Effect on Shear Strength of Machining Methods in *Pinus nigra* Arnold Bonded with Polyurethane and Polyvinyl Acetate Adhesives

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Specimens taken from *Pinus nigra* Arnold were subject to surfacing techniques by being cut with a circular saw, planed with a thickness machine, and sanded with a calibrating sanding machine (with P80 grit sandpaper). First, their surface roughness values were measured; then, the specimens were processed in the machines in a radial and tangential process. Afterwards, the change in shear strength (adhesiveness resistance) was analyzed as a result of bonding with various adhesive types (PVAc, PU) and pressure applications (0.45 N/mm² or 0.9 N/mm²). Approximately 600 specimens were prepared with the purpose of identifying the effect of variables on the bonding performance, and they were subjected to shear testing. The greatest shear strength achieved for both the tangential and radial surfaces in terms of cutting was observed in specimens processed in the thickness machine, on which polyvinyl acetate adhesive and 0.9 N/mm². pressure were applied. Specimens bonded with polyvinyl acetate adhesive displayed higher shear strength in general in comparison to those bonded with polyurethane for both tangential and radial surfaces.

Keywords: Shear strength; Surface roughness; Wood machining; Pinus nigra Arnold; Adhesives

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INTRODUCTION

The demand for trees that have technologically higher qualities has gradually been increasing. Meeting this demand is solely possible by cutting trees in the most productive manner. In turn, this is only possible by being knowledgeable about the physical and mechanical properties of the wood of various tree species, identifying their usage areas, and thus allowing them to be used rationally. In the Forestry Research Master Plan of Turkey it is stated that the wood properties of primary species whose origin is known (mechanical, physical, and chemical) should be identified to form a connection with their habitat. In Turkey, there is a total of 4,693,060 hectares (Normal: 2,580,193 hectares + Disorderly: 2,112,867 hectares) of *Pinus nigra* Arnold forests (GFD, 2012). *Pinus nigra* is one of Turkey's primary trees species. Therefore, the study of its primary wood characteristics has a high priority according to the Master Plan.

Adhesives, which are the main inputs of the woodwork industry, have a secondary importance after wood material in this industry area. They are used in the production of laminated material, plywood, particleboard, and MDF, and they are also used as adhesives in bonding applied to these products and solid wood materials. Shear strength in bonding with adhesives generally depends on the type of wood material and adhesive, the dampness of and cell structure of the wood, press pressure, in which machine the wood is processed prior to bonding, and characteristics of the adhesive. The last machine the wood material is processed in (surface roughness) both affects surfacing processes and bonding strength (Hiziroglu *et al*. 2013, 2014).

The success of surface layer applications carried out with the purposes of preserving and beautifying furniture as an end product and increasing their economic value (casking, painting, varnishing, *etc*.) depends on the smoothness of the surface of wood material (Richter *et al.* 1995). In addition, the smoothness of the material's surface can affect the general performance of the product in bonding the wood with adhesives (Burdurlu *et al.* 2005; Tiryaki *et al.* 2015). Because roughness is quite important in wood material, numerous studies have been carried out. Those that are closely related to this issue are presented below.

Studies on surface roughness of wood material have been initiated after the metal industry. These studies have been conducted by Marian and Suchsland (1956) in the USA, Kollman and Ehlers (1958) in Germany, and Patlitszch (1961) in Poland; adhesives have also been studied (Elmendorf and Vaughan 1958).

The surface roughness of *Abies nordmanniana* fir wood has been determined with the stylus method. The tangential section in comparison to radial section has provided smoother surfaces (Ilter *et al.* 2002).

The surface roughness of eucalyptus has also been studied. The smoothest surfaces were found to result from a 12% rate of moisture content, cut in a tangential technique, subject to a thickness machine with three blades operating at a 5-m/min feed speed, whereas the roughest surfaces were those with 30% rate of moisture content, radially cut, and subject to sand paper #60 (Ilter and Balkiz 2005).

