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Full Length Research Paper

Effect of wood moisture content on adhesion of varnish coatings

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In this research, experimental samples were prepared using Scots pine *(Pinus sylvestris* L.)*,* Eastern beech *(Fagus orientalis* L.*)* and oak *(Quercus petraea* L.*)* with moisture content of 8, 12 and 15% and were coated with cellulosic (nitrocellulose), two-part polyurethane (urethanealkyd), and waterborne (self-crosslinked polyurethane) varnishes in order to determine the effect of wood moisture content on adhesion. According to research results, it was found that the difference in moisture content had substantial effect on the adhesion of varnishes, applied on the wood surfaces. The highest adhesion was obtained from two-part polyurethane varnish, applied on oak specimens with a moisture content of 8%.

Key words: Adhesion, axial pull-off test, varnishes, moisture content, wood materials

INTRODUCTION

In furniture production, the finishing processes have a great importance for technical, economical and aesthetical evaluation of the wood materials. Wood surfaces coated with a varnishes/paints can be protected from certain adverse situations such as moisture, changes in dimensions and deterioration by microorganisms and fungi. The moisture content of the wood substrate is important for bending, drying, impregnating, and finishing processes. During water absorption by wood materials, water molecules are held by the hydroxyl groups (OH) of cellulose and lignin until saturation (Kollmann and Côté, 1984). This phenomenon is important for the varnish which is cured by polymerization. Subsequently taken or existing moisture level plays a critical role in success of the wood finishing processes (Wheeler, 1983; De Meijer and Militz, 2001; De Meijer, 2002). It is fact that porosity, which is void volume of wood typically, ranges form 55 - 70% depending on its specific gravity and moisture content is one of the significant factors affecting adhesion strength value of bonded samples (Zavarin, 1984). Also wet-ability and capillarity of the surface influence having a good penetration of the coating (Wicks et al., 1999; Allen, 1987; Rijckaert et al., 2001; Ahola et al., 1999). Penetration is a function of species and, its anatomical structure as well as and environmental conditions where process is carried out. For example ratio between latewood and early wood is one of the important parameters affecting penetration of a coating (Kollmann and Côté, 1984).

A plasticizer is an important ingredient of varnishes/ paints and is used in order to give flexibility to the organic coating (Morgans, 1969). If this flexibility is exceeded by moisture, related shrinking and swelling cracks in the coating will be inevitable on protective layers. In order to prevent the organic coating from such cracks, suitable wood moisture content should be provided for the intended final use of the coated product. Thus, the moisture content of the wood material used in furniture production differs in different places, that is for the places heated by stove it should be 8%, for the places heated by central heating system it should be 6 - 7%, for partly closed exterior places it should be 11 - 13%, and for the fully open places is should be 13 - 15% (Sonmez, 2000;

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Engler, 1992). The relation between the moisture content and the type of the finishing process should be taken into account for not having undesired results. Some information from the literature about proper moisture content for the finishing is given in Table 1 (Kurtoglu, 2000).

Adequate adhesion of the varnish layer on the wood surface may not be attained if the moisture content is too high (Sonmez and Budakci, 2004). General mechanism of adhesion between coating and wood surface has been reviewed in various studies. Typical adhesion mechanisms are chemical, mechanical, electrostatic and acid-base adhesion (Rijckaert et al., 2001; De Meijer and Militz, 2000; Jaic and Zivanovic, 1997; Ozdemir and Hiziroglu, 2007; Nelson, 1995; Corcoran, 1972; Mittal, 1995). Adhesion strength of a coating can be determined by using various methods, namely the axial pull-off tests, shear test with torque system, block shear test, and semi-quantitative cut or cross hedge test (Bardage and Bjurman, 1998; Williams et al., 1990). The first two methods are widely used for evaluation of adhesion strength of different types of coatings (Ozdemir and Hiziroglu, 2007).

