effect in determining paint film properties. Polyester-based powder coatings are mostly used in Europe, where they are produced as standard- and super-durable coatings. In standard-durable polyester coatings, terephtalic diacid (TPA) is used, whereas isophtalic acid (IPA) is used in super-durable polyester-based powder coatings. It has been stated that the use of IPA instead of TPA allows the coating film to have a lower elasticity, and that powder coating formulations using TPA have better mechanical characteristics due to their effect on properties such as the crosslinking density, thermal expansion coefficient, and glass transition temperatures.

The film-forming mechanisms of powder paints are different from those of liquid paints. The basic stages of powder paint film formation during curing are defined as the processes of melting, fluidization, gelation point, and curing. These phases that occur during film formation affect both the aesthetics and protection properties of the paints. The structure of the paint affects the duration of the film formation phases. The film formation stages are affected by the type of binder and crosslinker, pigmentation (natural particle size, coverage, and distribution of the paint), catalyst, additives, curing, and application conditions. Therefore, these factors are the main parameters that determine important properties of the paint such as the surface smoothness, adhesion strength, gloss, and resistance to chemicals and outdoor conditions (Belder *et al.* 2001).

Okadaa *et al.* (1998) classified conventional thermoset-based powder coatings according to five major curing systems: epoxy, polyester/epoxy, polyester/triglycidyl isocyanurate (TGIC), polyester/blocked polyisocyanate, and glycidyl functional acrylic resin (GMA-acrylic resin)/dibacic acid. Among these systems, the polyester systems are in high demand in the world powder-paint market because of their advantages and low cost. Both COOH and OH functional polyester powder coatings have good mechanical and appearance properties such as flexibility and durability. Conventional polyester systems are considered to be more resistant to external weather conditions than other systems.

Barletta *et al.* (2007) noted that the appearance properties of powder coatings were dependent on mechanical properties and stated that abrasion resistance depended especially on curing time and temperature together with the formulation of the material. Many powder-coating application costs are related to the curing procedure and thus, many scientists are examining film properties accordingly. Epoxy-based powder coating has been reported to give a good film appearance in the first stage of the curing process, although its adhesion strength and scratch and abrasion resistance are very weak. The maximum potential in terms of scratch and abrasion resistance was achieved in the fully cured film. In general, it was reported that the scratch resistance of the polymeric films was related to their adhesion strength.

In their study, Jocham *et al.* (2011) applied preheating to improve layer formation during the powder coating of MDF. They reported that the applied electrical resistance, temperature, and humidity were of great importance for the development of the powder coatings. To this end, they developed a new and versatile method of measuring electrical resistance (surface and middle-layer resistances) during preheating. They indicated that there was a sudden drop in electrical resistance as the board surface temperature increased and that it reached a minimum level for a short time before leaving the infrared furnace. Surface resistance decreased from 3×10^{10} to 8×10^{8}, while a slight increase in resistance was reported as the surface temperature decreased.

Barletta (2006) noted that in today's technology, metal sheets are electrostatically coated with thermoset powder paint and cured in conventional ovens at temperatures of

200 °C and above for 8 to 15 min. However, it was stated that if fiberboard was subjected to a similar heat treatment, deformations and even partial burning would be seen on the surface, and therefore, low-temperature-curing powder paints should be used in the coating. Moreover, for heat-sensitive surfaces, powder coating should be applied at temperatures below 150 ° C.

To apply electrostatic powder coating to the surfaces of wood-based panels, the desired value of electrical conductivity should be obtained on the panels' surfaces. Therefore, various research and development studies have been conducted, and a novel formulation has been devised to increase the conductivity of wood-based panels. The formulation involves a "primer coating mixture" that enables the electrostatic powder coating of insulating products. The primer coating mixture is comprised of a conductive metal powder, primer paint, epoxy resin, and an accelerator. The electrically conductive structure of the primer coating is derived from the conductive metal powder contained in the mixture. The primer coating mixture is in liquid form and is applied to the product using a spray gun or brush. The product, which provides electrical conductivity, has static grounding and thus, the powder that is applied on the product can be adhered *via* static electricity (Altıntaş 2012). In other research, a plasma modification was applied to beech, fir, and MDF materials at atmospheric pressure to increase the surface energy and conductivity value of the materials for the application of electrostatic polyester-based powder coating (Köhler *et al.* 2017). Moreover, the preheating process is the most frequently used method for applying powder coatings to MDF surfaces. The purpose of the preheating process is to allow the moisture in the MDF panel to condense onto its surfaces (Jocham *et al.* 2011). In this way, the condensing water molecules on the panel surfaces provide increased conductivity and therefore facilitate the application of the electrostatic powder coating to the surfaces. However, as a result of this method, it is thought that the thermoset-based urea, phenol, and melamine formaldehyde adhesives used in the production of wood-based panels can lead to deformations in the matrix during curing along with the acceleration of formaldehyde emissions. The degradation of the thermoset adhesive matrix, which provides internal adhesion of the panels, negatively affects the mechanical and physical properties.

