

EVALUATION OF WOOD SURFACE COATING PERFORMANCE USING WATER BASED, SOLVENT BASED AND POWDER COATING

Ender Hazir^{1,*}, Küçük Huseyin Koc²

ABSTRACT

The objective of this study was to evaluate the surface coating performance using water base, solvent base and powder coating on medium density fiberboard. Samples were coated using water-base, solvent-base and powder coating. Coating performance was performed by using adhesion strength, surface coating hardness, layer thickness and rapid deformation test. The results were analyzed with two different statistical methods. Adhesion strength, layer thickness and surface hardness were determined by using ANOVA analysis, while results of rapid deformation test were analyzed by using Kruskal-Wallis method. According to these results, coating type was effective factor on the adhesion strength, surface coating hardness, layer thickness and rapid deformation test. Water-based painting application for adhesion strength and impact deformation resistance were higher than solvent-based coating. In the powder coating application, although surface coating hardness was higher than solvent and water base coating application, rapid deformation results were lower than solvent and water base coating applications. Adequacy of models was performed R -square (R^2) and Adjusted R -square (Adj- R^2) values. R^2 values of adhesion strength, layer hardness and film layer thickness were 93,60 %; 95,33 % and 73,90 %, respectively. Adj- R^2 values of adhesion strength, layer hardness and film layer thickness were 93,45 %; 95,23 % and 73,30 %, respectively.

Keywords: Adhesion strength, coating hardness, coating thickness, layer hardness, medium-density fiberboard.

INTRODUCTION

Particleboard, fiberboard and wood based materials are widely used in furniture industry and cabinet production. Surface quality and type of the coating material are two significant factors influencing overall quality of the product (Ahola 1991, De Moura and Hernandez 2006, Ramananantoandro *et al.* 2018, Salca *et al.* 2017). It is a well-known fact that coating performance namely adhesion is depended on hygroscopic characteristic of wood composite panels. Therefore, coating type plays an important role on coating performance such as good bonding, coating hardness, abrasion resistance, UV resistance and film thickness (Salca *et al.* 2016 Sogutlu *et al.* 2016, Nejad and Cooper 2011, Darmawan *et al.* 2018, Erdinler *et al.* 2019). Coating applications of varnishes, stain and painting are the most popular method in order to enhance the stability and appearance of the wood and wood based materials. Surface coatings, as one of the final stages of production in wooden furniture and decoration applications, constitute the majority of production cost. In addition to this, it is effective in the performance of the products and the preferences of the customers. Moreover, these applications extend the service life. A good surface finishing increases the usage properties of the product (Cool and Hernandez 2011,

¹Faculty of Forestry, Department of Forest Industry Engineering, Istanbul University - Cerrahpasa, Istanbul, Turkey. ender.hazir@istanbul.edu.tr

²Faculty of Forestry, Department of Forest Industry Engineering, Istanbul University-Cerrahpasa, Istanbul, Turkey. hkoc@istanbul.edu.tr

*Corresponding author: ender.hazir@istanbul.edu.tr

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Landry *et al.* 2013). Medium density fiberboard and particleboards gradually increases in furniture and decoration applications due to covering surface treatments. Although there are various national and international standards of surface coatings and their characteristics, it's seen that the required importance is not considered in application and the controls remain at subjective evaluation level. Therefore, in the majority of the applications, the surface coatings may cause an increase in the production costs, prevent achieving the desired surface performance values and decreased surface coating performance (Acda *et al.* 2012, Nejad *et al.* 2012, Dilik *et al.* 2015, Gurleyen *et al.* 2017).

Hernandez and Cool (2008) evaluated three surfacing methods on paper birch wood in relation to water and solvent borne coating performance. Coating performance was determined by using pull-off strength test. The results showed that the water base coating of adhesion strength was higher than solvent borne coating.

Jocham *et al.* (2012) used pre-heating process in order to improve the powder application during the powder coating process for MDFs. According to the results, board temperature and moisture content were effective parameters to improve the adhesion strength.

Keskin and Tekin (2011) determined the abrasion resistance of cellulosic, synthetic, polyurethane, water-borne and acid hardening varnishes for Scots pine, Oriental beech, European oak, Black poplar, Basswood and Black walnut woods. It was found that varnish type and amount of layer thickness were significant factors for abrasion resistance.

