The Effects of Surface Roughness, Adhesive Type, and Veneer Species on Pull-Off Strength of Laminated Medium Density Fibreboard

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This study investigated the pull off strengths of various laminated medium density fiberboards (MDFs). The surface roughness of the MDF, adhesive type, and veneer type were all studied. Polyvinylacetate (PVAc), urea formaldehyde (UF), and gluten were used as the adhesives for beech, pine, and oak veneers. There were a total of 216 experimental specimens that were tested according to the principles specified in the TS 5339 (1987) standard. According to the statistical analyses of the data obtained from the tests, surface roughness, veneer species, and adhesive type all affected the pull-off strength of the laminated MDF. The highest pull-off strength (2.88 N/mm^2) was obtained with the MDF unsanded with 120-grit abrasive and laminated with PVAc adhesive and pine veneer. The lowest pull-off strength (1.60 N/mm^2) was obtained with the unsanded MDF laminated with PVAc adhesive and oak veneer.

Keywords: Pull-off strength; Adhesive; Surface roughness; Sanding; Veneer; Medium density fiberboard (MDF)

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INTRODUCTION

The primary surface characteristics obtained by the lamination and coating processes are resistance to scratch, abrasion, moisture, heat, and some household chemicals. Fiberboard is the most common substrate material. Laminating materials include wood veneers, decorative laminates, and papers impregnated with modified and unmodified resins. Lacquers and varnishes are used as coating materials. Surface improvement and quality of lamination and coating depend on the substrate material, laminating/coating material, and on the lamination/coating systems adopted for processes (variables relevant with gluing, pressing, and coating) (UNIDO 1981).

Adhesion is extremely important in the lamination and coating processes. The adhesion mechanism can be divided into three categories: mechanical interlocking, physical bonding, and chemical bonding. Together, these mechanisms are responsible for adhesion, and usually one of them plays a dominant role. Mechanical interlocking strength depends on the surface area. Increment in the surface area increase the binding sites for other adhesion mechanisms. Physical bonds include hydrogen and van der Waals bonds, which are generally relatively weak. Chemical bonding is stronger and includes metallic, covalent, and ionic bonds. The availability of physical and chemical bonds depends on the surface chemistry of the substrate and are sometimes collectively described as thermodynamic adhesion. Wettability of the surface is closely related to the adhesion, since better wettability usually indicates better adhesion. As most of the surface modification methods will influence both the roughness of the surface and the chemical composition, the separation of these two is important for comprehensive understanding of the adhesion process (Kinloch 1987; Rimai *et al*. 1995).

Varusombuti *et al*. (2010) investigated the surface characteristics and overlaying properties of MDF panels manufactured from untreated rubber wood fibers and fibers treated at three different temperatures (120, 150, or 180 °C) for 15 or 30 min and then laminated with beech (*Fagus orientalis* L.) veneer with a thickness of 0.60 mm. They pointed out that there were significant differences among the surface roughness, contact angle, and adhesive bonding strength of the panels following thermal treatment. Surface roughness, wettability, and adhesive bonding strength between the MDF surface and the veneer decreased with increasing thermal treatment temperature and time. Ozdemir *et al.* (2009) studied the effect of polyurethane finish on the pull-off strength of commercially manufactured medium density fiberboard (MDF) panels and the effect of the relative humidity on the surface roughness and adhesion strength. They noted that surface roughness of the MDF panels were influenced adversely by increasing relative humidity and adhesion strength of the panels decreased with increasing relative humidity exposure level. A study by Ayrilmis and Winandy (2009) showed that surface roughness values of the commercially manufactured medium density fiberboard (MDF) panels decreased as heat-treatment temperature increased. Also, as heat-treatment temperature increased, contact angle increased and consequently wettability decreased. Kilic (2009) investigated the effects of steaming of beech and sapele wood on the adhesion strength of the varnishes of cellulosic, polyurethane, and water-based bright. He noted that beech wood had a higher adhesion strength than sapele wood. Steamed wood had a lower strength than unsteamed wood. The highest adhesion strength was obtained with the polyurethane varnish. Ozdemir and Hiziroglu (2009) studied the effect of surface roughness and wood species on adhesion strength between wood and two types of finishes. They stated that as the moisture contents of the wood were increased, adhesion strength values of the wood coated with varnish and lacquer decreased. Adhesion strength values of the wood coated with cellulosic varnish were significantly higher than those of the wood coated with polyurethane lacquer. Surface characteristic (surface roughness and wettability) and hardness of sandwiched panels produced from medium density fiberboard and thermally compressed wood veneer was investigated by Buyuksari (2013). The results showed that the roughness values of the compressed veneer laminated panels decreased as press pressure and temperature were increased. Press pressure had no significant effect on the contact angle values of the panels while temperature affected significantly. The objective of this study was to determine the effects of surface roughness, veneer species, and adhesive type on the pull-off strengths of laminated MDF.