Considering this knowledge, the current study attempted to minimize the negative properties of preheating by using a cooling method instead for the application of electrostatic powder coatings on surfaces of wood-based composite panels. Consequently, the non-conductive surfaces of MDF, particleboard, and plywood were rendered partially conductive by the cooling method of curing at moderately low temperatures (120 °C to 130 °C) to facilitate adhesion on the wood and wood-based composite panels. Static powder coating paints, including epoxy, polyester, and epoxy-polyester (hybrid) paints, were then applied to the panel surfaces. The prepared samples were analyzed for the performance characteristics of dry film thickness, thickness swelling, water absorption, adhesive strength and abrasion, and scratch resistance.

EXPERIMENTAL

Materials

Powder paint coatings

The powder paints were obtained from the Pulver Chemical Supply Company in Kocaeli, Turkey. Table 1 gives the technical characteristics of the epoxy, polyester, and hybrid (50% polyester + 50% epoxy)-based powder paints formulated for use on substrates sensitive to temperature and with very low conductivity values.

Wood Based Panels

According to TS EN 622-5 (2008) standard, medium density fiberboards (MDF), with a density of 729 kg/m^3, made of pine, beech, and oak trees were obtained from Kastamonu Integrated Wood Industry Factory, Gebze, Turkey. According to TS EN 312 (2005) standard, particleboards, with a density of 620 kg/m^3, made of pine, poplar, and oak trees were obtained from Kastamonu Integrated wood Industry Factory, Gebze, Turkey. Plywood, with a density of 730 kg/m^3, made of beech veneers were obtained from Pelit Arslan Plywood Factory, Istanbul, Turkey.

Table 1. Technical Characteristics of Epoxy, Polyester, and Hybrid-based Powder Paints

	Epoxy	Polyester	Hybrid
Moisture Content	0.27%	0.28%	0.33%
Glass Transition Temperature	47 °C	48 °C	48 °C
Cure Time (At 120 °C)	10 min	10 min	10 min
Gel Time	At 180 °C 35 s, at 140 °C 130 s	At 180 °C 39 s, at 140 °C 142 s	At 180 °C 37 s, at 140 °C 133 s
Flow (At 140 °C)	15 mm	17 mm	14 mm
Density	1.46 g/cm^3	1.49 g/cm^3	1.50 g/cm^3
Average Particle Size	41 micron	44 micron	42 micron

Application of electrostatic powder paint coatings

The wood-based panels were cooled to achieve an equal amount of water mass on each surface, before being coated with electrostatic powder paint. The cooling process (Fig. 1) applied to the panels was varied depending on the type of panel. The forced cooling method was applied to the materials that were to be painted in a climate-controlled chamber. With the temperature lowered under atmospheric conditions, the panels were cooled and then held in a saturated humidity environment. The panels, with a temperature lower than the ambient temperature, absorbed heat from the air. Because the air could no longer carry more water vapor due to the heat loss, water vapor condensed on the panels to form a dew layer, which provided an electrical field (Fig. 1).

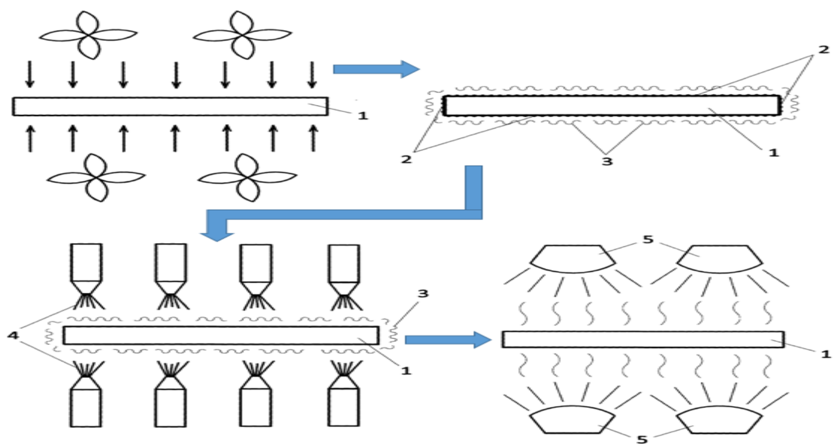

Fig. 1. Application of electrostatic powder paint to a material surface using a pre-cooling process: (1) material, (2) dew layer, (3) water vapor, (4) electrostatic powder paint, and (5) heater (Akkuş 2018)

The electrostatic powder paint was applied on the surfaces by utilizing this electrical field (Okutan and Ozcan 2014). After the panels were cured at low temperatures inside the chamber, the epoxy, polyester, and epoxy-polyester (hybrid)-based powder paints were applied at 120 g/m^2 to the MDF and at 150 g/m^2 to the particleboard and plywood surfaces using a corona electrostatic spray gun (Elektron Powder Coating Equipment , Istanbul, Turkey) (Fig. 2).

