Determination of the Effect of Surface Roughness on the Bonding Strength of Wooden Materials

Cevdet Söğütlü

The purpose of this study was to determine the effect of surface roughness on bonding strength in Oriental beech, cherry, Scots pine, and Taurus cedar woods. In conformance with this objective, after planing the wooden materials under different conditions, their surface roughness values were determined in accordance with various standards using scanning equipment. The bonding strength test specimens were prepared using polyvinyl acetate (PVAc) and polyurethane (PUR) adhesives after the wooden materials were separated into three groups of varying surface roughness values, after which bonding strength experiments were carried out. The data obtained from the experiments were evaluated statistically at a 95% level of confidence. According to the test results, the highest bonding strength was obtained in the Oriental beech (9.27 N/mm^2), whereas the lowest bonding strength was obtained in the Scots pine (3.65 N/mm^2). There was not a statistically significant difference between the bonding strength of the cherry and Oriental beech woods. The PVAc adhesive (7.61 N/mm^2) produced more successful results than the PUR adhesive (5.63 N/mm^2). Furthermore, it was found that in the specimens with low surface roughness values for each wood type and used adhesives had high bonding strengths.

Keywords: Wood species; Adhesive; Surface roughness; Bonding strength

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INTRODUCTION

Adhesive bonding of wood plays an increasing role in the forest products industry and is a key factor for efficiently utilizing the timber resources. The main use of adhesives can range from wood-based panels, structural composite lumber, doors, windows, laminated wood products, and furniture to picture frames. Such items are commonly used in the building and construction industry as well as in the residential and commercial structures (Özçifçi 2008; Ross 2010).

A number of advantages can be underlined in terms of having qualified joints. An adhesive joint can distribute the applied load over the entire bonded area and with a more uniform distribution of stress, requires little or no damage to the adherends, adds very little weight to the structure, has a superior fatigue resistance to other joining methods, is suitable for joining dissimilar materials, and can reduce manufacturing costs. Achievement of these objectives generally requires careful surface preparation of the adherends (Custodió *et al.* 2009; Ross 2010).

A number of related studies in the literature indicate the significance of surface roughness for bonding strength. Depending on the wood species' anatomical characteristics and tissues, such as tracheids, rays, parenchyma, resin canals, and fibers, together with machining, creates surface irregularities that have an impact on the wood surface roughness (Fujiwara *et al.* 2005). The type of wood, planing, and sanding under different conditions have an effect on the surface roughness and bonding strength (Yang *et al.* 2012). Moreover, high roughness also may cause decreasing bond strength (Kılıç 2016). Murmanis *et al.* (2007) showed, *via* fluorescence microscopy, morphological differences in bonded wood specimens with respect to their surface machining. Knife-planing gave much smoother surfaces as seen at the cellular level than abrasive planing. According to de Moura and Hernández (2007) and Hernández and Cool (2008), cutting depth did not affect the surface quality, however, the feed speed had a significant effect on the surface quality (R_a increased as feed speed increased) and the adhesion strength for the face-milled specimens. Helical planing produced smoother surfaces (R_a: 6.48) and higher pull-off strength (2.03 MPa) than face milling (R_a: 8.75 µm, 1.15 MPa). Furthermore, increasing of feed speed resulted in an increase of cutting power of 30% (Kubs *et al.* 2016).

Other studies have shown that the surface roughness decreases with an increase in spindle speed and feed rate. Milling tests show the important role spindle speed plays on the evolution of the surface roughness as a function of material removal rate (Davim *et al.* 2009). On the other hand, higher cutting speeds corresponded to a lower surface roughness (Kvietková *et al.* 2015). In a study by Yang *et al.* (2012), wood species and sanding had significant influence on the surface machining roughness and adhesion strength. For certain wood species, surface roughness and adhesion strength can be controlled by changing machining methods.