The surface roughness parameters of radial and tangential cut materials obtained from beech and poplar wood after processing with circular saws and sanding machines were analyzed. To assess the roughness variations in radial and tangential surfaces after planing and sanding processes, the stylus method can be used successfully, and the data can be used as a control tool for bonding and surfacing processes (Kılıç *et al.* 2006).

Surface quality and gluing performance of black spruce samples prepared by peripheral straight-edge knife planing and sanding were studied. In general, sanding process produced better wood surfaces for bonding with the adhesive studied (Kuljich *et al.* 2013).

Oblique cutting, peripheral planing, face milling, and sanding were used to surface black spruce wood prior to gluing with a two-component poly(vinyl acetate) adhesive (Cool and Hernandez 2011a). Surface roughness, anatomical features of surfaces, and glueline interfaces as well as the glueline shear strength before and after aging were evaluated. Regarding the glueline shear strength before and after weathering, no significant differences occurred among the surfacing treatments. The microscopic and topographic differences among the surfacing treatments were not sufficient to generate significant differences in glueline shear strength. Peripheral planing and face milling should be better alternatives with respect to productivity.

The sanding of black spruce wood prior to coating application was optimized for feed speed and grit size. A two-stage sanding program combined with a feed speed of 17 m/min resulted in good surface quality and pull-off strength (Cool and Hernandez 2011b).

Kläusler *et al.* (2014) determined the influence of mechanical surfacing on tensile shear strength (TSS) and wood failure percentage (WFP) of beech wood (*Fagus sylvatica* L.) at the wet stage according to prEN 302-1:2011 (tensile shear tests). Planing with very dull knives caused the lowest TSS and WFP after A4 and the most subsurface damage.

Face milled and sanded batches revealed the best performance. The TSS and WFP decreased significantly from A1 to A4, but recovered after mA5.

Helical planing and face milling were applied across the grain to surface paper birch wood prior to coating application (Hernandez and Cool 2008). Three feed speeds and three cutting depths were evaluated for face milling while three cutting depths were studied for helical planing. The roughness and wetting properties of wood as well as pull-off strength of a solvent-borne coating after aging were evaluated. Helical planing produced smoother surfaces with equivalent wetting properties and higher pull-off strength than face milling. Scanning electron microscopy showed more exposed cell lumina and sound cells for helical planed surfaces, which enhanced their wetting and adhesion performance.

The changes in shear strength of *Pinus brutia* Ten. wood material with different roughness values as a result of cutting, planing, and sanding surface processing techniques with a circular saw were analyzed. The tests also involved evaluation of bonding with different adhesive types and different pressure applications in the radial and tangential cutting directions. According to the results of the experiment, the greatest shear strength (11.8 N/mm²) in terms of cut surfaces in the tangential surface was achieved after the sanding process, by applying polyvinyl acetate adhesive and 0.9 N/mm² of pressing pressure. As was the case for tangential surfaces, specimens bonded with polyvinyl acetate had higher shear strength in comparison with those bonded with polyurethane in radial surfaces (Burdurlu *et al.* 2006).

Also studied was how steaming beech and sapele wood affects the bonding strength of certain varnish types. The surface roughness of tangential and radial surfaces of steamed and non-steamed specimens of beech and sapele wood was measured. Afterwards, these surfaces cellulosic, polyurethane, and water-based shiny varnishes were applied and the bonding strength of varnish layers was analyzed. As a result, in places that require high bonding strength, it was suggested to use beech wood material with radial surfaces; and because steaming increases roughness, it was suggested to sand the material once again and apply polyurethane varnish (Kılıç 2009). Another study was aimed at determining the surface roughness and surface brightness properties of Scots pine (*Pinus sylvestris* L.) wood samples to which water-based varnishes were applied after thermo-mechanical densification and heat treatment. According to results of the research, surface roughness decreased and surface brightness increased in densified samples (Pelit *et al.* 2015).