Fig. 2. a) The application of powder coating on particleboard by using electrostatic manual spray gun. **b)** The curing system with infrared lambs applied to powder coating on particleboard

After the powder coatings were sprayed into the surface of the panels, they were cured in an infrared (IR) lamp oven (Sarmico, Istanbul, Turkey) at a temperature of 120 °C for 10 min. To obtain smoother surfaces, the panels were sanded with 220-grit sandpaper and the powder paints were reapplied as a second layer.

Application of Water-based Paint Coatings

The MDF, particleboard, and plywood were applied with water-based and UV-based coatings by using a roller coater line, as shown in Fig. 3. It was used to apply acrylic-based water-based white coats in the process shown in Fig. 4. Technical specifications of these coats are given in Table 2. The experimental design of the study is shown in Table 3.

Fig. 3. Roller coater system used to coat panels

Table 2. Technical Specifications of the Applied Coats

Type of Coat	Density (g/mL)	Flame Point (°C)	pH Degree	Solid Content (%)	Viscosity	Amount of Paint (g/m^2)
Primer Coat	1.5 to 1.65	› 75	8.42	63	60*	105
Top Coat	1.5 to 1.6	› 75	8.30	63	55*	60
UV Acrylic	1.2 to 1.35	› 65	8.71	95	40**	10

*DIN (German Institute for standardization) cup / 6 mm, 20 °C ** DIN cup / 4 mm, 20 °C

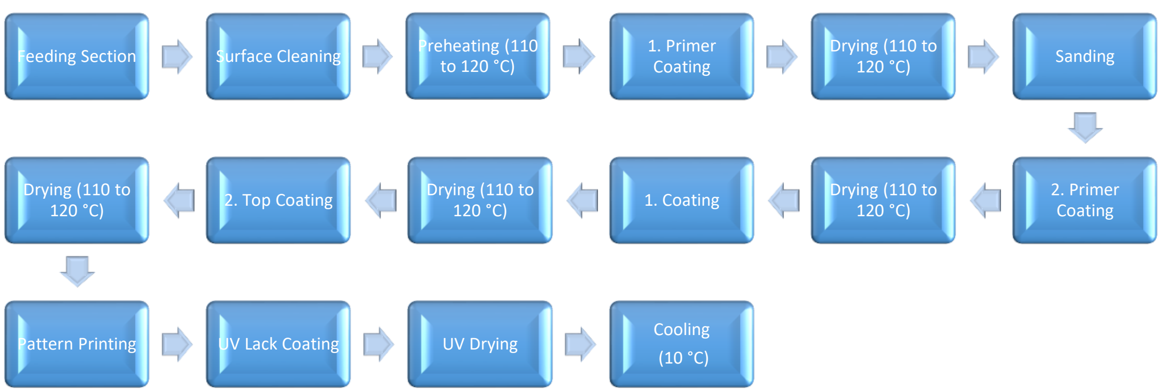

Fig. 4. Steps for water-based paint application on panel surfaces

Table 3. Experimental Design of the Study

<table>
<tr><th>Code</th><th>Board Type</th><th>Used Coating Type</th><th>Tests</th></tr>
<tr><td>ML</td><td>MDF</td><td>Water-based liquid coating</td><td rowspan="12">Dry film thickness
Adhesion strength
Thickness swelling
Water absorption
Scratch strength
Abrasion strength</td></tr>
<tr><td>MP</td><td>MDF</td><td>Polyester powder coating</td></tr>
<tr><td>ME</td><td>MDF</td><td>Epoxy powder coating</td></tr>
<tr><td>MH</td><td>MDF</td><td>Hybrid (polyester-epoxy) powder coating</td></tr>
<tr><td>PL</td><td>Particleboard</td><td>Water-based liquid coating</td></tr>
<tr><td>YP</td><td>Particleboard</td><td>Polyester powder coating</td></tr>
<tr><td>YE</td><td>Particleboard</td><td>Epoxy powder coating</td></tr>
<tr><td>YH</td><td>Particleboard</td><td>Hybrid (polyester-epoxy) powder coating</td></tr>
<tr><td>WL</td><td>Plywood</td><td>Water-based liquid coating</td></tr>
<tr><td>WP</td><td>Plywood</td><td>Polyester powder coating</td></tr>
<tr><td>WE</td><td>Plywood</td><td>Epoxy powder coating</td></tr>
<tr><td>WH</td><td>Plywood</td><td>Hybrid (polyester-epoxy) powder coating</td></tr>
</table>