It is, however, not so easy to measure or evaluate the roughness because the surface texture of wood is composed of anatomical roughness as well as the roughness due to processing (Okumura and Fujiwara 2007). The wood surface roughness values obtained using standards developed for homogenous materials have been related to several other properties, such as glueability, varnish adhesion, and weathering characteristics (Stumbo 1963; Peters *et al*. 1970; Richter *et al*. 1995; Taylor *et al*. 1999; Söğütlü *et al*. 2016). Based on the findings of Hiziroğlu *et al.* (2013), it can be concluded that fine stylus-type equipment can be used to quantify the surface quality of specimens from wood species used as a function of sanding with different grit sizes of sandpapers. The effect of decreasing the resolution on roughness parameters was examined as compared with a resolution of 1 µm, which was taken as a reference. The results showed that a measuring resolution of 5 µm seems reliable for all species sanded with common grit sizes (Gurau *et al.* 2013). Furthermore, it has been designated in the determination of the surface roughness that making measurements perpendicular to the fibers, in the direction of the fibers, or at a 45° angle to the fibers, leads to a nonlinear change in surface roughness (Budakci *et al.* 2007; Vitosyte *et al.* 2012)

There are many factors affecting the quality of bonding such as surface roughness, chemical structure of the adhesive, press pressure and duration, and climatic properties of the environment. In addition, there are the difficulties of separating shallow wood failure, as well as adhesion and cohesion failure in the bond line from each other, especially when adhesive and wood have almost the same color. Particularly in such cases, the noted wood failure percentage (WFP) of one and the same sample can vary quite a bit, depending on the person evaluating it (Künniger 2008; Kläusler *et al.* 2014; Hass *et al.* 2014). According to Burdurlu *et al.* (2006), the shear strength values of black pine specimens bonded with PVAc adhesive were higher (8.16 N/mm^2) than those bonded with PUR adhesive (7.95 N/mm^2).

Experimental results and statistical analysis suggest that processing pressure is the most important factor, and penetration is a secondarily important factor in determining adhesion strength. Moreover, determined primarily by adhesive viscosity and surface roughness, contact angle was found to be a major factor in controlling penetration (Cheng and Sun 2006). Good penetration of the adhesive is promoted by excellent wood-to-adhesive-surface interaction and excellent adhesive mobility. In experimental efforts to improve the wood-adhesive interaction and provide a smooth surface with minimal extractives and machining debris, wood is often resurfaced prior to bonding. Nevertheless, penetration of adhesive into wood does not always correlate with bond strength confirmed also for modified wood that lumen (Chandler *et al.* 2005; Bastani *et al.* 2016). By applying existing and newly developed techniques to the study of specific adhesives, a much better knowledge of the factors that lead to durable bonds can be obtained. A high roughness also may cause decreasing bond strength (Murmanis *et al.* 2007; Kılıç 2016). It is important to use analysis techniques in concert and to apply them to samples evaluated by the standard adhesive performance evaluation methods (Frihart 2005).

Cherry, Oriental beech, Scots pine, and Taurus cedar are important economic species in Turkey. Although these species are widely used in applications, there is limited available information to guide producers on the best practices to obtain optimal performance in terms of bonding strength. Therefore, it is important to examine the relationship between the processing parameters and wood adhesive performance in these species. The goal of this study was to evaluate the effect of wood surface roughness on bonding strength.

EXPERIMENTAL

Materials

Samples of cherry (*Prunus cerasus* L.), Oriental beech (*Fagus orientalis* Lipsky), Scots pine (*Pinus sylvestris* L.), and Taurus cedar (*Cedrus libani* A. Rich.) were obtained from Turkey for this study. Average air-dried densities with standard deviation, given in parenthesis were 0.59 (0.02) g/cm^3 for cherry, 0.65 (0.03) g/cm^3 for Oriental beech, 0.52 (0.01) g/cm^3 for Scots pine, and 0.51 (0.01) g/cm^3 for Taurus cedar. Test specimens were selected according to the TS 2470 (1976) standard, and criteria such as natural color uniformity, smoothness of fibers, absence of knots, heart uniformity, absence of reaction wood, and absence of fungal and insect damage were used to identify specimens for further processing. Two commercial adhesives, *i.e.*, polyvinyl acetate (PVAc) and polyurethane (PUR), were used. PVAc is produced by Kleiberit Company with code 303 which is single component and specific gravity is 1.10 g/cm^3 at the 20 °C. PUR is produced by Kleiberit Company with code 501 which is single component and specific gravity is 1.13 g/cm^3 at the 20 °C.