Cakicier *et al.* (2011) studied the effects of different heat treatment and varnish coating on hardness, scratch resistance and glossiness of wood materials such as limba, iroka, ash and chestnut. In the different heat treatment application, coating hardness and scratch resistance decreased for the all wood species.

Rield *et al.* (2014) used to determine the effect of atmospheric pressure plasma treatment on wood surface coating performance using contact angle measurement and pull off testing. The results showed that type of plasma gases and treatment time were significant factors on the wettability and adhesion strength for maple and spruce wood samples.

Dilik *et al.* (2015) evaluated adhesive strength of particleboard and medium density fiberboard (MDF) finished with different types of paints such as cellulosic and polyurethane based paints. The highest adhesion strength value of 3,62 MPa was found for polyurethane coated MDF samples.

MATERIALS AND METHODS

Experimental procedure

This experimental procedure involved four steps in order to determine the coating performance. These steps were:

The coating factors were selected as painting type such as water base, solvent base and powder coating. Adhesion strength, surface hardness, layer thickness and rapid-deformation test were used to determine the coating performance.

Grubb's test was used to determine the outlier value. Analysis for normal distribution data were performed by using probability plot with 95 % interval confidence. One-way ANOVA analysis was applied to determine the significant parameters. Tukey test was used to determine the difference between the groups. Rapid deformation test was evaluated with Kruskal-Wallis method.

ANOVA analysis was performed by using R-square (R^2) and adjusted coefficient of (R^2 -adj) values.

Adequacy of developed model was tested by performing normal probability plot (NPP) and histogram of residuals.

Preparation of wood-based material

MDF (medium density fiberboard) was selected as test material in order to determine the coating performance. A total of 90 specimens with dimensions of 100 mm by 100 mm by 18 mm were conditioned in climate at $(20 \pm 2)^\circ\text{C}$ and $(65 \pm 5)\%$ relative humidity (RH) until they reach a moisture content of $(10 \pm 1)\%$. Density value of MDF was measured as $0,76 \text{ g/cm}^3$. The experiments were conducted on a sanding process known as belt sanding machine. Open coat aluminum oxide abrasive type was used to prepare the samples. The MDF materials were sanded with feed rate of 5 m/min, cutting speed of 18 m/sec and grit size of 150 as belt tension of 3 kg/cm^2 .

Preparation of wood coating surface

In this study, three different coating materials such as water-based, solvent-based and powder coating applications were applied on the MDF samples. MDF samples were conditioned in a climate room having a temperature of 20°C and relative humidity of 65% until they reach a moisture content of 8-10% before they were coated with various types of finishes. In the water-base and solvent-based coating application, specimens were coated with a pneumatic-spray gun using a pressure of 0,80 MPa. Each of the surface panels with an angle of 90 degrees were applied primer and top coat of the finishes.

In the powder coating application, the MDF surfaces were not subjected to any chemical pretreatments. The application of heat prior to application provides an even earthing of the substrate for deposition of the powder. After the MDF board was pre-conditioned with convection heat 3 mins at 120°C , the samples were stoved on the air temperature with 10 minutes at 140°C . In the powder coating system, application of primer coating thickness and top coating thickness was applied 80-120 μm and 70-100 μm , respectively.

Evaluation of the coating performance

Adhesion strength measurement

Adhesion strength is one of the most significant indicator for determining the coating performance. It is affected the good coating, resistance and durability performance. In this study, pull-off test method was used to determine the adhesive performance. The test method was carried out EN ISO 4624-2016.

Coating hardness measurement

Coating hardness is a significant quality characteristic for evaluating the behavior of the finished product during its transport and manufacturing process. Hardness effects many various properties such as impact resistance, stretches and abrasion effects for final products. In this study, EN ISO 1522-2016 method was applied to measure the samples. It is a damping method to evaluate the coating hardness equipped with konig pendulum apparatus.

Film thickness measurement

Film thickness is one of the important index of coating performance and appearance. As wood and wood based material have a complex structure, values of film thickness measurement have a different variance. In this study, the layer thicknesses of the coats were measured with PosiTector. This equipment is a non-destructive method and it measure the layer thickness of between 20 and 300 μm .