EXPERIMENTAL

Materials

Medium density fiberboard (MDF)

In this study, because it is one of the most used materials in lamination, MDF was preferred as the substrate material. It had a thickness of 18 mm, dimensions of 183 cm x 366 cm, and a density of 0.71 g/cm^3, manufactured according to the standard procedure TS EN 622-5 (TS EN 622-5 2008).

Urea formaldehyde

The urea formaldehyde (UF) adhesive used in lamination was supplied by Polisan Corporation. There were urea resin, formaldehyde, and ammonium chloride as curing agent in its structure. Its density was 1.24 g/cm^3 at 20 °C, pH value 8.1, viscosity 170 cP. It had a solids content of 55% and its free formaldehyde content was 0.025%.

Polyvinyl acetate (PVAc)

The polyvinyl acetate (PVAc) adhesive used in lamination was Kleibit 302.2 supplied by Polisan Corporation. Its density was 1.19 g/cm^3 at 20 °C, pH value 3.0, and viscosity 120 cP.

Gluten

Gluten glue used in lamination was supplied by Iclek Corporation. Its density was 1.28 g/cm^3 at 20 °C, pH value 6.2, and viscosity 148 cP.

Veneers

Beech (*Quercus petraea* L.), oak (*Fagus orientalis* L.), and pine (*Pinus sylvestris* L.) veneers with thicknesses of 0.6 mm were used as the laminating materials. All were obtained from flitches by the slicing method specified in TS 1250 (TS 1250 1986).

Preparation of the Test Specimens

ASTM–D 1666–87 (1999) principles were conformed to in the preparation of the specimens. With this objective, 18 preliminary specimens were prepared with dimensions of 18 mm x 400 mm x 500 mm ±1 mm. The preliminary specimens were kept in a climatization chamber at a temperature of 20±2 °C and a relative humidity of 65±5%. They obtained a moisture content of approximately 12±0.5% according to TS 2471 (1976). The density of the MDF was determined to be 0.71 g/cm^3 according to TS EN 323 (1999).

Nine of the 18 preliminary specimens were sanded with a 120-grit sander in a wide belt sanding machine to obtain different roughness levels. The remaining preliminary specimens were left unsanded and used as the control specimens. The feeding speed for sanding was 12 m/min and the cutting speed was 22 m/s; these settings were kept stable during the process. The sanding process was performed in the same feeding direction on both surfaces of each specimen.

The principles specified in ISO 4287 (1997) were conformed to in the measurement of the average surface roughness value (R_a) with a TIME TR–200 stylus-type profilometer. To bring the moisture content to air-dry level (12 %), the preliminary specimens were kept again in a climatization chamber at a temperature of 20±2 ºC and a relative humidity of 65±5 %. The measurements were made at five different points on two opposite surfaces of each specimen. After adjusting the measuring step to 2.5 mm and the cut-off to three measuring numbers, the measuring needle of the equipment was placed between two lines with an interval of 20 mm. The measurements were started after checking that the specimen and the equipment were parallel to the mechanism. The results were read from the LCD screen of the equipment and recorded in Ra.