Methods

Sample preparation

Preparation of the samples was carried out in accordance with the standard ASTM-D 1666-87 (1999). A total of 240 samples were prepared with dimensions of 5 mm x 55 mm x 650 mm. From the 240 samples, 10 replicates were prepared for wood species (4), adhesive type (2), and surface roughness (3) tests. The prepared samples were stored in a well-ventilated area with no direct exposure to sunlight. The average temperature in the storage area was 20±2 °C, and the relative humidity was 65±5%. The specimens were stored under these conditions until they reached a constant weight. The average moisture content (MC) was determined to be 12 ± 0.5% in the 10 pre-control specimens, according to TS 2471 (2005).

Planing

The samples were planed at feed rates of 6, 9, and 12 m/min in the radial direction of their annual rings. The planing procedure was carried out by means of a horizontal milling machine by the head of 4 replaceable blades cutter with a diameter of 85 mm. In this process, the rotation speed was 7200 rpm, the cutting speed was 32 m/s, and feed per knife was 0.035 mm.

The cutting speed (v) was calculated from Eq. 1, and the feed per knife (u_t) was calculated from Eq 2.

$$v = \frac{\pi \cdot D \cdot n}{1000 \cdot 60} m/s \quad (1) \qquad u_t = \frac{1000}{n \cdot z} mm \quad (2)$$

where D is the diameter of cutter head (mm), n is the rotations per minute of cutter (rpm), z is the number of blades.

Measurement of surface roughness

Surface roughness was determined according to ISO 4287 (1997) and TS 2495 EN ISO 3274 (2005) standard procedures using a stylus-type profilometer (TIME TR-200, Time High Tech Ltd., China) with TIMESurf software. This equipment had a 10-mm/min measuring speed, a 5-μm pin radius, and a 90° probe angle. After adjusting the equipment to a 12.5 mm sampling length (5 cut-off length x 2.5 mm tracing length), the measurements were made on the samples in a direction perpendicular to the grain. Three parameters are commonly used in the evaluation of the surface roughness. These are the arithmetical mean deviation of profile (R_a), ten-point height of irregularities (R_z) and the maximum height of profile (R_y) (Hiziroglu *et al.* 2013; Thoma *et al.* 2015). The surface roughness values of the specimens were grouped according to the feeding speed for planing. These were evaluated as the first group for the 6 m/min feeding speed, the second group for the 9 m/min feeding speed, and as the third group for the 12 m/min feeding speed.

Bonding

In the gluing process, the adhesive solution was spread with a brush to create a 160 to 180 g/m^2 layer for one of the surfaces, in compliance with the suggestions of the manufacturing company (Kleiberit 2016). The pressing pressure was 0.9 N/mm^2, the pressing period 24 h, and the pressing temperature was 20 ± 2 °C in the bonding procedure. The TS EN 204 (2004) standard was complied with for the samples properties and the bonding strength tests (Fig. 1).

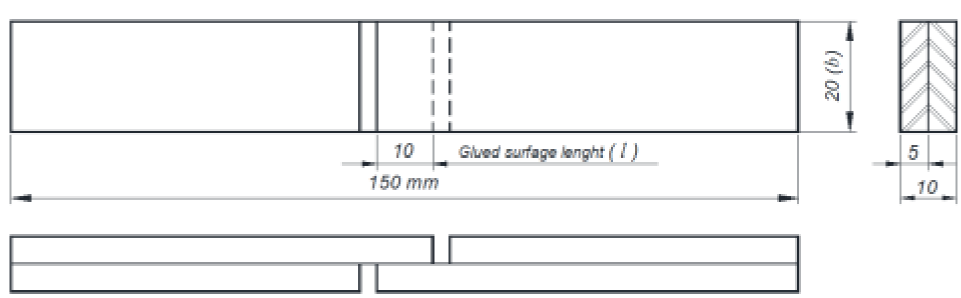

Fig. 1. Dimensions of tensile share specimen (mm)

Determination of tensile shear strength

The tensile shear strength was determined using the TS EN 205 (2004) standard. Experiments were processed with 50 mm/min loading speed by applying a static tensile load (Fig. 2).