Methods

The thickness swelling and water absorption tests were conducted according to TS EN 317 (2005) and ASTM D1037 (2012), respectively. The dimensions of the test specimens were 50 mm × 50 mm × board thickness. For the swelling and water absorption tests, 20 samples were prepared for each group. The samples were conditioned in a climate-controlled chamber at a temperature of 20 °C and a relative humidity of 65% prior to water immersion. The samples were then soaked for 24 h in water. The scratch and abrasive resistance of the samples was determined according to method B of the TS EN 15186 (2012) (Circular method) and TS EN 15185 (2013) standards using the TABER abrasion and scratch tester (Taber Industries, Tonawanda, NY, USA). The 18-mm-thick painted panels were cut into sections measuring 100 × 100 mm ± 5 mm. The samples were conditioned for one week at a temperature of 23 ± 2 °C and 50 ± 5% relative humidity. Abrasion and scratch testing were performed on 10 samples from each group. The adhesion strength of the coated panels was determined using the PosiTest AT adhesion tester (DeFelsko Inspection Instruments, Wilmington, NC, USA) according to the ASTM D4541 (2017) standard. The samples for the adhesion strength tests were cut into 150 × 150 mm sections. Adhesion strength testing was performed on 20 samples for each group. The samples were kept in a condition-controlled chamber with a relative humidity of 50 ± 5% and a temperature of 23 ± 2 °C for 24 h prior to the adhesion test. The dry film thicknesses of the painted samples were measured *via* a non-destructive method using the PosiTector coating thickness gauge (DeFelsko Inspection Instruments, Wilmington, NC, USA) according to ASTM D6132 (2017). A total of 20 thickness swelling samples were prepared from each sample group. The obtained data were statistically analyzed using the SPSS statistical software (Version 21.0, SPSS Inc., Chicago, IL, USA) using an analysis of variance (ANOVA) and Duncan's mean separation test ($P < 0.05$).

RESULTS AND DISCUSSION

Dry Film Thickness and Adhesion Strength

Descriptive statistical values of the dry film thickness and adhesion strength of the coatings applied to surfaces of MDF, particleboard, and plywood coated with epoxy, polyester, and hybrid powder paints, and water-based liquid paint are shown Table 4.

Table 4. Descriptive Statistical Values of the Dry Film Thickness and the Adhesion Strength of Coatings Applied to Surfaces of MDF, Particleboard, and Plywood

Material Type	Dry Film Thickness (μm)	Adhesion Strength (N)	n
ML (MDF Liquid)	75.2 (6.26)*	1.23 (0.230) g	20
MH (MDF Hybrid)	112.6 (9.95)	2.09 (0.261) cd	20
ME (MDF Epoxy)	103.4 (2.63)	2.33 (0.148) b	20
MP (MDF Polyester)	97.8 (4.39)	2.21 (0.101) bc	20
PL (Particleboard Liquid)	70.6 (2.59)	1.45 (0.190) f	20
PH (Particleboard Hybrid)	148.6 (15.98)	1.72 (0.128) e	20
PE (Particleboard Epoxy)	149.6 (10.16)	1.60 (0.171) ef	20
PP (Particleboard Polyester)	109.4 (9.65)	1.51 (0.210) f	20
WL (Plywood Liquid)	146.6 (6.20)	1.50 (0.219) f	20
WH (Plywood Hybrid)	171.4 (15.25)	2.93 (0.459) a	20
WE (Plywood Epoxy)	157.8 (7.37)	1.98 (0.678) d	20
WP (Plywood Polyester)	151.8 (8.36)	2.27 (0.295) bc	20

The values in parentheses are the standard deviations; different letters in the adhesion strength column indicate statistical differences at the 95% confidence level.