With 12 replications for each variable, a total of 216 test specimens in a factorial design of 2 x 3 x 3 x 12 (surface condition x adhesive type x veneer type x replications) were prepared according to TS 5339 (1987) (Table 1).

Table 1. Test Variables and Number of Specimens

Surface condition of MDF	Adhesive type	Veneer (thickness of 0.6 mm)			TOTAL
		Pine	Oak	Beech	
Unsanded	PVAc	12	12	12	108
	Gluten	12	12	12	
	UF	12	12	12	
Sanded with 120-grit sander	PVAc	12	12	12	108
	Gluten	12	12	12	
	UF	12	12	12	
TOTAL		72	72	72	216

After measuring the surface roughness of 108 specimens, adhesives were coated on two surfaces of the 216 specimens with a glue roller by taking into consideration the application recommendations of the adhesives. Pressing of the veneers on the MDF specimens was realized at the conditions given in Table 2.

Table 2. Pressing Conditions of Veneers on the Specimens

Type of adhesive	Amount of adhesive (±10 g/m^2)	Pressing pressure (N/mm^2)	Pressing time (min)	Pressing temperature (^{o}C)	Viscosity (cP) (20 ^{o}C/6 mm/ 30 sn)
PVAc	160	0.8	60	20*	120
UF	160	0.8	4	80*	170
Gluten	160	0.8	180	25*	150

*Determined by considering proposals of manufacturers of the adhesives

After lamination, the specimens were removed from the press and were kept for three weeks in a closed space with air circulation, but no sunlight, for the adhesives to become completely solid.

Method (Pull-Off Test)

A test instrument (Fig. 1) that operates with a pneumatic system for measuring the pull-off strength of the laminated MDF, according to the principles specified in TS EN 2462 (1996) and ASTM D-4541 (2009), was used in this study. This instrument was developed in a project supported by the Scientific and Technological Research Council of Turkey (TUBITAK) (Sonmez and Budakcı 2003).

Pull-off test specimens with dimensions of 120 mm x 120 mm ±1 mm were cut from the preliminary specimens of dimensions 500 mm x 400 mm ±1 mm and grouped by taking the test variables into consideration. Before pull-off testing, the specimens were acclimatized at a temperature of 20±2 °C and a relative humidity of 65±5% according to TS 2470 (1976) to bring the moisture content to air-dry level (12%).

Subsequently, 160 g/m^2 of epoxy adhesive was coated onto the lower surface of stainless steel test cylinder which have a diameter of 35.7 mm**.** The test cylinders were placed on the center of each specimen by holding molds and compressed with pressing apparatuses. The specimens were kept in this mold for 24 h. During these procedures, care was taken that the pressure applied was perpendicular to the surfaces of the specimens. The average pressure was 15 N/mm^2.

After 24 h, the specimens were removed from the molds. A 2-mm-wide groove around the cylinder descending to the surface of the MDF substrate from the top surface of the specimen was cut so as not to tear out the specimen during pull-off testing. The specimens prepared for the pull-off strength test were placed in the pneumatic pull-off test machine and the pull-off force was applied by increasing 0.1N per minute (Fig. 1).

Fig. 1. Pull-off test instrument and specimens used in the study

Data Analysis

The aim of this study was to determine the effects of surface roughness, adhesive type, and veneer species on the pull-off strength of the laminated MDF. For data analysis, surface roughness, adhesive type, and veneer species were taken as the independent variables and pull-off strength was taken as the dependent variable. Multiple analyses of variance (MANOVA) were used to determine whether or not the independent variables had a single or group effect on the dependent variable. If an effect existed, the Duncan test was used to determine whether or not the differences between levels of the independent variables were significant.

RESULTS AND DISCUSSION

The pull-off strength data for the laminated MDF are given in Table 3. Results are provided for the various surface roughness, adhesive types, and veneer species.