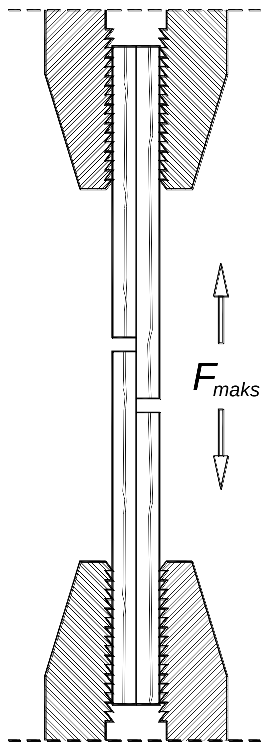

Fig. 2. Principle of tensile shear experiment

The goal of the tensile test was to break the specimen from the glue line with the balanced and gradated withdrawal force implemented. The bonding strength (σ) was calculated from Eq. 3 by determining the maximum force (F_{max}, N) at the moment of breaking,

$$\sigma = \frac{F_{max}}{l \cdot b} = \frac{F_{max}}{A} N / mm^2 \qquad (3)$$

where l is the glued surface length (mm), b is the glued surface length (mm), and A is the test surface area (mm^2)

Statistical analysis

To determine the effects of the wood type, adhesive type, and surface roughness on adhesion strength, multiple analyses of variance (MANOVA) were conducted using the MSTAT-C, a computer-based statistical package, developed by Michigan State University (USA). When the differences emerged as statistically significant according to $P<0.05$, the importance was determined amongst groups with the Duncan test. Thus, data sets were separated into homogeneity groups according to the least significant difference (LSD) critical values. Regression analyses were used to determine a relation between the surface roughness and bonding strength.

RESULTS AND DISCUSSION

The surface roughness values of the specimens were grouped according to the feeding speed for planing. These were evaluated as the first group for the 6 m/min feeding speed, the second group for the 9 m/min feeding speed, and as the third group for the 12 m/min feeding speed (Table 1).

Table 1. Classification of Surface Roughness Values

Classification		Wood type-Surface Roughness (µm)											
		Cherry			Oriental beech			Scots pine			Taurus cedar		
		Min	*Max*	$\bar{X}$	*Min*	*Max*	$\bar{X}$	*Min*	*Max*	$\bar{X}$	*Min*	*Max*	$\bar{X}$
1st Group	R_a	2.93	3.08	3.00	4.85	5.10	4.95	3.96	4.57	4.27	3.81	4.03	3.92
	R_z	19.82	21.09	20.94	29.74	31.93	30.66	21.69	23.86	22.70	21.09	23.70	22.09
	R_y	23.92	27.88	25.92	37.26	39.66	38.47	30.46	32.89	31.52	26.64	30.13	27.15
2nd Group	R_a	3.69	3.88	3.78	5.15	5.46	5.28	4.14	4.59	4.38	4.08	4.35	4.22
	R_z	22.54	24.29	23.51	30.19	31.78	31.17	23.03	25.17	24.20	22.59	25.16	23.97
	R_y	29.02	31.33	30.16	38.69	39.67	39.26	31.61	33.91	32.76	27.94	31.57	30.31
3rd Group	R_a	3.92	4.17	4.03	5.32	5.72	5.54	4.29	4.74	4.54	4.31	4.58	4.42
	R_z	22.23	25.44	24.04	31.39	33.13	32.39	24.64	26.93	25.66	23.49	26.20	24.28
	R_y	27.98	32.59	30.42	39.38	42.63	41.02	32.12	35.70	34.37	29.12	32.97	30.39

Table 1 shows that the surface roughness values of the 1st group are lower than 2nd and 3rd groups. In other words, surface roughness increased as feeding speed increased. In the planing process, the increase of surface roughness with increasing feed speed has been previously reported (de Moura and Hernández. 2007; Budakçı *et al.* 2007; Hernández and Cool 2008; Kubš *et al*. 2016).