In this study, cutting with a circular saw, planing with a thickness, and sanding with a sanding machine, which are the most widely used cutting techniques in wood product production, primarily furniture, were performed. This study was aimed at determining the changes in shear strength of wood material achieved from *Pinus nigra* with different roughness values and processed with these machines, as a result of being bonded with two different types of adhesives (PVAc, PU) and two different pressures (0.45 N/mm² or 0.9 N/mm²) in two different cutting directions.

EXPERIMENTAL

Wood Materials

Experimental materials were taken from the Çamkoru Dr. Fuat Adalı Research Forest affiliated with the Central Anatolia Forestry Research Institute Directory after being cut. *Pinus nigra* Arnold trees were cut and obtained from section number 6, with an altitude of 1500 to 1550 m, in accordance with ISO 4471 (1982). A total of five trees were cut.

After the trees were cut, the branches on the trunks were cleaned, and branches were taken starting from 0.30 m in height from the ground and their height and diameter at 1.30 m were measured (Table 1).

Table 1. Properties of Experimental Trees

Black Pine				
Tree Number	Length (m)	Diameter at 1.30 m (cm)	Air dried density (g/cm^3)	Age (years)
1	24	31	0.46	120
2	30	32	0.48	130
3	23	29	0.45	115
4	22	28	0.44	115
5	22	26	0.42	110
Average air-dried density (g/cm^3) = 0.45				

The trees were cut to dimensions of 60 x 500 mm and placed in an environmental test chamber until an air-dried moisture content of 12% was reached.

Adhesives

To determine the effect of surface roughness values of surfaces processed with different machines on the bonding performance of adhesives, PVAc- and PU-based adhesives were used. These adhesives are the most widely used adhesive types in the wood working industry. The adhesives were applied in as-received form to the surfaces, and the recommendations of the producing companies were followed in the application. Both adhesives were applied at 200 g/m^2.

Equipment

The following tree processing machines were used in the processing of *Pinus nigra* wood and preparation of bonding surfaces:

1- Band saw machine
2- Thickness machine
3- Planing machine
4- Calibrating sanding machine
5- Circular saw machine
6- Surface roughness measurement device
7- Drying oven and environmental test chamber
8- Laboratory press
9- Universal test device

To achieve different roughness values on the specimen surfaces, planing was done with the thickness machine (4500 rpm), cutting with the circular saw machine (6000 rpm), and calibrating sanding with the sanding machine (with #P80 grit sanding paper at 1400 rpm). During the processing, the feed speed was fixed at 10 m/min. For pressing the specimens according to their cutting directions, a hydraulic laboratory press with table dimensions of 550 x 550 mm, whose temperature and pressure can be adjusted, was employed. To measure surface roughness values, a Mitutoyo Surfest- SJ 301 series tester, which uses the stylus method, was employed; a 4-ton universal testing device was used in the identification of shear strength.

Specimen Preparation

The cutting direction, surface processing type, adhesive type, and pressing pressure in the preparation of the specimens were the basic variables. To determine the effect of two cutting directions, *i.e.*, tangential and radial; three different surface processing types, *i.e.*, cutting, planning, and sanding; two different adhesive types, *i.e.*, polyurethane (PU) and polyvinyl acetate (PVAc); and two different types of pressure, *i.e.*, 0.45 N/mm² and 0.9 N/mm² on shear strength with a repetition of 25 tests, a total of 600 specimens (2 x 3 x 2 x 2 x 25 = 600) were prepared.

Because of the effect of moisture content on roughness, specimens kept in natural environments after drying were placed in a conditioning chamber with a temperature of 20 ± 2 °C and a suitable relative humidity until they reached a fixed weight (until the air dryness reached the target moisture content (12%)). After this stage, to prevent moisture content loss, the specimens were insulated and the surface processes were suspended.