The dry film thickness of the coated MDF, particleboard, and plywood surfaces were determined as 75.2 µm to 112.6 µm, 70.6 µm to 149.6 µm, and 146.6 µm to 171.4 µm, respectively (Table 4). This variation in the dry film thicknesses of the powder paints used in the same group could have been caused by the use of a laboratory-scale manual powder-coating process. The difference between dry film thicknesses that are obtained in the automatic mass production of powder coating systems is minimal. The liquid water-based paint was applied to the plywood samples in two layers. Therefore, the plywood coated with liquid water-based paint had a higher dry film thickness compared to those of the other panels. The other panels coated with liquid water-based paint were thought to have a lower dry film thickness because of the solvent evaporation that occurred during drying. There was no solvent evaporation on the panels coated with powder paints, and as a result, film formation occurred in almost all of the powder coatings used, and the dry film thicknesses were considered to be higher in the panel groups with powder paint applications. To obtain smoother painted surfaces in the particleboard and plywood groups, the powder paint was applied at 150 g/m^2, while for the MDF groups it was applied at 120 g/ m^2. The dry film thickness value increased along with the increase in the amount of applied powder paint. For this reason, the dry film thickness formed by the higher amount of powder paint used on the surfaces of the particleboard and plywood was effective. Previous studies have stated that dry film thicknesses are higher in liquid-based varnishes because of the higher content of solids and the high amounts applied to the surfaces (Sönmez *et al.* 2002). The thickness of the film in powder coatings varies according to the particle size of powder coating as well as the carrier air pressure and dosing adjustment pressure of the powder-coating device. Corrective adjustments of the powder-coating spray gun and the nozzle type are also effective (Boymak Report 2017).

As a result of the interaction between panel type and coating type, the highest adhesion strength was found for the plywood coated with hybrid-based powder paint, whereas the lowest values were found for the MDF panels coated with water-based liquid paint. Generally, the low adhesion strength of the water-based paint groups could have been caused by dry film thickness and the use of water as the resin solvent.

It has been reported that the adhesion strength values of water-soluble varnishes prepared for furniture surfaces is lower than the values for solvent-soluble polyurethane and acrylic varnishes (Sönmez *et al.* 2004; Demirci *et al.* 2013). The coating type to be used in preparing the protective layer should exhibit great bonding, both with the material surface and among its molecules. This is important in terms of maintaining layer strength (Sönmez 2000). Adhesion fractures in the coatings applied to the MDF and particleboard surfaces developed from within the panels. This was explained by the fact that the adhesion force between the coating and substrate was higher than the cohesion force of the substrate (Müller and Poth 2011). The coating applied to plywood surfaces generally was fractured at the bonding line between the coating and the substrate. In this case, when coating residues are in the fracture area, adhesion and cohesion forces are nearly equal. Because the adhesion test found no coating in the fracture area, the fracture could have occurred because the cohesion force of the paint was greater than the adhesion force (Müller and Poth 2011). In general, the most successful carrier surfaces were obtained with MDF and plywood panels in terms of adhesion strength of the paints. Factors such as their surface density, the wood types used in board production, glue type, press temperature, and pressure were considered to be effective on the different adhesion strength value outcomes of the paints. Budakçı and Pelit (2015) applied a colorless, oil-based wood preservative polyester varnish on 18-mm particleboard surfaces covered with Scots pine, Eastern beech, and sessile oak veneer. As a result, the tree species with the highest level of adhesion strength was the Eastern beech, while the lowest was detected with the Scots pine. In their study, Budakci and Sonmez (2010) applied cellulosic, polyurethane, acrylic, and water-based varnish to Scots pine, fir, Eastern beech, and oak surfaces. They found higher adhesion strength values in the deciduous wood and lower adhesion strength in the coniferous wood. The highest adhesion strength levels of the varnish varieties were detected for the polyurethane and acrylic varnishes. In addition, the varying moisture content of the MDF, particleboard, and plywood panels resulting from the acclimatization may have affected the different adhesion strengths of the paints.

The powder paints applied to the panel surfaces exhibited a cross-linking reaction during curing in the infrared oven, and it was thought that the matrix of the coating had been negatively affected by the gases (*e.g.*, formaldehyde) released from the board from the effect of the heat during the reaction. As a result, depending on the board type, the released gases may have adversely affected the adhesion of the paint to the panels. Moreover, the differences among the adhesion strength values of the coatings applied to panels surfaces could have been related to the dry film thickness. It was reported that when the dry film thickness increased in polymeric-structured varnishes, the coating adhesion strength also increased (Sönmez *et al.* 2004). In this study, the differences in coating adhesion strength resulted from the adhesion and cohesion forces, depending on the coating formulations, and from the gases released from the board because of heat.

Thickness Swelling and Water Absorption

The descriptive statistical values of the thickness swelling and water absorption of the MDF, particleboard, and plywood samples coated with epoxy, polyester, and hybrid powder paints and water-based liquid paint are shown in Table 5.