The bonding strength results for wood type, adhesive type, and surface roughness are given in Table 2.

Table 2. Bonding Strength Results

Wood type / Adhesive type		Surface Group-Bonding Strength (N/mm²)								
		1st Group			2nd Group			3rd Group		
		Min	*Max*	$\bar{X}$	*Min*	*Max*	$\bar{X}$	*Min*	*Max*	$\bar{X}$
Cherry	PVAc	9.59	11.90	10.86	9.19	10.93	10.19	8.34	10.22	9.47
	PUR	8.96	10.96	10.13	7.17	9.63	7.82	5.40	7.94	6.49
Oriental beech	PVAc	11.47	13.22	12.42	10.86	12.20	11.68	8.77	11.52	10.37
	PUR	7.15	8.16	7.74	6.47	8.01	7.27	5.48	7.91	6.11
Scots pine	PVAc	3.71	4.64	4.19	3.28	4.36	3.85	3.37	3.90	3.61
	PUR	3.05	3.99	3.59	2.92	3.99	3.41	2.64	3.75	3.23
Taurus cedar	PVAc	5.00	6.66	5.80	3.63	5.06	4.48	3.63	5.47	4.25
	PUR	3.68	4.62	4.27	3.13	4.67	3.87	2.85	4.07	3.59

Table 2 shows that the adhesion values of each wood type, glue type, and surface group are different. The analysis of variance results were used to determine if wood type, adhesive type, or surface roughness had an effect on adhesion strength (Table 3).

Table 3. Analysis of Variance

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	Probability
Wood Type (A)	3	1638.239	546.080	1861.667	0.0000*
Adhesive Type (B)	1	232.746	232.746	793.465	0.0000*
Interaction (AxB)	3	141.511	47.170	160.811	0.0000*
Surface Roughness (C)	2	88.312	44.156	150.535	0.0000*
Interaction (AxC)	6	26.496	4.416	15.055	0.0000*
Interaction (BxC)	2	0.350	0.175	0.596	NS**
Interaction (AxBxC)	6	16.605	2.768	9.435	0.0000*
Error	216	63.359	0.293		
Total	239	2207.617			

*: Significant at 95% confidence level, **: No significance at 95% confidence level

The wood type, adhesive type, and surface roughness factored into the bonding strength values and the reciprocal interactions of these factors (excluding the AxB interaction) were found to be statistically significant at a 95% level of confidence.

The Duncan test comparison results at the level of wood type, adhesive type, and surface roughness are given in Table 4.

Table 4. Comparison Results of the Duncan Tests for the Wood Type, Adhesive Type, and Surface Roughness

Bonding Strength Average ($\bar{X}$) and Standard Deviation (*s*) Values (N/mm^2)								
Wood type				Adhesive Type		Surface roughness		
Cherry	O. Beech	Scots pine	T. Cedar	PVAc	PUR	1st Group	2nd Group	3rd Group
9.16^{A} ±1.24	9.27^{A} ±0.98	3.65^{C} ±0.38	4.38^{B} ±0.68	7.61^{A} ±0.80	5.63^{B} ±0.83	7.38^{A} ±0.69	6.57^{B} ±0.53	5.89^{C} ±0.46
LSD value: ±0.195				LSD value: ±0.138		LSD value: ±0.169		

Note: Number followed by the same letter indicates no statistical significant differences (Least Significant-Difference Test with 0.95 confidence).

The highest bonding strength was obtained in the Oriental beech wood (9.27 N/mm^2) followed by cherry (9.16 N/mm^2), Taurus cedar (4.38 N/mm^2), and Scots pine (3.65 N/mm^2). The difference between the Oriental beech and cherry was statistically insignificant. The PVAc adhesive (7.61 N/mm^2) provided a higher bonding strength than the PUR adhesive (5.63 N/mm^2). The first group displayed the highest bonding strength (7.38 N/mm^2) from the aspect of surface roughness; this was followed by the second group (6.57 N/mm^2), and finally the third group (5.89 N/mm^2). Similar results were determined in the study of Burdurlu *et al.* 2006. The PVAc adhesive produces higher shear strength values compared with the PU adhesive. PVAc penetrates deeper and makes a better bond formation compared with PU and the fact that its capability of penetration is higher and that it produces a more flexible bond could be influential in the increase of shear strength.