To determine the effect of different surface roughness values that emerged from the different surface processing techniques on bonding, the specimens were subjected to cutting with a 40-tooth circular saw, planing with a thickness machine with three blades, and sanding with #P80 grit sand paper by taking the tangential and radial cutting directions and specimen thickness into consideration within the suitable processes. The process type was indicated with symbols in the front and back parts of wood samples. According to the surface processing types, the roughness measurements were carried out in a perpendicular direction and ± 0.01 μm sensitivity to the fibers (measurement speed of 0.5 m/s, using a diamond tip stylus with a border wave length (lc) of 4 mm and measurement length (lt) of 21 mm, tip angle of 90°, and tip radius of 2 μm) in accordance with ISO 4288 (1996), and the resulting values were recorded (Kılıç 2015).

Specimens whose roughnesses were measured were matched as pairs in line with the tangential-tangential and radial-radial surfaces by taking the different surface process techniques into consideration (Fig. 1). In line with the suggestion of the producer company, PVAc and PU adhesives were separately applied on the surfaces at 200 g/m^2. The pieces were then pressed and specimen blocks were achieved by being pressed for 60 min with a pressure of either 0.45 or 0.9 N/mm² (Fig. 2). During pressing, the recommendations of the producer company were followed; the pressing temperature was 50 °C for specimens with PVAc and 60 °C for specimens with PU.

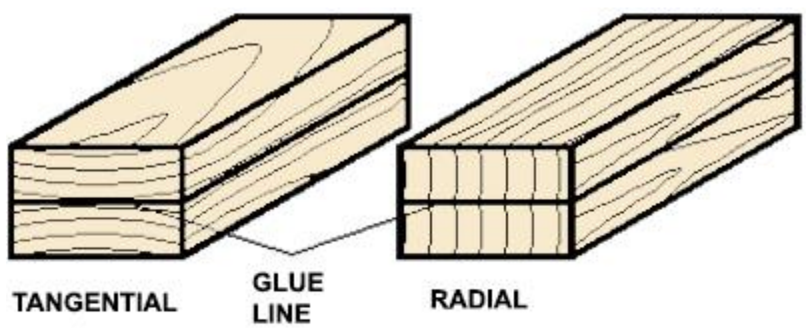

Fig. 1. Bonding of the specimens by being matched with their tangential-tangential and radial-radial surfaces

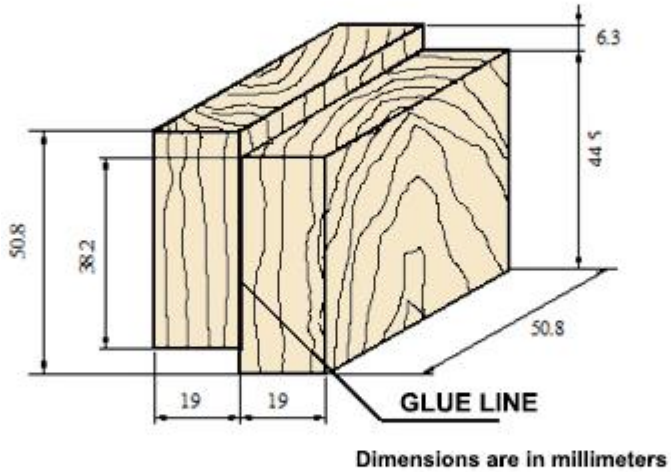

Fig. 2. Shear test specimens

The pressed specimen blocks were sized 50 x 51 mm at least 48 h later, placed in the test device, and laps were formed at the edges in line with ASTM D905 (2008) to form test specimens (Fig. 2). The prepared specimens were then placed in an environmental test chamber with a temperature of 20 ± 2 °C and relative moisture content of 65% ± 3 to homogenize them and bring air dryness to moisture content value and left there until their weight reached a fixed state (12% moisture content value). After this point, the specimens were isolated to prevent the loss of moisture content and left to rest.

Methods

Approximately 600 specimens were prepared to determine the effect of cutting direction, roughness values that emerged with different processing types, adhesive type, and pressing pressure in *Pinus nigra* wood on bonding performance subject to shear testing in a 4-ton universal testing device in accordance with ASTM D905 (2008). The specimens for the test were tied to the machine in line with the standard, and pressure was applied on the specimens in accordance with the model presented in Fig. 3. During the experiment, the machine's loading speed was adjusted to 12.7 mm/min.