Rapid-deformation test

Rapid-deformation tests evaluate the effects of accidental contact damage that may occur during use. They are usually carried out by the direct evaluation of the effect of a falling object, sphere or dart of specified shape and hardness, onto the tested surface from different heights. During impact on coated surfaces, the deformation of the substrate can be relevant, significantly affecting the final results. It is of importance that the coating film is flexible enough to withstand, to a certain extent, the stretching at the fringes of the deformation without any cracking or cleavage. In this study, EN ISO 4211-4-2017 test was used to measure the specimens.

Statistical procedure

In this study, in order to determine the quality characteristics of adhesion strength, coating hardness, layer thickness and impact deformation test, (30x3) measurements were taken for each quality characteristic. The Anderson-Darling test is used to test if a sample of data came from a population with a specific distribution. Grubb's method was used to determine the outlier analyzes. This test detects outliers from normal distributions. The test can detect one outlier at a time with different probabilities from a data set with assumed normal distribution. Analysis of variance and Tukey's test were applied to evaluate the effective parameters.

Analysis of variance

Analysis of variance (ANOVA) based F -test was applied to evaluate the significance factor on the coating performance. This analysis investigates the following for each parameter are given in Equation 1 and Equation 2:

$$\left. \begin{array}{l} H_0 : \mu_1 = \mu_2 = \dots = \mu_\alpha \\ H_1 : \mu_i \neq \mu_j \text{ for at least one pair } (i, j) \end{array} \right\} \quad (1)$$

The F value is calculated by:

$$F_0 = \frac{SS_A / \alpha - 1}{SS_E / N - \alpha} = \frac{MS_A}{MS_E} \quad (2)$$

The terms of $(\alpha-1)$ and $(N-\alpha)$ are the degrees of freedom and the error degrees of freedom for the parameter A, respectively. MS_A and MS_E are indicated the sum squares of means and errors for the variable A, respectively. The null hypothesis is rejected when the F_0 is higher than critical value of $F_{\alpha, \alpha-1, N-\alpha}$, where α is the level of the significance .

Tukey's test

Tukey's multiple comparison test is one of several tests that can be used to determine which means amongst a set of means differ from the rest. It is to use a one-way analysis of variance (ANOVA) to evaluate whether there is any evidence that the means of the populations differ. Tukey multiple comparison test assumes that the data from the different groups come from populations where the observations have a normal distribution and the standard deviation is the same for each group.

Non-Parametric test

Kruskal-Wallis test is a nonparametric test, and is used to categorical independent variable for two or more groups. Kruskal-Wallis test can be used for both continuous and ordinal-level dependent variables. The Kruskal-Wallis test statistic for k samples, each of size n_i is given in Equation 3 and Equation 4:

$$T = \frac{1}{s^2} \left[\sum_{i=1}^k \frac{R_i}{n_i} - N \frac{(N+1)^2}{4} \right] \quad (3)$$

$$S^2 = \frac{1}{N-1} \left[\sum_{all} R_j^2 - N \frac{(N+1)^2}{4} \right] \quad (4)$$

Where N is the total number (all n_i) and R_i is the sum of the ranks (from all samples pooled) for the each sample.

RESULTS AND DISCUSSION

The results of adhesion strength, layer thickness and coating hardness for solvent base, water base and powder coating are given in the (Table 1). For each type of coating types, 30 x 3 arrays were measured and these results were evaluated with ANOVA analysis. In order to reduce the variation during measurement, the measurements were performed in a random order for determining the coating performance.

Table 1: Coating performance results for water based, solvent based and powder coating.