The Duncan test comparison results at the level of wood type-adhesive type are given in Table 5.

Table 5. Comparison Results of the Duncan Tests for Interaction of Wood Type–Adhesive Type

Bonding Strength Average ($\bar{X}$) and Standard Deviation (*s*) Values (N/mm²)								
Adhesive type	**Wood type**							
	Cherry		**Oriental beech**		**Scots pine**		**Taurus cedar**	
	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*
PVAc	10.17^{B}	1.02	11.49^{A}	0.89	3.89^{F}	0.59	4.84^{E}	0.74
PUR	8.15^{C}	1.04	7.04^{D}	0.91	3.41^{G}	0.61	3.91^{F}	0.77
LSD value: ±0.275								

Note: Number followed by the same letter indicates no statistical significant differences (least-significant-difference test with 0.95 confidence).

The highest bonding strength was obtained in Oriental beech wood bonded with the PVAc adhesive (11.49 N/mm^2), whereas the lowest bonding strength was obtained in the Scots pine wood bonded with the PUR adhesive (3.41 N/mm^2). The difference between the bonding strength of Scots pine bonded with the PVAc adhesive (3.89 N/mm^2) and the Taurus cedar wood bonded with PUR (3.91 N/mm^2) was found to be statistically insignificant (LSD ±0.275).

The fact that the density of Oriental beech wood was high could be effective in obtaining a high bonding strength in Oriental beech wood compared with cherry wood. It was reported in previous studies that the wooden material whose density was high also had a high bonding strength (Söğütlü *et al.* 2016; Burdurlu *et al.* 2006; Kılıç 2016).

The Duncan test comparison results of the wood type-surface roughness group interaction are given in Table 6.

Table 6. Comparison Results of the Duncan Tests for Interaction of Wood Type–Surface Roughness

Bonding Strength Average ($\bar{X}$) and Standard Deviation (*s*) Values (N/mm²)								
Surface roughness	**Wood type**							
	Cherry		**Oriental beech**		**Scots pine**		**Taurus cedar**	
	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*
1st Group	10.49^{A}	0.97	10.08^{B}	0.84	3.89^{GH}	0.54	5.04^{F}	0.69
2nd Group	9.01^{D}	0.89	9.47^{C}	0.76	3.63^{HI}	0.46	4.17^{G}	0.61
3rd Group	7.98^{E}	0.87	8.24^{E}	0.72	3.42^{I}	0.43	3.92^{GH}	0.57
LSD value: ±0.337								

Note: Number followed by the same letter indicates no statistical significant differences (least-significant-difference test with 0.95 confidence).

From the aspect of the wood type-surface roughness group interaction, the highest bonding strength was obtained in the first group surface roughness in cherry wood (10.49 N/mm^2), whereas, the lowest bonding strength was obtained in the third group surface roughness in Scots pine wood (3.42 N/mm^2). The difference between the surface roughness of cherry wood (7.98 N/mm^2) in the third group and the surface roughness of Taurus cedar (5.04 N/mm^2) in the first group, as well as the difference between the surface roughness of Scots pine (3.89 N/mm^2) in the first group with the surface roughness of Taurus cedar (3.92 N/mm^2) in the first group, were found to be insignificant (LSD ±0.337).

The Duncan test comparison results of the wood type-adhesive and type-surface roughness group interaction are given in Table 7.