It is claimed in the literature that, in some cases, the presence of excess moisture in the wood creates layer defects in polyester, polyurethane and some other reaction curing varnishes. It is also stated that, especially in polyurethane varnish applications which is cured by allophone formation, high moisture content inhibits the drying and reacting of varnish (Sonmez, 1989). In another study, some hardness and adhesion tests on the two components polyurethane varnish were carried out on wood with moisture content of 7.3, 10.3 and 13%. Results indicated that the highest hardness and adhesion were achieved with the 10.3% moisture content (Jaic and Zivanovic, 1997).

From these perspectives of views, currently there is no significant information about adhesion strength characteristics samples of Scots pine *(Pinus sylvestris* L.*)*, Eastern beech *(Fagus orientalis* L.*)* and oak *(Quercus petraea* L.*)* with moisture content of 8, 12 and 15% and coated with cellulosic, two-part polyurethane, and water-borne varnishes. Therefore, the axial pull-off test was used to determine the adhesion strength of samples, manufactured from three different species to provide an initial data for possible quality improvement of finished products, manufactured from such species.

EXPERIMENTAL SECTION

Wood materials

Scots pine *(Pinus sylvestris* L.*)*, Eastern beech *(Fagus oriantails* L.*)* and oak *(Quercus petraea* L.*)* were selected as the wooden materials for the research experiments. Two significant factors were taken into consideration when choosing these species. The first was that these species are widely used in the furniture and decoration sectors, where most varnishes are consumed in Turkey.

Table 1. Moisture content for the finishing

Finishing material	Wood moisture content (%)
Oil based paint, synthetic paint-varnish	≤ 16
Chlorinated rubber paint	≤ 14
Cellulosic paint-varnish	≤ 12
Polyester and polyurethane varnishes	≤ 11
Waterborne and dispersion paints	Varies

The second one was that they represent different anatomical structures. The research samples were randomly obtained from timber merchants in Ankara, Turkey. Special emphasis was given to the selection of the wood material (lumber). Accordingly, no-defects, suitable, knotless, normally grown wood materials (without zone lines, without reaction wood and without decay, insect, or fungal infections) were selected, according to the Turkish Standard (TS. 2470, 1976).

Air dried samples were cut to nominal dimensions of 110 x 110 x 12 mm. Then, the samples were kept in the moisture conditioned room until weight gain reach to equilibrium. Three conditioned rooms were selected as follow; 20 ± 2℃ temperature and 42 ± 5% relative humidity with 8% moisture, 20 ± 2℃ temperature and 65 ± 5% relative humidity with 12% moisture, 20 ± 2℃ temperature and 73 ± 5% relative humidity with 15% moisture TS. 2471, (1976). Mean humidity of the samples was determined as 8 ± 0.5, 12 ± 0.5 and 15 ± 0.5% on randomly selected samples respectively. After conditioning, the samples were cut to dimensions of 100 x 100 x 10 mm. Then they were sanded with 80 - 100 grit (on Norton scale) sandpapers. A total of 270 samples were prepared.

Varnishes

In this research, solvent based cellulosic (nitrocellulose), two-part polyurethane (urethane alkyd), and waterborne (self crosslinked polyurethane) varnishes were used. The characteristics of the varnishes are given in Table 2.

In varnish applications, ASTM-D 3023, (1998) specifications were followed, while the suggestions of the manufacturer were also taken into account for hardener and thinner mixture ratios. One filling and two top layers of the varnishes were applied by spray gun. During application and drying, temperature was 20 ± 2℃ and the relative humidity was set to 65 ± 5% (Dewilux, 1996; Boxall et al., 1984).