Water base			Solvent base			Powder coating		
Adhesion (MPa)	Hardness (counts)	Thickness (m μ)	Adhesion (MPa)	Hardness (counts)	Thickness (m μ)	Adhesion (MPa)	Hardness (counts)	Thickness (m μ)
3,24	288	162	2,11	234	159	2,78	322	189
3,16	286	155	2,15	241	155	2,64	317	193
3,47	291	159	2,21	225	163	2,59	327	191
2,95	278	169	2,18	231	174	2,71	328	188
3,14	293	162	2,13	246	177	2,56	342	193
3,27	290	160	2,25	240	164	2,73	333	182
3,18	301	173	2,18	233	168	2,68	327	185
3,01	298	165	2,14	214	179	2,76	329	190
3,09	278	168	2,31	241	175	2,54	319	193
3,11	274	174	2,28	237	164	2,62	327	188
3,23	283	164	2,31	231	169	2,69	331	186
3,31	284	163	2,35	229	184	2,72	337	186
3,25	281	171	2,31	216	184	2,59	338	190
2,98	291	160	2,3	213	158	2,81	330	188
3	302	152	2,2	220	154	2,83	318	193
3,32	299	158	2,01	230	158	2,79	322	189
3,17	297	160	2,06	234	174	2,66	325	185
3,29	293	172	2,11	226	179	2,82	329	188
3,24	288	164	2,08	216	153	2,59	320	186
3,22	285	165	2,15	223	154	2,68	319	188
3,16	273	160	2,17	221	155	2,75	316	191
3,18	284	154	2,24	220	160	2,79	332	183
3,03	281	164	2,18	241	171	2,88	337	184
3,12	294	170	2,24	252	165	2,84	339	182
3,46	303	164	2,26	246	169	2,78	330	185
2,89	296	157	2,21	249	173	2,81	329	189
3,1	289	169	2,16	236	165	2,79	326	188
3,28	279	168	2,19	238	166	2,67	319	184
3,25	300	164	2,2	234	170	2,6	323	186
3,17	281	169	2,21	225	165	2,82	326	188

Analysis of adhesion strength, layer thickness and coating hardness

Probability plot of coatings adhesion strength values of for solvent base, water base and powder coating is displayed in (Figure 1). This plot was presented with results of mean, standard deviation (StDev), sample size (N), Andersen darling test (AD) and *P*-critical values. According to the results of 95% confidence level, *P*-values were high than 0,05 showing the model the observations have a normal distribution. Water-based,

powder coating and solvent-based mean values for adhesion strength were found as 3,176; 2,717 and 2,196 MPa respectively.

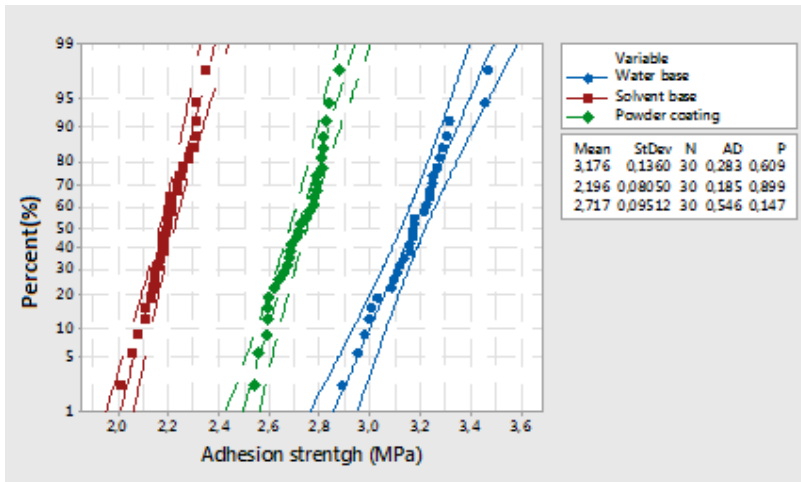


Figure 1: Probability plot of coatings adhesion strength values of for solvent-based, water- based and powder coating.

Probability plot of coatings hardness values of for solvent base, water base and powder coating is displayed in (Figure 2). Powder coating, water-based and solvent-based mean values for coating hardness were found as 327,2; 288,7 and 231,4; respectively. In (Figure 3), powder coating, water-based and solvent-based mean values for coating layer thickness values were found as 187,7; 166,8 and 163,8 μm respectively.

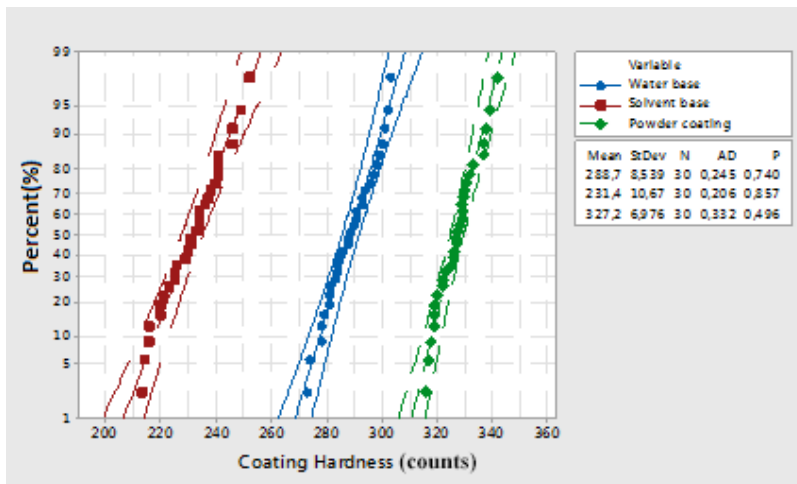


Figure 2: Probability plot of coatings hardness values of for solvent base, water base and powder coating.