Table 7. Comparison Results of the Duncan Tests for Interaction of Wood Type–Adhesive Type–Surface Roughness

Bonding Strength Average ($\bar{X}$) and Standard Deviation (s) Values (N/mm²)									
Adhesive type	**Surface roughness**	**Wood type**							
		Cherry		**Oriental beech**		**Scots pine**		**Taurus cedar**	
		$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*
PVAc	1st Group	10.86^{C}	0.91	12.42^{A}	0.82	4.19^{JK}	0.62	5.80^{I}	0.72
	2nd Group	10.19^{D}	0.86	11.68^{B}	0.77	3.85^{KL}	0.57	4.48^{J}	0.67
	3rd Group	9.47^{E}	0.83	10.37^{D}	0.75	3.61^{LM}	0.55	4.25^{JK}	0.65
PUR	1st Group	10.13^{D}	0.92	7.74^{FG}	0.83	3.59^{LM}	0.63	4.27^{JK}	0.73
	2nd Group	7.82^{F}	0.87	7.27^{G}	0.78	3.41^{LM}	0.58	3.87^{KL}	0.68
	3rd Group	6.49^{H}	0.84	6.11^{HI}	0.75	3.23^{M}	0.56	3.59^{LM}	0.66
LSD value: ±0.477									

Note: Number followed by the same letter indicates no statistical significant differences (least significant-difference test with 0.95 confidence).

The highest bonding strength was obtained in the Oriental beech wood (12.42 N/mm^2) in the first surface roughness group glued with the PVAc adhesive, whereas the lowest bonding strength was obtained in the Scots pine wood (3.23 N/mm^2) in the third surface roughness group glued with the PUR adhesive. The results in Table 7 showed that the wood type-adhesive and type-surface roughness interaction for cherry, oriental beech, Scots pine, and Taurus cedar woods whose surface roughness was low and were glued with PVAc adhesive had a high bonding strength. The effect of the surface roughness factor determined in previous studies was also observed in this study (Cheng and Sun 2006). The fact that the PVAc adhesives had high values of bonding strength compared to the PUR adhesives showed a resemblance to the results of similar studies (Özçifçi and Yapıcı 2008; Altun *et al.* 2010).

The wood failure percentage values of the specimens are shown in Figs. 3 to 4.

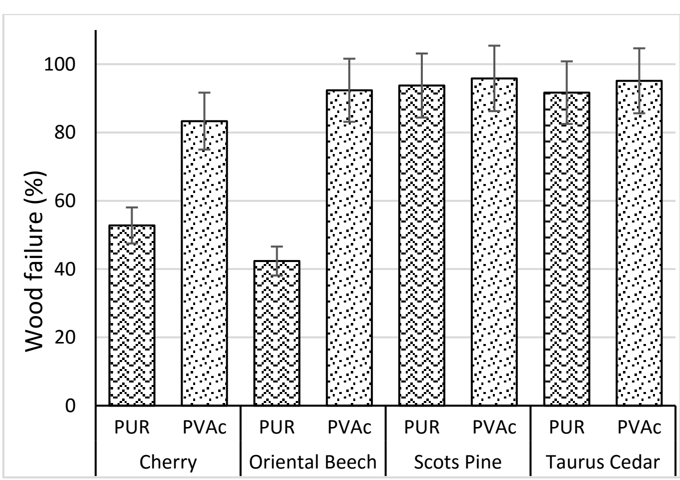

Fig. 3. Wood failure percentage of the specimens

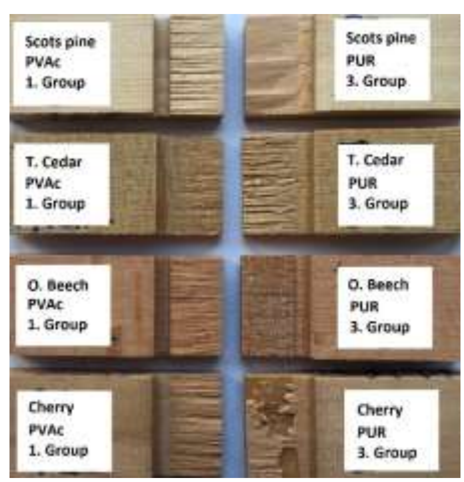

Fig. 4. Wood failure

According to the Fig. 2, PVAc adhesive display higher wood failure percentage PUR adhesive. Although PUR glue has been reported to have a higher penetration, PVAc glue seems to be more successful under the in terms of the flexibility structure of the glue. As Zheng *et al.* (2004) and Bastani *et al.* (2016) have reported; difficulties arise in establishing direct relationships between adhesive penetration and bond performance.