Table 5. Descriptive Statistical Values of the Thickness Swelling and Water Absorption of the Coated MDF, Particleboard, and Plywood

Material Type	Thickness Swelling (%)	Water Absorption (%)	n
ML (MDF Liquid)	6.67 (1.232) d	31.64 (1.328) e	20
MH (MDF Hybrid)	2.41 (0.326) e	15.36 (1.333) j	20
ME (MDF Epoxy)	2.57 (0.391) e	16.20 (0.881) j	20
MP (MDF Polyester)	1.93 (0.331) e	12.35 (2.370) l	20
PL (Particleboard Liquid)	21.64 (1.352) a	147.51 (3.126) a	20
PH (Particleboard Hybrid)	19.17 (2.408) b	86.04 (1.910) c	20
PE (Particleboard Epoxy)	19.68 (0.770) b	87.89 (2.821) b	20
PP (Particleboard Polyester)	18.54 (0.884) c	54.71 (1.070) d	20
WL (Plywood Liquid)	1.88 (0.467) e	23.03 (1.643) i	20
WH (Plywood Hybrid)	2.32 (0.353) e	26.54 (1.617) g	20
WE (Plywood Epoxy)	2.41 (0.252) e	27.77 (1.169) f	20
WP (Plywood Polyester)	2.28 (0.451) e	24.88 (1.047) h	20

The values in parentheses are the standard deviations; different letters in the same column indicate statistical differences at the 95% confidence level.

After soaking in water for 24 h, the thickness swelling values of MDF, particleboard, and plywood treated with epoxy, polyester, hybrid electrostatic powder paints, and acrylic water-based liquid paint were between 1.88% and 21.64%. As a result of the interaction between the board type and coating type, the highest thickness swelling value was obtained by the particleboard group coated with water-based paint, while the lowest was determined for the plywood group coated with water-based liquid paint. The lowest values of thickness swelling for the MDF and particleboard groups were found in the groups that were coated with polyester powder paint. Because one layer was insufficient, the water-based paint was applied in two layers to the plywood panels, in contrast to the MDF and particleboard groups that only had one layer. Therefore, the high dry film thickness in the plywood group coated with water-based paint was responsible for the decreased amount of thickness swelling. All panel groups that were coated with polyester-based powder paint achieved lower levels of thickness swelling. It has been reported that polyester-based powder paints are more resistant to outdoor conditions (Okadaa *et al.* 1998; Jochen 2008). The dry film thickness formed by the paint and the cross-linking (hardening) reaction between the paint and substrate were thought to be effective on the increased thickness swelling of the painted boards after the boards were soaked in water. Many properties of thermoset-based polymers have been reported to result from a high crosslinking structure (Levita *et al*. 1991). It was pointed out that during the oven-curing process, the film-forming mechanisms (melting, fluidizing, gelation point, and curing process properties) of powder paints differed from those of liquid paints. The curing process has been reported to affect both the aesthetic and protective properties of powder paints (Li *et al.* 2016). The reason for the high rates of thickness swelling for the water-based paint applied to the surfaces of the panels arose from its low film thickness. Furthermore, the water-soluble resin interacted with the water during the long submersion, causing the dry film layer of the water-based liquid paint to become detached. As a result of the coating of wood and wood-based boards with various coatings, thickness swelling was reported to decrease, but with longer holding time in the water, the effect of the thickness swelling improvement was reduced (Nemli and Çolakoğlu 2004). In general, the most favorable results in thickness swelling were obtained with plywood panels. It is thought that thickness swelling affected the plywood panels the least because the phenol formaldehyde glue used during production is resistant to outdoor conditions and because plywood is a coating-based composite material. After 24 h the swelling rate of the uncoated MDF used in this study was average 6.63%. When we consider this value, the water-based paint was found to have had no effect on thickness swelling, while the thickness swelling was significantly reduced on the powder-coated MDF panels.

In the MDF groups, the highest rate of water absorption was found for the water-based liquid paint (31.6%), and the lowest rate was found for the polyester-based powder paint (12.4%). The water absorption values of the MDF groups coated with hybrid and epoxy-based powder paints were similar to each other. In the particleboard groups, the highest rate of water intake was found for the water-based liquid paint (147.5%) and the lowest rate was found for the polyester-based powder paint applied to the samples (54.7%). The values for the hybrid and epoxy powder paints were similar in the particleboard groups. In the plywood groups, the highest water uptake rate was found for the water-based liquid paint (23.0%), and the lowest rate was found for the epoxy-based powder paint (27.8%). For the water intake rate, the powder paints yielded more effective results than the water-based liquid paint. There was a significantly ($p<0.05$) positive difference in the water intake rates of the MDF and the particleboard coated with polyester-based powder paint. This difference was because the polyester-based powder paint was more resistant to external conditions than the other powder paints. In addition, the dry film thickness and the cohesion and adhesion forces of the paints could have been effective on the water intake rate. Nemli (2000) reported the results of various coating processes on particleboard surfaces and the effect of surface coating material types on the amount of water uptake and thickness increase of samples kept in water for 2 and 24 h. Water intake amount and thickness increases on chipboard were ranked, from the highest to the lowest, as: lacquer paint-coated, melamine impregnated paper-coated, wood veneer-coated panels, and roll laminate-coated chipboard. In addition, it was explained that the types of surface coating materials exhibited different resistance properties to water. It was also stated that the properties of the resins, varnishes, and dyes contained in surface coating materials may cause changes in the amount of water uptake and increases in thickness. The water absorption rates of wood-based boards have been reported to be associated with the wood type used during board production, chip size, board density, glue type and ratio, amount of paraffin, suitability of the chip-glue mixing process, and pressing conditions (press temperature, duration and pressure) (Nemli 2000). In the literature, it is stated that as a result of examining the thickness swelling values and the rate of water intake, particleboard produced using large-size chips and phenol formaldehyde glue showed lower water absorption and thickness swelling values than that produced using urea formaldehyde and phenol formaldehyde glues and different chip sizes (Viswanathan *et al*. 2000). Büyüksarı *et al.* (2012) reported that, for MDF panels coated with wood veneers at different pressures and temperatures and soaked in water for 2 and 24 h, the water intake rate decreased with increased pressure and temperature on the board. This situation was attributed to the decrease in the porous structures of the coatings as a result of the densification process. In light of information obtained from the literature, it is thought that the high water absorption rate of the particleboard was due to its structure being more porous than that of the other boards. In the case of MDF, its low water intake may have been caused by the less porous structure and density of the board.