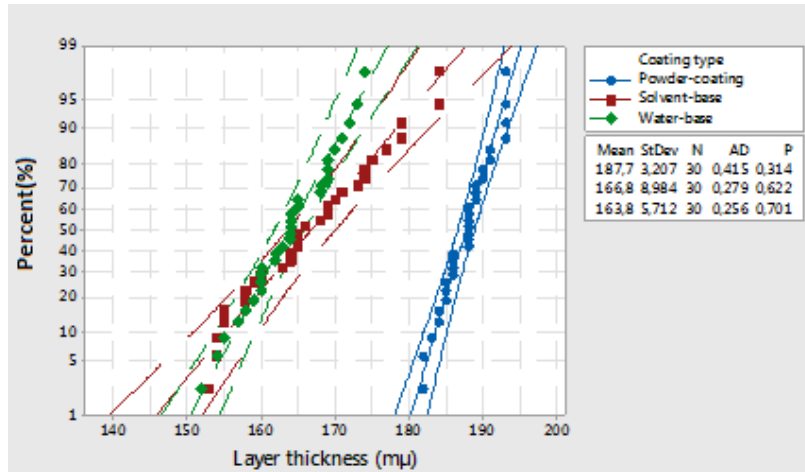


Figure 3: Probability plot of coatings layer thickness values of for solvent base, water base and powder coating.

Outlier test results are given in Table 2, Table 3 and Table 4. These results were presented with results of sample size (N), standard deviation (StDev), minimum value (Min), maximum value (Max), Grubb’s test (G) and P-critical values. According to the results, at the 5% level of significance was not outlier values for adhesion strength, layer thickness and coating hardness.

Table 2: Result of outlier test for adhesion strength.

Variable	N	Mean	StDev	Min	Max	G	P
Water base	30	3,1757	0,1360	2,8900	3,4700	2,16	0,746
Solvent base	30	2,1960	0,0805	2,0100	2,3500	2,31	0,477
Powder coating	30	2,7173	0,0951	2,54	2,88	1,86	1,000

Table 3: Result of outlier test for coating hardness.

Variable	N	Mean	StDev	Min	Max	G	P
Water base	30	288,67	8,54	273	303	1,83	1,000
Solvent base	30	231,40	10,67	213	252	1,93	1,000
Powder coating	30	327,23	6,98	316	342	2,12	0,858

Table 4: Result of outlier test for layer thickness.

Variable	N	Mean	StDev	Min	Max	G	P
Water base	30	163,83	5,71	152	174	2,07	0,975
Solvent base	30	166,80	8,98	153	184	1,91	1,000
Powder coating	30	187,70	3,21	182	193	1,78	1,000

Table 5, Table 6 and Table 7 displayed the P-value is less than 0,05 showing the model is significant at 95% confidence level. All the terms of model were tested and verified statistically by F-test at probability

levels ($p < 0,05$). Adequacy of model for adhesion strength was tested by performing R^2 and $Adj-R^2$ values were 93,60 % and 93,45 %, respectively. Adequacy of model for coating hardness was tested by performing with R^2 and $Adj-R^2$ values were 95,33 % and 95,23 %, respectively. Adequacy of model for layer thickness was tested by performing with R^2 and $Adj-R^2$ values were 73,90 % and 73,30 %, respectively.

Table 5: ANOVA analysis for adhesion strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Paint type	2	14,4160	7,20802	635,72	0,000
Error	87	0,9864	0,01134		
Total	89	15,4025			

Table 6: ANOVA analysis for surface coating hardness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Paint type	2	139509	69754,4	888,63	0,000
Error	87	6829	78,5		
Total	89	146338			

Table 7: ANOVA analysis for layer thickness.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Paint type	2	10152	5076,14	123,18	0,000
Error	87	3585	41,21		
Total	89	13748			

In Table 8, Table 9 and Table 10, dual comparisons were performed employing Tukey's test. These results show that two pairs of each group were compared and the mean difference between the groups was given numerically. These numerical values indicated the significant difference between the averages of these factors for adhesion strength, layer thickness and coating hardness.