The regression analysis proposed a predictive relationship between bonding strength and surface roughness and is shown in Fig. 5.

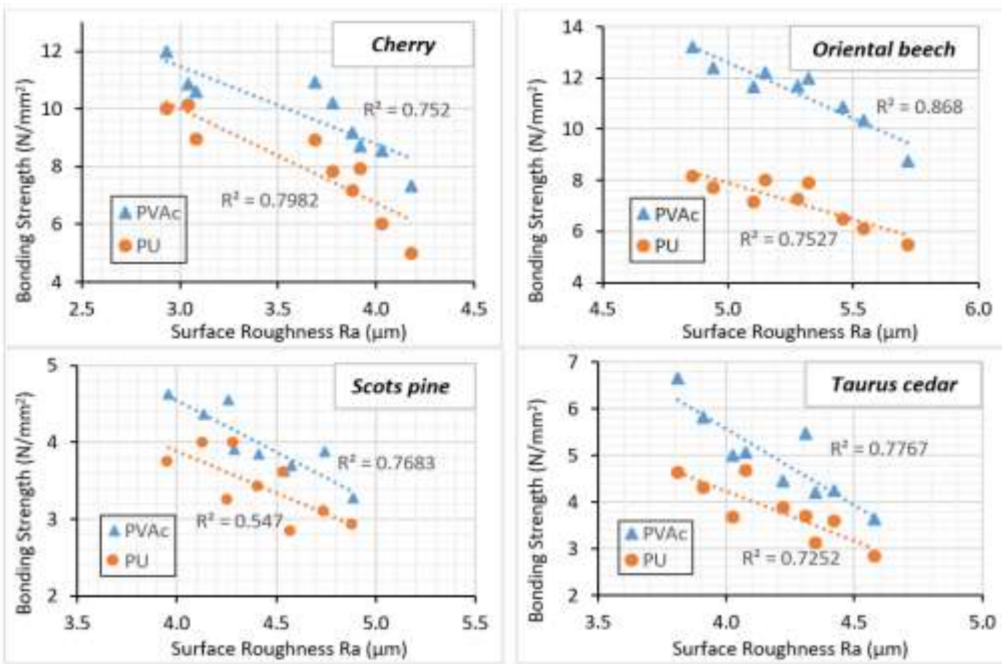

Fig. 5. Relationship between bonding strength and surface roughness

Within this scope, the effect of the surface roughness on bonding strength was observed. In other words, as the surface roughness increased, the bonding strength decreased. Results were found in the literature that shows that surface roughness affects bonding strength. This study showed results similar to the literature (Burdurlu *et al.* 2006; Yang *et al.* 2012; Knorz *et al.* 2015; Kılıç 2016).

CONCLUSIONS

1. This study showed that the wood type, adhesive type, surface roughness, and the reciprocal interactions of these (excluding the AxB interaction) were effective relative to bonding strength. When cherry and Oriental beech, which are in the hardwood group, and Scots pine and Taurus cedar, which are in the softwood group, were compared, more successful results were obtained with the wood types in the hardwood group. Consequently, it can be stated that in situations where bonding strength and carrying capacity are important, it would be more appropriate to use hardwoods.
2. From the aspect of surface roughness, it was understood within the scope of this study that every wood type having low values of roughness produced a higher bonding strength. Thus, it is important to keep the roughness values as low as possible in the wooden surfaces that would be bonded.

3. In the use of adhesives, the PVAc adhesive produced more successful results. It can be stated that the use of the PVAc adhesive would be more appropriate in interior spaces and dry surroundings and in wooden constructions where it is desired for the bonding strength to be high.
4. There were different procedures applied in the process of shaping a great number of wood types, adhesive types, and wooden materials in industry. It was thought that it would be beneficial to make studies that aim to obtain suitable combinations within this diversity, and that would test wooden materials processed under different conditions from different wood types and with adhesives manufactured with different contents.

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