Abrasion and Scratch Strength

The descriptive statistical values of the abrasion and scratch resistance of MDF, particleboard, and plywood samples coated with epoxy, polyester, and hybrid powder paints and water-based liquid paint are shown in Table 6.

Table 6. Descriptive Statistical Abrasion and Scratch Resistance Values of Paints Applied to Surfaces of MDF, Particleboard, and Plywood

Material Type	Abrasion Strength (Cycle)	Scratch Strength (Cycle)	n
ML (MDF Liquid)	35 (2.45) h	2.35 (0.241) c	10
MH (MDF Hybrid)	451 (28.20) c	2.50 (0.333) bc	10
ME (MDF Epoxy)	238 (54.58) f	2.55 (0.158) bc	10
MP (MDF Polyester)	345 (46.46) e	2.65 (0.241) ab	10
PL (Particleboard Liquid)	35 (8.11) h	2.45 (0.158) bc	10
PH (Particleboard Hybrid))	514 (52.78) a	2.80 (0.258) a	10
PE (Particleboard Epoxy)	401 (40.57) d	2.55 (0.158) bc	10
PP (Particleboard Polyester)	468 (35.45) bc	2.65 (0.241) ab	10
WL (Plywood Liquid)	77 (5.49) g	2.40 (0.210) c	10
WH (Plywood Hybrid)	486 (31.94) ab	2.65 (0.241) ab	10
WE (Plywood Epoxy)	396 (34.38) d	2.85 (0.241) a	10
WP (Plywood Polyester)	328 (20.20) e	2.65 (0.241) ab	10

The values in parentheses are the standard deviations; different letters in the same column indicate statistical differences at the 95% confidence level.

As a result of the correlation between the board type and the coating type, the highest abrasion resistance was found in the particleboard group coated with hybrid powder paint, whereas the lowest was found in the particleboard and MDF coated with water-based liquid paint. According to the findings, the highest values of abrasion resistance in the MDF group were obtained for the samples coated with hybrid-based powder paint (451 cycles) and the lowest was found in the samples coated with water-based liquid paint (35 cycles). In the particleboard group, the highest value (514 cycles) of abrasion resistance was determined in the samples coated with hybrid-based powder paint and the lowest was found in those coated with water-based liquid paint (35 cycles). In the plywood group, the highest abrasion resistance value was found in the samples coated with hybrid-based powder paint (486 cycles) and the lowest was found in those coated with water-based liquid paint (77 cycles). Although the abrasion resistance of thermoset-based polyester and hybrid-based powder paints have been categorized as “good”, the epoxy-based powder paints have been classified as “very good” (Boymak Report 2017). However, the formulations, crosslinking reaction, densities, and dry film thicknesses of the coatings formed on the substrate were considered to have had a significant effect on the abrasion resistance. It has previously been stated that the mechanical properties, durability, adhesion, and abrasion resistance, and appearance properties of powder paints were especially dependent on the curing duration and temperature along with the paint formulation (Barletta *et al.* 2007). The fully cured film of powder paint will have reached its maximum potential in terms of scratch and abrasion resistance. It has been reported that the scratch resistance of polymeric films is generally associated with adhesion resistance (Barletta *et al.* 2007). The low abrasion resistance values were thought to be due to the dry film thicknesses of the water-based liquid paint applied to the MDF, particleboard, and plywood panels (75 µm, 71 µm, and 147 µm, respectively). Previous studies have found that the hardness values of water-soluble varnishes were low and therefore, the impact, abrasion, and scratch resistance values of these varnish layers were low (Sönmez *et al.* 2004). The water-based liquid paint was applied to the MDF and particleboard groups in a single layer, whereas this was applied in two layers on the plywood samples due to the insufficiency of the water-based paint coating. The dry film thicknesses of the plywood group water-based paint were higher than those of the MDF and particleboard groups because of the double layer of water-based paint. For this reason, it was thought that the dry film thickness was effective, noting the high increase in the abrasion resistance of the plywood group.