Multiple analyses of variance (MANOVA) was used to determine whether or not the surface condition, veneer type, and adhesive type had a single or group effect on the pull-off strength according to the data given in Table 3. Because all of the single or group interactions had a probability smaller than 0.05 ($p<0.05$), the surface roughness, adhesive type, and veneer species were effective at improving the pull-off strength of the laminated MDF. This observation was true for the single and group interactions.

Homogeneity tests were conducted to determine whether or not the differences among the values of pull-off strengths of the effective variables were significant. The homogeneity groups of the pull-off strength values connected to the surface roughness, veneer species, and adhesive type are given in Table 4.

Table 3. Statistical Results for Pull-Off Strength of MDF

Surface condition of MDF	Veneer	Glue	Pull-off strength (N/mm²)		
			Mean	Sd	Cv (%)
Sanded with 120-grit sander (R_a = 3.32 µm) (SD=0.65) (CV = 19.58)	Pine	PVAc	2.46	0.18	7.32
		Gluten	1.99	0.18	9.05
		UF	2.29	0.11	4.80
	Oak	PVAc	1.60	0.19	11.88
		Gluten	2.02	0.10	4.95
		UF	2.10	0.12	5.71
	Beech	PVAc	1.95	0.11	5.64
		Gluten	2.16	0.12	5.56
		UF	2.58	0.17	6.59
Unsanded (R_a = 2.85 µm) (SD = 0.34) (CV = 11.93)	Pine	PVAc	2.88	0.16	5.56
		Gluten	2.51	0.10	3.98
		UF	2.36	0.11	4.66
	Oak	PVAc	2.29	0.10	4.37
		Gluten	2.42	0.14	5.79
		UF	2.43	0.12	9.99
	Beech	PVAc	2.23	0.11	4.93
		Gluten	2.34	0.07	2.99
		UF	2.10	0.08	3.81
MDF: medium density fiberboard, SD: Standard deviation					
PVAc: polyvinylacetate; UF: urea formaldehyde, CV: Coefficient of variation					

Table 4. Homogeneity Groups for Surface Roughness, Veneer Species, and Adhesive Type

Surface condition of MDF	Pull-off strength (N/mm²)	HG	Species of veneer	Pull-off strength (N/mm²)	HG	Adhesives type	Pull-off strength (N/mm²)	HG
Sanded	2.129	B	Pine	2.415	A	PVAc	2.236	B
Unsanded	2.394	A*	Oak	2.145	C	Gluten	2.240	B
			Beech	2.226	B	UF	2.309	A
*A: The highest value								

The pull-off strength of the unsanded MDF (2.394 N/mm^2) was higher than that of the sanded MDF (2.129 N/mm^2). Depending on the species of veneer, the highest pull-off strength (2.415 N/mm^2) was that of pine, followed by beech and then oak (2.226 N/mm^2 and 2.145 N/mm^2, respectively). When adhesive type was taken into account, the UF adhesive had the best pull-off strength. The difference between the pull-off strengths (2.236 N/mm^2 and 2.240 N/mm^2, respectively) of the PVAc and gluten adhesives was not important.

Increasing of surface area depending on roughness decrease, deeper penetration of the adhesive depending on the density decrease and therefore increasing in mechanical adhesion, and creating a strong bond layer of UF with chemical curing could have been effective on the above results.

The homogeneity groups of the pull-off strengths connected to the surface roughness, veneer species, and adhesive type are given in Table 5.