A filling layer was applied to the samples for the application of cellulosic and two-part polyurethane varnishes. The operation was made parallel and across to the grain and the samples were left to dry for 24 hours (Sonmez, 1989). Following that, they were sanded by 220 and 320 grit sandpapers by using a sanding paper. After cleaning out the dust, the samples were weighed on a ± 0.01 g sensitive analytic scale. Then, the first top layer was applied and left to dry again. Afterwards, the surfaces were sanded smoothly by 400 grit sandpaper prior to second top layer coating. The application of waterborne varnish was carried out just like the two-part polyurethane and cellulosic varnishes. However, first top layer coating was applied as filling layer as well as the top layer.

Adhesion measurement

Varnished and dried samples were conditioned with 23 ± 2℃ temperatures and 50 ± 5% relative humidity for a period of 16 hours according to ASTM D-3924 (1996). Stainless steel experimental cylinders (20 mm in diameter) were attached to the conditioned sur-

Table 2. Characteristics of varnishes used.

Type of Varnish	pH	Density (g /cm3)	Solid Content (%)	Application Viscosity (second / DIN Cup 4mm / 20°C)	Amount of Varnish Applied (g / m2)	Nozzle gap (mm)	Air Pressure (bar*)
Cellulosic Filling	2.9	0.95	31	20	120	1.8	3
Cellulosic Topcoat (gloss)	3.4	0.99	30	20	120	1.8	3
Two-part Polyurethane Filling	5.95	0.98	49	18	120	1.8	2
Two-part Polyurethane Topcoat (gloss)	4.01	0.99	45	18	120	1.8	2
Waterborne Topcoat (gloss)	8.71	1.03	32	18	70	1.3	1

Table 3. Multiple variance analysis results.

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob.
Varnish Type (A)	2	131.747	65.873	131.2611	0.0000*
Wood Type(B)	2	11.397	5.698	11.3547	0.0000*
Interaction (AB)	4	4.111	1.028	2.048	0.0883
Moisture Content (C)	2	9.278	4.639	9.2441	0.0000*
Interaction (AC)	4	2.931	0.733	1.4602	0.2150
Interaction (BC)	4	6.415	1.604	3.1959	0.0139*
Interaction (ABC)	8	12.116	1.515	3.0179	0.0030*
Error	243	121.949	0.502		
Total	269	299.945			

*: significant at 95% confidence level

faces at ambient temperature (20°C) to perform a pull-out test as outlined in the standard. A double component high strength epoxy with no dissolving effect on varnish layers was used 150 ± 10 g/m^2rate as specified in ASTM D-4541 (1995). The adhesion strength of varnish layers was determined with a standard adhesion device (Budakci, 2003).

The adhesion (X) was calculated in terms of MPa using the equation below:

$$X = 4F / \pi . d^2 \quad (1)$$

Where;
F = the rupture force (Newton)
d = the diameter of the experiment cylinder (mm) (ASTM D-4541, 1995).

Statistical evaluation

In the evaluation of data, statistic package software called MSTATC was used. In the analysis, the values of factor effects based on the wood type, varnish type, and moisture content were determined as a result of multiple variance analysis, ANOVA, and in cases where factor effects were significant with $\alpha = 0.05$, error rate according to variance analysis "ANOVA" results, Least Significant Difference (LSD) critical values were used and causing factors were determined.

RESULTS

The results of 'ANOVA' carried out to determine the effects of wood type, varnish type, and moisture content on adhesion are shown in Table 3.

Table 4. Single comparison results for varnish type, wood type, and moisture content.

Factor		$\bar{x}$ (MPa)	HG
Varnish Type	Cellulosic	2.711	C
	Two-part Polyurethane	4.417	A*
	Water Borne	3.459	B
Wood Type	Scots Pine	3.283	C
	Eastern Beech	3.517	B
	Oak	3.786	A
Moisture Content (%)	8	3.766	A
	12	3.507	B
	15	3.313	B
	LSD ± 0.2080		

*: The highest adhesion value. $\bar{x}$: Average value. HG: Homogeneous group.