In general, the high abrasion resistance in the chipboard groups can be attributed to the high dry film thickness and porous structure of the chipboard, which may have enabled the powder paints applied to penetrate more deeply into the board pores. Furthermore, it is thought that factors such as wood varieties, glue type and ratio, press pressure, and temperature used in the production of the boards affect the interaction with paints applied to the board surfaces and may cause differences in abrasion resistance. Keskin and Tekin (2011), as a result of different varnishes applied to Scots pine, Eastern beech, oak, poplar, linden, and walnut wood material surfaces, found the highest level of abrasion resistance to be in the walnut, and stated that this stemmed from the porous structure of walnut wood. It is thought that the low abrasion resistance of the MDF boards was due to the fact that the paint dry film thickness was low, while the board surface density was high and had a less porous structure. Wear and scratch resistance and other such properties of veneer-coated boards have been linked to board quality and paint type.

The correlation between the board type and the paint coating type showed that the highest scratch resistance was obtained in the plywood panels coated with epoxy-based powder paint and the lowest was obtained by the MDF group coated with water-based paint. The lowest values of scratch resistance could have been due to the low dry film thicknesses of the water-based paint. Previous research found that the hardness values of water-soluble varnishes were not high and therefore, the impact, abrasion, and scratch resistance values of these varnish layers were low (Sönmez and Budakçı 2004). The high scratch resistance values obtained in the powder paint groups varied because of the manual coating process (using the electrostatic spray gun by hand) and therefore, a homogeneous dry film thickness could not be achieved with the powder paint. In addition, the varieties and ratios of resins, hardeners, additives, and fillers in the paint formulations could have influenced the scratch resistance. It has been demonstrated that the resins, curing agents, fillers, and additives used in powder paints affected the paint coating properties (Lambourne and Strivens 1999). The binding agent (resin) of the paint has a decisive effect on the mechanical properties of the coating including hardness and abrasion and scratch resistance. Moreover, the mechanical properties of the coating can be improved by using additives (Veigel *et al.* 2014). It was reported that silicon dioxide, aluminum oxide, and various metal silicates and sulfates with high hardness values, when used in paint coatings, have been shown to greatly enhance their abrasion and scratch resistance (Veigel *et al.* 2014). Hybrid-based and epoxy-based powder paints applied to the surfaces of particleboard and plywood were found to exhibit high scratch resistance. This could have been related to the dry film thicknesses of the coatings and the bonding reaction formed between the coating and the substrate. It was previously reported that when the viscosity change of the powder paint during the curing process was matched with a differential scanning calorimetry thermogram obtained at the same heating rate, there was a correlation with both the progression of the cross-linking degree and the activation energy. Moreover, the degrees of cross-linking could have been related to the surface properties of the coated substrates (Wuzella *et al*. 2011).

CONCLUSIONS

Over the last few years, studies have shown that the moisture content of MDF panels prior to powder paint coating has a notable influence on the MDF powder paint results. Preheating of wood-based panels is generally completed before electrostatic powder paint is applied so that the moisture content from the core of the panel is concentrated on the surfaces to provide increased electro-conductivity. The increased electrical conductivity enables the static powder paint to adhere to the panel surface. The preheating of uncoated boards can cause some disadvantages involving the mechanical and physical properties of the boards.

1. In this study, the cooling method used increased the amount of moisture on the surfaces of the wood-based panels and consequently decreased the electrical resistance on their surface and facilitated the adherence of the electrostatic powder paint to the panel surfaces. As a result of the correlation between the coating type and the board type, the plywood panels coated with hybrid-based powder paint and the MDF panel groups coated with epoxy-based powder paint were found to be least affected of the thickness swelling test samples.
2. The water absorption test results showed the least affected samples were those of MDF coated with polyester, epoxy, and hybrid powder paints. It was concluded that it is extremely important to determine the optimum dry film thickness, depending on the type of substrate and coating paint, to obtain strong adhesion.
3. According to the results of the abrasion test, the least affected of the samples, and therefore those recommended, were determined as the particleboard and plywood coated with hybrid powder paint. The scratch testing found optimum results for the plywood samples coated with epoxy powder paint and the particleboard samples coated with hybrid powder paint.

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