Table 5. Homogeneity Groups for the Dual Interaction of Surface Roughness and Veneer Species

Surface condition of MDF	Veneer species					
	Pine		Oak		Beech	
	Pull-off strength (N/mm^2)	HG	Pull-off strength (N/mm^2)	HG	Pull-off strength (N/mm^2)	HG
Sanded	2.247	C	1.910	D	2.231	C
Unsanded	2.583	A	2.379	B	2.221	C
A: The highest value						

According to Table 5, the highest pull-off strength (2.583 N/mm^2) was obtained in the unsanded MDF laminated with pine veneers. While a statistically significant difference was not shown for the pull-off strengths (2.231 N/mm^2 and 2.221 N/mm^2) of the sanded and unsanded MDF laminated with beech veneer, there were important differences between the pull-off strengths of the MDF laminated with oak and pine veneers.

Roughness increase led to a decrease in the pull-off strength, and all pull-off strength values were closer to each other. Decreasing of contacted surface area depending on the roughness increase may be effective relative to these results. The higher pull-off strength in the specimens with pine veneer may originate from the lower density. Increasing of cavity content in the wood provides deeper penetration of adhesive and mechanical interlocking increases

The homogeneity groups of the pull-off strengths connected to the surface roughness and adhesive type are given in Table 6.

Table 6. Homogeneity Groups for the Dual Interaction of Surface Roughness and Adhesive Type

Surface condition of MDF	Adhesive types					
	PVAc		Gluten		UF	
	Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG
Sanded	2.006	C	2.058	C	2.323	B
Unsanded	2.467	A	2.421	A	2.295	B
A: The highest value						

The highest pull-off strength (2.467 N/mm^2 and 2.421 N/mm^2) depending on the dual interaction of surface roughness and adhesive types was obtained in the unsanded MDF laminated with the PVAc and gluten adhesives. The same adhesives caused the lowest pull-off strengths (2.006 N/mm^2 and 2.058 N/mm^2) in lamination of sanded MDF. In lamination with UF adhesive, it did not seem to matter whether the MDF surfaces were sanded or not sanded.

Increased speed of solidification reduces mobility-dependent adhesive action because of increasing viscosity and reduced time for actions to occur. High temperature levels always decrease the speed of solidification of chemically hardening adhesive (Marra 1992). At the lower roughness level, the fact that UF is a chemically hardening adhesive at the higher temperature level and cannot penetrate deeper compared to PVAc and gluten could be effective in the decrease of pull-off strength.

Homogeneity groups of pull-off strengths connected to the veneer species and adhesive type are shown in Table 7.

Table 7. Homogeneity Groups for the Dual Interaction of Veneer Species and Adhesive Type

Veneer Type	Adhesive type					
	PVAc		Gluten		UF	
	Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG
Pine	2.671	A	2.248	CD	2.325	BC
Oak	1.946	F	2.222	D	2.266	BCD
Beech	2.092	E	2.250	CD	2.336	B
A: The highest value						

The use of PVAc adhesive in lamination of MDF caused significant pull-off strength differences depending on the veneer type. A PVAc adhesive can be preferred, especially for the gluing of pine veneers in the lamination of MDF. It can be concluded that the veneer type is unimportant in lamination with gluten and urea formaldehyde adhesives.

The highest pull-off strength (2.671 N/mm^2) depending on dual interaction of veneer and adhesive types was obtained in the MDF laminated with the pine veneer and PVAc adhesive, followed by the MDF laminated with beech veneer and UF adhesive and then the MDF laminated with pine veneer and UF adhesive (2.336 N/mm^2 and 2.325 N/mm^2, respectively). Lamination of the MDF with the oak veneer and PVAc adhesive resulted in the lowest pull-off strengths (2.222 N/mm^2). Lower density of pine and lower speed of solidification of PVAc could provide deeper penetration and higher pull-off strength. The pull-off strengths of the specimens laminated with UF adhesive were higher than that of specimens laminated with PVAc and gluten adhesives, excluding the specimens laminated with pine veneer and PVAc adhesive. Curing of UF with chemical reaction and giving more durable bond compared to the other adhesives may have contributed to this result. Further, in the ranking of pull-off strength values of specimens with UF adhesive according to the veneer type, extractive contents may have been effective. It is a well-known fact that higher extractive content adversely affects the bond properties of UF adhesive because of acidic nature (Marra 1992).