According to Table 3, the interaction (AB) and interaction (AC) were found statistically not meaningful at 95% confidence level ($\alpha = 0.05$). LSD analysis (Table 4) showed that the highest adhesion was obtained with two-part polyurethane varnish while the lowest was obtained

Table 5. Bilateral comparison results for wood type-moisture content interaction.

Wood Type	Moisture Content (%)					
	8		12		15	
	$\overline{x}$ (MPa)	HG	$\overline{x}$ (MPa)	HG	$\overline{x}$ (MPa)	HG
Scots Pine	3.456	BCD	3.372	CDE	3.022	E
Eastern Beech	3.815	AB	3.64	ABC	3.095	DE
Oak	4.025	A*	3.511	BC	3.823	AB
LSD±0.3603						

*: The highest adhesion value $\overline{x}$: Average value HG: Homogeneous Group.

Table 6. Total comparison results for varnish type-wood type-moisture content interaction.

Wood Type	Moisture Content (%)	Varnish Type					
		Cellulosic		Two-part Polyurethane		Water Borne	
		$\overline{x}$ (MPa)	HG	$\overline{x}$ (MPa)	HG	$\overline{x}$ (MPa)	HG
Scots Pine	8	2.560	IJK	4.436	AB	3.373	CDEFG
	12	2.465	JK	4.456	AB	3.194	DEFGHIJ
	15	2.401	K	3.322	CDEFGH	3.344	CDEFGH
Eastern Beech	8	3.035	EFGHIJK	4.952	A	3.459	CDEFG
	12	2.847	GHIJK	4.819	A	3.255	CDEFGHI
	15	2.653	HIJK	3.669	CDEF	2.962	FGHIJK
Oak	8	3.073	EFGHIJK	5.076	A*	3.927	BCD
	12	2.815	GHIJK	3.946	BC	3.771	BCDE
	15	2.544	IJK	3.801	BCD	3.844	BCD
LSD±0.6241							

*: The highest adhesion value; $\overline{x}$: Average value; HG: Homogeneous Group.

with cellulosic varnish. For the type of the wood, the oak gave the highest while Scots pine gave the lowest adhesion. For the level of the moisture content the highest adhesion was achieved at 8%. The moisture content with 12 and 15% showed the same effect on the adhesion.

For wood type - moisture content interaction, LSD test results (Table 5) showed that the highest adhesion was obtained from oak wood at 8% moisture content while the lowest adhesion was obtained from Scots pine wood at 15% moisture content.

LSD test results for varnish type-wood type and moisture content interaction (Table 6) indicated that the highest adhesion value was found in oak at 8% moisture content with two-part polyurethane varnish and also in the Eastern beech with 8 and 12% moisture content. On the other hand, the lowest adhesion value was found in the Scots pine at 15% moisture with cellulosic varnish.

DISCUSSIONS

During the comparison on varnish type level, the highest adhesion was obtained with two-part polyurethane while the lowest one was obtained with the cellulosic varnish. It is possible to discuss that this highest adhesion two-part polyurethane varnish completes its polymerization reaction on the surface of wood which makes chemical bonding with wood, so it creates a stronger adhesion on surface. Low adhesion strength of the high polymer weight cellulosic varnish, which is completes its formation, is in a good agreement with the literature (Budakci, 2003). It is also informed in the literature that cellulosic based samples, which were left in water for a short period, did not give the results as good as the samples which were processed with polyurethane varnishes. Furthermore, in a long period effect of moisture, cellulosic coatings lost their adhesion more rapidly (Kureli, 1996).

As a result of analyses, it is stated that the adhesion of waterborne varnish is less than that of the two-part polyurethane varnish but more than that of the cellulosic varnish. It is thought that the acid value of the waterborne varnish (pH 8.71) had an effect on this result. According to the acid-base theory, the changes in acidity of the substrate affect the adhesion (Allen, 1987; Nelson, 1995; Corcoran, 1972; Mittal, 1995). Furthermore, in another study, it is stated that the waterborne varnishes are weaker than the organic solvent varnishes regarding the hardness, brightness, adhesion to the surface (Yakin, 2001).