Table 8: Tukey's test results for adhesion strength.

Factor	N	Mean	Grouping
Water base	30	3,1757	A
Powder coating	30	2,7173	B
Solvent base	30	2,1960	C

Table 9: Tukey's test results for surface coating hardness.

Factor	N	Mean	Grouping
Powder coating	30	327,23	A
Water base	30	288,67	B
Solvent base	30	231,40	C

Table 10: Tukey’s test results for layer thickness.

Factor	N	Mean	Grouping
Powder coating	30	187,7	A
Solvent base	30	166,8	B
Water base	30	163,8	B

Boxplot and Interval plot

The box plot is a standardized way of displaying the distribution of data based on the five number summary: minimum, first quartile, median, third quartile, and maximum. The interval plot shows a 95% confidence interval for the mean of each group. From the (Figure 4a and Figure 4b), water-based adhesion strength value was higher than solvent-based and powder coating values. In the (Figure 4c and Figure 4d), powder coating surface hardness value was higher than solvent-based and water-based coatings. In the (Figure 4e and Figure 4f), powder coating layer thickness value was higher than solvent-based and water-based coatings.

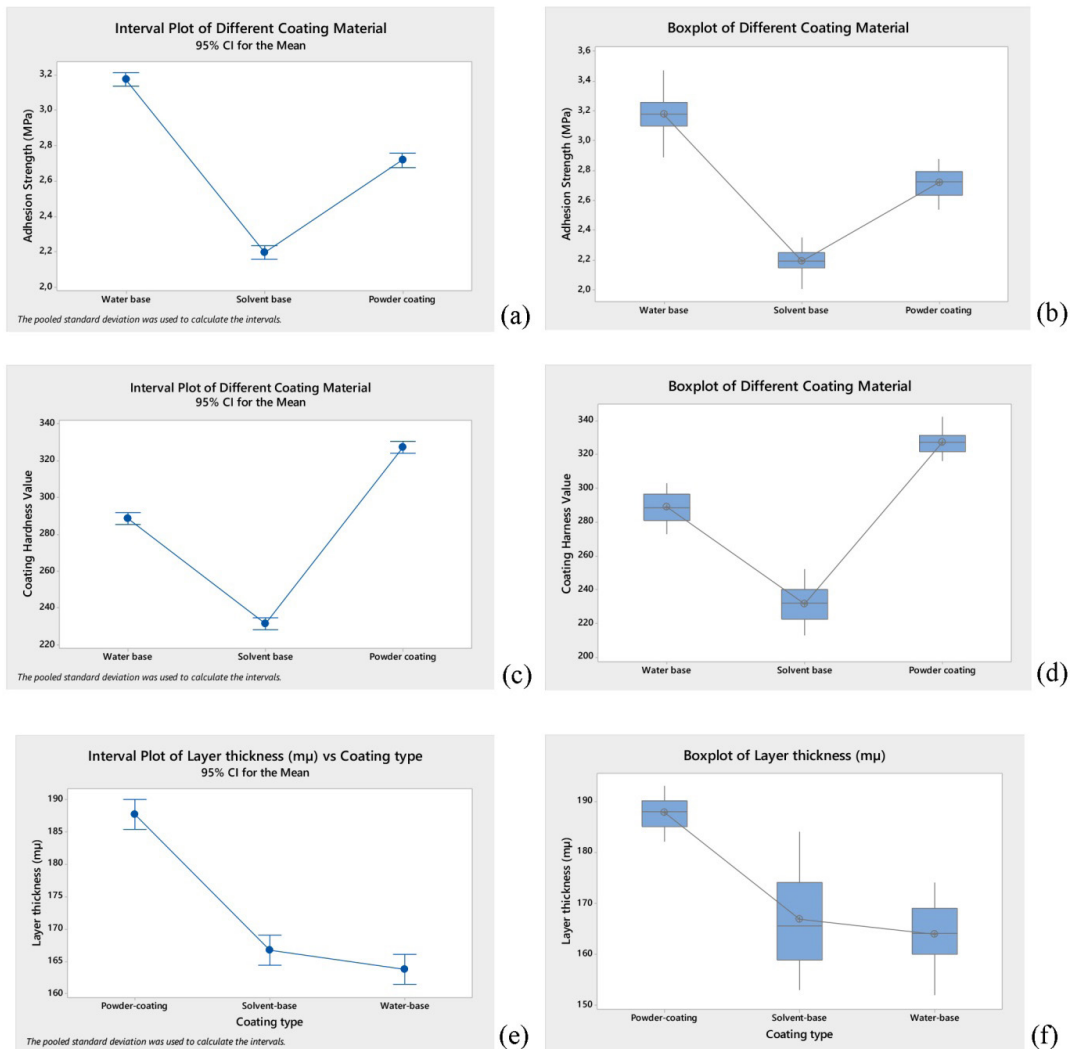


Figure 4: (a-b) Boxplot and interval plot results for adhesion strength (c-d) Boxplot and interval plot results for coating hardness (e-f) Boxplot and interval plot results for layer thickness.

Evaluation of the adhesion strength, layer thickness and coating hardness model

Normality assumption is verified by applying the normal probability plot and histogram of residuals. From the (Figure 5a, Figure 5c and Figure 5e), as the residuals generally fall on a straight line implying, the errors were resembled the normal distribution. (Figure 5b, Figure 5d and Figure 5f) show standardized residuals, instead of ordinary, the residuals were applied to identify the outliers. Standardized residuals d_i was computed by Equation 5:

$$d_i = \frac{e_{ij}}{\sqrt{MS_E}} \quad (5)$$

The term of $\sqrt{MS_E}$ is mean error sum of square. In (Figure 5b, Figure 5d and Figure 5f), standardized residuals values were found in interval $-3 \leq d_i \leq 3$. Therefore, the proposed approach was adequate and there was not any violation of the independence or constant variance assumption.