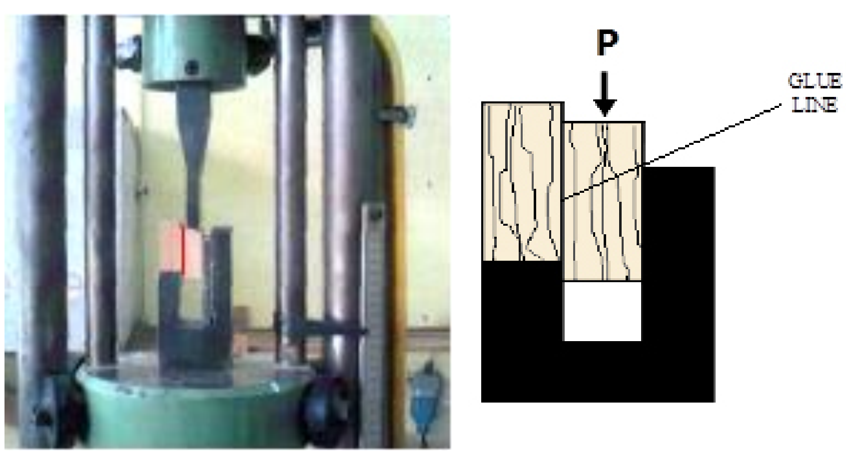

Fig. 3. Shear strength testing model for the universal testing machine

The pressure at the moment the pieces broke away from each other was read from the scale and recorded. The achieved values were used in the equation below to determine the shear strength of each piece,

$$\sigma_M = \frac{P_{max}}{A} \quad (1)$$

where σ_M is the shear strength (N/mm^2), P_{max} is the maximum pressure at the moment of separation (N), and A is the bonding surface area (mm^2)

Evaluation of Data

Data obtained by the testing of 600 specimens in accordance with different variables were subjected to statistical analysis. To determine whether the surface processing type, cutting direction, adhesive type, and pressing pressure had an effect on the shear strength (bonding) of *Pinus nigra*, multi-variance analysis was carried out.

If the value resulting from this analysis was smaller than ± 5%, the variable was considered to be effective on the shear strength; otherwise, the variable was considered ineffective. The IBM SPSS 21(Statistical Package for the Social Sciences, USA) package program was used for this analysis.

RESULTS AND DISCUSSION

Surface Roughness

The roughness values of *Pinus nigra* determined in an earlier study are given in Table 2.

When the surface roughness values were analyzed (for R_a, R_y, and R_z) according to machine type, it was seen that the surfaces processed with the thickness were the ones with the smoothest surfaces. The roughness values of surfaces cut in a tangential manner were identified as having the lowest values.

Shear Strength

According to the variation analysis of the shear strength, it was determined that the machine type, cutting direction, adhesive type, and press pressure each affected the shear strength. In addition to these, it was observed that double, triple, and quadruple interactions were statistically not important. These results are presented in Table 3.

According to the results of the Tukey test conducted for machine type, the highest shear strength was achieved in the thickness machine (8.35 N/mm^2), the sanding machine (8.12 N/mm^2), and circular saw machine (7.69 N/mm^2), and the results are shown in Table 4.

When the statistical values related to cutting directions for shearing strength were analyzed, the shear strength values of specimens bonded after being cut tangentially were higher ($\sigma_{MTangential}$= 8.27 N/mm^2 ($\sigma_{MRadial}$ =7.84 N/mm^2) than the specimens bonded after being cut radially (Table 4).