It was also observed that waterborne varnishes caused color change on oak samples. This color change was probably because of the relation between the tannin content ($C_{14}H_{10}O_9$) of the oak and the alkaline water-borne varnish (pH 8.71). It is also stated in the literature that chemical staining can occur on materials when using alkaline solvents (Sonmez, 2000; Budakci and Cinar, 2004).

It is stated that the water, used as a solvent in water-borne varnishes, causes swelling of wood fibers near the wood surfaces and it has a big effect on the Scots pine. Swelling not only destroys the surface smoothness, it also reduces the brightness of the layer. For this reason, it is necessary to pay an extra attention for surface preparations of the wood, especially while applying waterborne varnishes. Surface preparation is very important for wood species that have distinct density differences between earlywood and latewood (Kollmann and Côté, 1984; Ozdemir and Hiziroglu, 2007).

During the adhesion tests, some parts were broken off from Scots pine samples which were processed with two-part polyurethane and waterborne varnishes (Figure 1). This could be occurred with low adhesion of varnish molecules and wood material or the high penetration of varnish molecules because of molecular cohesion of Scots pine (De Meijer, 2002; Rijckaert et al., 2001; Ahola et al., 1999). In experiments, it was seen that the failure occurred in the interface of the wood material and filling coat. Therefore, it is possible to argue that the top layer coating has no effect on the adhesion strength.

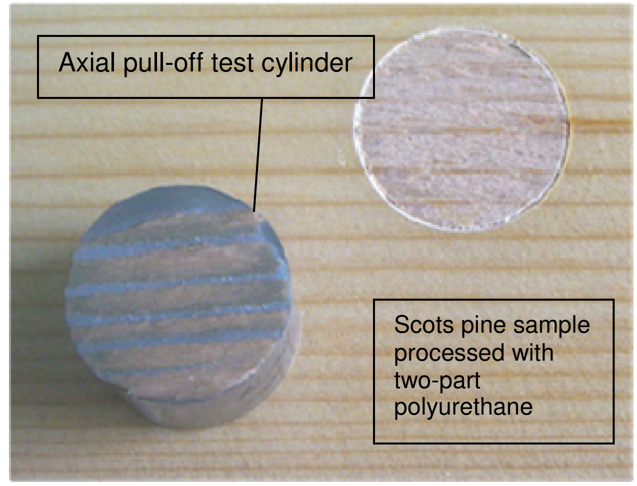

Figure 1. Sample surface after the axial pull-off test.

According to the wood species, the adhesion strengths of Eastern beech and oak are higher than Scots pine. In the literature, it is claimed that the adhesion strength in hardwoods is high but in softwoods it is low (Budakci, 2003). There are a lot of factors that may cause this difference among the species e.g. intensity, cell structure, basic and secondary compounds of wood, texture, extractive substances (Kaygin and Akgun, 2008). Further research is suggested to elucidate the factor(s) that may cause this difference.

In terms of moisture content, the highest adhesion strength was obtained at 8% moisture content, while 12 and 15% moisture contents gave lower adhesion strengths. It can be said that the increasing moisture decreases the chemical and specific adhesion strength (De Meijer and Militz, 2001; De Meijer, 2002; Rijckaert et al., 2001; Ahola et al., 1999; Bardage and Bjurman, 1998). In this sense, varnish layer adhesion gets weaker with the saturating of the OHs on cellulose polymer chain with the water molecules.

Conclusion

Based on the results of this study, it can be pointed out that the moisture content, the type of wood and the type of varnish all have significant effect on the adhesion. In the layers where high adhesion strength is desired, the moisture content of the wood material should not exceed 8%. It can also be suggested that two-part polyurethane varnish must be applied on materials such as Eastern beech and the oak.

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