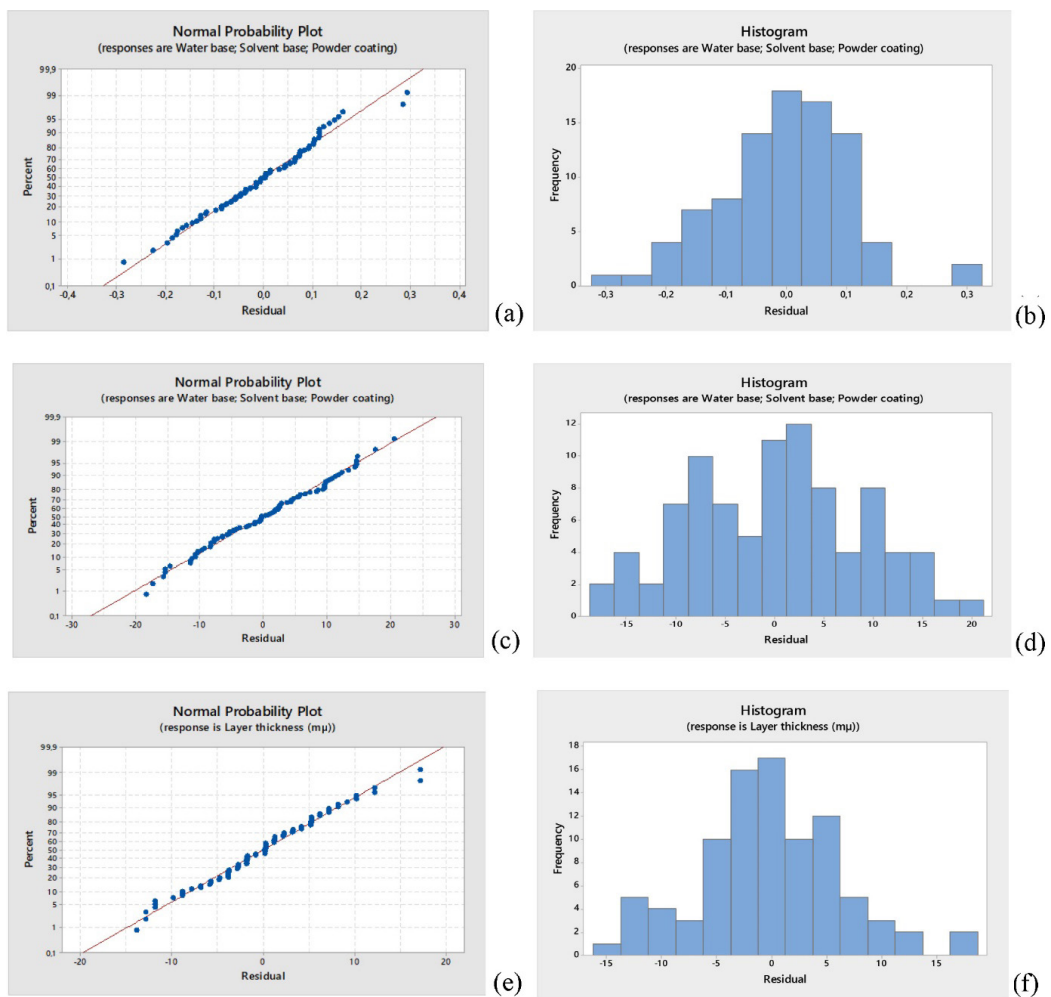


Figure 5: (a-c-e) Normal probability plot for standardized residuals (b-d-f) histogram of standardized residuals.

Analysis of rapid-deformation test

Rapid-Deformation test was performed according to EN ISO 4211-4-2017. Steel ball with a diameter of 14 mm was dropped freely with a weight of 500 g. from the standardized heights on the sample surface. The deformations were observed and the resistances were determined representing impact value from 1 to 5; 1 referring to holes, cracks and peel offs for non-resistant coating and 5 referring to no changes for resistant coating. The results of the evaluation using 30 samples are given in (Table 11).

Table 11: Results of rapid- deformation test.

Sample of number	Solvent-based	Water-based	Powder-coating
1	4	4	4
2	3	4	3
3	5	4	4
4	3	4	4
5	4	3	4
6	4	5	3
7	5	4	3
8	4	5	4
9	4	4	3
10	4	4	3

Kruskal-Wallis test result is given in Table 12. It was presented with results of sample size (N), median, average of rank and Z-critical values. The results of average of rank for water-based, solvent-based and powder coating were 18,4; 17,1 and 11,0 respectively. According to these results, it is found that the deformation in the powder coated surface is higher than the other coating types.

Table 12: Result of Kruskal-Wallis test.

Paint type	N	Median	Ave Rank	Z
Water-base	10	4,000	18,4	1,28
Solvent-base	10	4,000	17,1	-1,98
Powder-coating	10	3,500	11,0	0,70
Overall	30		15,5	

CONCLUSIONS

In this study, MDF samples were coated with water-base, polyurethane-base and powder coating applications. Adhesion strength, surface coating hardness and impact deformations test were used to evaluate the surface coating performance.

The results are as follows:

Grubb's test was used to find the outlier data. Analyze of the normally distribution data was performed by using normal probability plot. One-way ANOVA analysis was applied to determine the significant parameters. Tukey's test was used to determine the significance differences for each group. Rapid deformation test was evaluated with Kruskal-Wallis method.

The results of adhesion strength and surface coating hardness were analyzed by using ANOVA method. According to the results, coating type was the effective factor on strength adhesion, layer thickness and surface coating hardness. R^2 values of adhesion strength, layer hardness and film layer thickness were 93,60 %; 95,33 % and 73,90 %, respectively. Adj- R^2 values of adhesion strength, layer hardness and film layer thickness were 93,45 %; 95,23 % and 73,30 %, respectively.

The highest layer thickness value was determined as powder coating application, while the lowest layer thickness was determined as water and solvent-based application. The reason for this situation, the solid content ratio of powder coatings was higher than solvent and water based coatings. Moreover, powder coated MDF surface was applied with primer and top coat.

The highest adhesion resistance was found as water-base coating application, while the lowest resistance was determined as solvent-based application. The highest surface coating hardness was resulted as powder coating application, while the lowest coating hardness was resulted as solvent-based application.

Coating type was the effective factor on the rapid-deformation test. The highest impact deformation resistance was found as water-based application, while the lowest resistance is found as powder coating application. The reason for this situation, water-based coating has more tough flexible than solvent based and powder coating.

From the powder coating application, surface coating hardness test results were higher than solvent and water based coating application. The reasons for this can be explained by the fact that the coating types have different chemical structures.

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