Table 2. Statistical values for R_a, R_y, and R_z (Kılıç 2015)

R_a

Direction	Number of Samples	Mean	Standard Deviation	Minimum	Maximum
Radial	90	5.82	0.074	5.67	5.96
Tangential	90	5.40	0.074	5.26	5.55

Machine	N	α=0.05		
		1	2	3
Thickness	60	4.76		
Sanding	60		5.06	
Circular	60			7.01

R_y

Direction	Number of Samples	Mean	Standard Deviation	Minimum	Maximum
Radial	90	43.708	0.781	42.166	45.249
Tangential	90	41.594	0.781	40.052	43.135

Machine	N	α=0.05		
		1	2	3
Thickness	60	35.57		
Sanding	60		41.78	
Circular	60			50.59

R_z

Direction	Number of Samples	Mean	Standard Deviation	Minimum	Maximum
Radial	90	34.609	0.451	33.719	35.498
Tangential	90	31.923	0.451	31.034	32.813

Machine	N	α=0.05		
		1	2	3
Thickness	60	28.54		
Sanding	60		30.62	
Circular	60			40.63

Table 3. Average Shear Strength Values

Cutting Direction	Machine Type	Adhesive Type	Pressure (N/mm²)	Shear Strength (N/mm²)
Tangential	Circular saw	PVAc	0.45	7.98
			0.9	8.10
		PU	0.45	7.97
			0.9	7.80
	Thickness	PVAc	0.45	8.40
			0.9	**8.80**
		PU	0.45	8.29
			0.9	8.53
	Sanding	PVAc	0.45	8.20
			0.9	8.40
		PU	0.45	8.08
			0.9	8.26
Radial	Circular saw	PVAc	0.45	7.65
			0.9	7.60
		PU	0.45	**7.17**
			0.9	7.28
	Thickness	PVAc	0.45	8.10
			0.9	8.30
		PU	0.45	8.18
			0.9	8.19
	Sanding	PVAc	0.45	7.98
			0.9	8.05
		PU	0.45	7.67
			0.9	7.92

Table 4. Statistical Values Related to Shear Strength

Machine		**N**	**α = 0.05**		
			1	**2**	**3**
Circular saw		200	7.69		
Sanding		200		8.12	
Thickness		200			8.35
Cutting Direction	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Radial	300	7.84	0.77925	6.05	7.94
Tangential	300	8.27	0.70468	5.96	10.27
Adhesives	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
PVAc	300	8.16	0.75058	5.96	7.89
PU	300	7.95	0.77910	6.05	10.27
Press Pressure	**N**	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
0.45 N/mm²	300	7.97	0.7188	5.96	9.62
0.9 N/mm²	300	8.14	0.8243	6.10	10.27

Values in N/mm^2

When the statistical values related to adhesive type for shear strength in Table 4 were analyzed, it was observed that the shear strength values of specimens bonded with PVAc adhesive were higher (σ_{MPVAc}= 8.16 N/mm^2 (σ_{MPU} =7.95 N/mm^2) than those for specimens bonded with PU adhesive.

When the statistical values related to press pressure for shear strength (Table 4) were analyzed, it was observed that the average shear strength values of specimens bonded with 9 kg/cm^2 press pressure were higher ($\sigma_{M0.9}$ = 8.14 N/mm^2, $\sigma_{M\,0.45}$ = 7.97 N/mm^2) than those for specimens bonded with 0.45 N/mm^2 press pressure.

According to the statistics related to shear strength (Table 3), the highest shear strength (8.80 N/mm^2) was achieved in specimens with tangential surfaces processed in the thickness machine, with PVAc adhesive and 0.9 N/mm^2 of pressure. The lowest shear strength with a tangential surface (7.80 N/mm^2) was observed on surfaces cut with a circular saw, with PU adhesive and 0.9 N/mm^2 of pressure. In other words, as roughness decreases in tangential surfaces, shearing strength increases (Tables 4 and 5). Also, as pressure increases, shear strength in general increases as well. Similar results were determined in a previous study (Burdurlu *et al.* 2006).

The greatest shear strength in radial surfaces (8.30 N/mm^2) was achieved in specimens processed with the thickness machine, with PVAc adhesive and 0.9 N/mm^2 of pressure. The lowest value (7.17 N/mm^2) was observed on surfaces processed with the circular saw, with PU adhesive and 0.45 N/mm^2 of pressure. As is the case for tangential surfaces, specimens bonded with PVAc displayed higher shear strength in comparison with the ones bonded with PU adhesive for radial surfaces as well. The results are in line with a previous study (Burdurlu *et al.* 2006).