Homogeneity groups for the pull-off strengths relative to three-way interaction of the surface roughness, veneer species, and adhesive type are given in Table 8.

Table 8. Homogeneity Groups for the Triad Interaction of Surface Roughness, Veneer Species, and Adhesive Type

Surface condition of MDF	Veneer Type	Adhesive type					
		PVAc		Gluten		UF	
		Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG	Pull-off Strength (N/mm^2)	HG
Sanded	Pine	2.461	CD	1.987	KL	2.291	FG
	Oak	1.604	M	2.024	JKL	2.103	IJ
	Beech	1.953	L	2.163	HI	2.577	B
Unsanded	Pine	2.881	A	2.509	BC	2.360	DEF
	Oak	2.288	FG	2.419	CDE	2.430	CDE
	Beech	2.231	GH	2.336	EFG	2.095	IJK
A: The highest value							

The highest pull-off strength (2.881 N/mm^2) was obtained in unsanded MDF laminated with the PVAc adhesive and pine veneer and the lowest pull-off strength (1.604 N/mm^2) was obtained in the lamination of sanded MDF with the PVAc adhesive and oak veneer. In the lamination of sanded MDF, the best result was obtained with bonding beech veneer on the MDF with the UF adhesive.

When the data in the (Table 8) is considered as a whole, it can be seen that lower roughness, lower density, and lower solidification speed stood out, since pull-off strength values of the unsanded MDF laminated with the pine veneer with PVAc and gluten adhesives were higher than that of other specimens excluding the specimens unsanded and with the adhesive of UF. Moreover, with some exceptions, the pull-off strengths of the specimens with UF adhesive were higher than that of other specimens. As previously explained, increasing of surface area depended on the decrease of roughness. Deeper penetration of the adhesive depended on the density decrease, giving rise to increases in mechanical adhesion, speed of solidification of adhesives, extractive contents of veneers, and creating a strong bond layer of UF with chemical curing. All of these factors could have affected the results.

An experimental study on the effect of the surface roughness on the tensile strength perpendicular to the surface of medium density fiberboard (MDF) overlaid with polyvinyl chloride (PVC) was carried out (Kilic *et al*. 2009). The results showed that the sanding process decreased the surface roughness of the MDF. As the surface roughness of the MDF decreased, the tensile strength perpendicular to the surface of the MDF overlaid with veneer increased. A study by Kilic (2006) showed that species and cut direction of wood veneer and types of adhesives affected the adhesive bonding strength of medium density fiberboard (MDF) and oriented strand board (OSB) panels. The pull-off strength of the OSB laminated with the urea formaldehyde adhesive and radial cut beech veneer were the highest. The lowest pull-off strength was obtained in the MDF laminated with rubber adhesive and tangentially cut beech veneer. The results of these studies related to surface roughness and adhesive type seem generally consistent with the results of this study.

According to these findings, a MDF substrate should not be sanded with a 120-grit sander before lamination. A PVAc adhesive with pine veneer, UF adhesive with oak veneer, and gluten adhesive with beech veneer can be preferred for the lamination of MDF.

CONCLUSIONS

1. The highest pull-off strength was obtained in the unsanded MDF laminated with the PVAc adhesive and pine veneer. The lowest pull-off strength was obtained in the sanded MDF laminated with the PVAc adhesive and oak veneer.
2. Decreasing the surface roughness from 3.32 to 2.85 µm reduced the pull-off strength of the laminated MDF by 11%.
3. In lamination of the MDF, using pine veneer, which is a softwood species, increased the pull-off strength. The use of beech and oak veneers, which are hardwood species, had a lower pull-off strength compared to that of the pine veneer at rate of 8 to 10%.
4. Depending on the adhesive type used in lamination, the highest pull-off strength was obtained with the UF adhesive. The difference between the pull-off strengths of the MDF laminated with the PVAc and gluten adhesives was not significant.

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