Table 5. Shear Strength Values of Various Tree Species

Material, Adhesive, and Pressure	Shear Strength (N/mm^2)
Beech PU (0.7 N/mm^2) (Kılıç 2004)	13.766
Beech PVAc	**14.385**
Poplar PU	9.822
Poplar PVAc	10.021
Scots Pine PVAc (0.6 N/mm^2) (Balkız 2000)	10.210
Scots Pine PU	**10.740**
Calabrian Pine PVAc (0.3 N/mm^2) (Burdurlu *et al.* 2006)	8.14
Calabrian Pine PVAc (0.6 N/mm^2)	9.07
Calabrian Pine PVAc (0.9 N/mm^2)	**9.24**
Calabrian Pine PU (0.3 N/mm^2)	5.92
Calabrian Pine PU (0.6 N/mm^2)	6.65
Calabrian Pine PU (0.9 N/mm^2)	7.07
Black Pine PVAc (0.45 N/mm^2)	8.054
Black Pine PVAc (0.9 N/mm^2)	**8.281**
Black Pine PU (0.45 N/mm^2)	7.897
Black Pine PU (0.9 N/mm^2)	8.001

In terms of cutting direction, with the bonding of tangential surfaces, greater shear strength values were achieved. Depending on the processing techniques in the machines, when roughness values that emerged in both directions (tangential, radial) were considered, roughness in the tangential direction was lower in general. With a decrease in roughness value, shear strength increased.

According to the obtained data, while greater shear strength was achieved in the tangential direction, this surface also displayed the lowest roughness values. As roughness decreased, increases in adhesion might have effectively increased shear strength. According to this result, if higher shear strength is sought in bondings in terms of cutting direction, then it will be more suitable to bond tangential surfaces by making them face each other.

In terms of surface processing technique in machines, the difference in the shear strength values of surfaces bonded with circular saw cutting, planing, and sanding in the thickness machine was significant ($p<0.05$). These three variables are among different homogeneity groups (Table 4). In terms of surface processing technique, as roughness decreased, shear strength increased. According to this, as surface roughness decreases, bonding becomes better.

The difference between shear strength values achieved according to the adhesive used in the bonding of the specimens was significant ($p<0.05$), PVAc adhesive displays higher shear strength values than PU adhesive. Similar results were determined in the study of Burdurlu *et al*. (2006). The penetration ability of PVAc adhesive is higher in comparison with PU adhesive, so it penetrated deeper, making the adhesive link formation better and producing a more flexible adhesive layer. This in turn may have caused the increase in the shear strength.

As can be seen in Tables 3 and 4, as pressing pressure increased, shear strength values also increased. With 0.9 N/mm^2 pressure, higher shear strength was achieved in comparison with 0.45 N/mm^2 pressure. Higher pressure levels, increasing adhesion and creating better link formation by increasing the pumping of adhesive to the gaps, might be effective at this high strength. According to this result, to increase shear strength in bonding with adhesives, it would be beneficial to increase pressing pressure to a value that would not harm the inner structure of the material.

CONCLUSIONS

1. As a result, to be able to increase shear strength in wood structured elements under effects related to bonding, surfaces to be bonded should be tangential cut surfaces.
2. The use of surfaces achieved through planing prior to bonding, taking the endurance characteristics of the material in bonding into consideration, would be appropriate, as would applying higher pressing pressures in a manner not causing structural defect and using polyvinyl acetate adhesive instead of polyurethane.

ACKNOWLEDGMENTS

The author is grateful for the support of the Turkey General Directorate of Forestry, Central Anatolia Forestry Research Institute, Grant. No. 23.7133/2009-2011-2013.

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Article submitted: March 10, 2016; Peer review completed: May 31, 2016; Revised version received: June 9, 2016; Accepted: June 13, 2016; Published: June 29, 2016.
DOI: 10.15376/biores.11.3.6663-6676