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Evaluation of Dynamic Contact Angle of Loose and Tight Sides of Thermally Compressed Birch Veneer

Procjena dinamičkoga dodirnog kuta površine toplinski komprimiranoga bukova furnira

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ABSTRACT • *Rotary-cut veneer is characterised by two sides, namely loose and tight surface, which have different properties. The information concerning dynamic contact angle behaviour of veneer sides plays an important role in efficient use of veneer. Therefore, the objective of this study was to investigate the influence of different compression temperatures and pressures on various wetting behaviour of loose and tight sides of birch veneer. Veneer sheets were compressed in a hot press at temperatures of 150 and 180 °C using seven pressure levels from 0.5 to 3.5 MPa. Wettability of loose and tight sides of thermally compressed veneer was evaluated by measuring the dynamic contact angle with distilled water. The results showed that thermal compression decreased the surface wettability of both loose and tight sides of the samples, especially for veneer samples compressed at a temperature of 180 °C. Tight side of the samples had lower wettability than loose side, even after thermal compression. Therefore, adhesive or any kind of finishing can be applied to both sides of thermally compressed veneer sheets without having any adverse influence on not only the bonding quality but also the whole finishing process.*

Keywords: *birch veneer, thermal compression, loose and tight sides, wettability, dynamic contact angle*

SAŽETAK • *Za ljuštene je furnire karakteristično da njihove dvije površine, tzv. otvorena i zatvorena strana, imaju različita svojstva. Za učinkovitu uporabu furnira važni su podatci o ponašanju dinamičkoga dodirnog kuta površina furnira. Stoga je cilj istraživanja bio ispitati utjecaj različitih temperatura i tlakova kompresije na ponašanje površina furnira pri kvašenju. Listovi furnira komprimirani su u vrućoj preši pri temperaturi 150 i 180 °C te uz primjenu sedam različitih tlakova, od 0,5 do 3,5 MPa. Ispitana je sposobnost kvašenja površine na obje strane toplinski komprimiranog furnira mjerenjem dinamičkoga dodirnog kuta primjenom destilirane vode. Rezultati su pokazali da toplinsko komprimiranje smanjuje površinsko kvašenje na obje strane furnira, posebice na uzorcima furnira koji su komprimirani pri temperaturi 180 °C. Zatvorena strana uzoraka furnira pokazala je manju sposobnost kvašenja nego otvorena, čak i nakon toplinske kompresije. Stoga se ljepilo ili neko drugo sredstvo za završnu obradu furnira može nanositi na obje strane toplinski komprimiranog furnira bez ikakve opasnosti od nepovoljnog utjecaja na kvalitetu lijepljenja i završnu obradu furnira.*

Ključne riječi: *bukov furnir, toplinska kompresija, otvorena i zatvorena strana furnira, sposobnost kvašenja, dinamički dodirni kut*

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1 INTRODUCTION
1. UVOD

In general, the thermal compression process is used to improve the properties of wood and wood-based materials to facilitate their versatile applications. For example, densified wood veneers may potentially be used in various products in wooden building, furniture, flooring, and numerous other applications (Candan *et al*., 2010; Diouf *et al.,* 2011). In addition to the advantageous effect on properties such as strength, surface hardness and durability (Kutnar *et al.,* 2008; Büyüksari *et al.,* 2012; Büyüksari, 2013; Rautkari *et al.,* 2013), surface quality of their aesthetic-decorative features could also be improved. The colour of wood becomes more attractive (Diouf *et al.,* 2011), surface roughness decreases (Candan *et al.,* 2010; Arruda and Del Menezzi, 2013; Bekhta *et al.,* 2014), and the surface becomes glossier and smoother, while minimising the need for sanding. Despite the fact that thermal compression is an environmentally friendly process, after this treatment, the surface of the member becomes hydrophobic, which could result in serious problems during gluing or finishing.

Surface qualities of veneer are decisive to surface wettability and bonding quality between veneer sheets. Wood wettability is an important parameter that provides information on physical and chemical affinity between wood surface and adhesives/coatings (Gray, 1962; Elbez, 1978; Gindl *et al.,* 2004), while it also has a great influence on bonding strength and mechanical properties of veneer-based products. Clearly, wetting of wood surfaces is a complex process influenced by many factors (Piao *et al.,* 2010; Bekhta and Krystofiak, 2016).

Although many studies have been conducted on the evaluation of wettability of solid wood, fewer studies have been performed on wood veneer. As well known, rotary-cut veneer sheets are characterised by the presence of small lathe checks on the loose side of the veneer, while there are no checks on the reverse tight side of the sheet (Kollmann *et al*., 1975). Since properties including morphology, porosity, roughness, density, hardness, and moisture content of these veneer sides show variation, they will behave differently due to the absorbtion of adhesive or finishing products. The depth of penetration and the area of adhesive spreading will vary between rough and smooth veneer. This leads to an uneven thickness of the adhesive layer, resulting in increased concentration of stresses in the adhesive layer, and consequently adversely influencing overall bonding quality. Hse (1972) concluded that surface roughness and possibly surface chemical properties of the tight side differed from those of the loose side and that these differences may affect the contact angle. Moreover, in most of the previous studies on wood wettability, instantaneous or equilibrium contact angles were used (Liptakova and Kudela, 1994; Scheikl and Dunky, 1998; Kutnar *et al.,* 2012), neglecting adhesive penetration and the spreading process. However, studying the wetting process may be more meaningful than evaluating only the initial equilibrium contact angle on the surface of the sample (Liptakova and Kudela, 1994).

Currently, despite some studies related to surface roughness (Fang *et al.*, 2012), aesthetic features and wettability (Arruda and Del Menezzi, 2013; Diouf *et al.,* 2011; Bekhta *et al.,* 2015; Bekhta and Krystofiak, 2016) of compressed veneer, there is still insufficient information on surface characteristics, especially dynamic contact angle, wettability processes of different veneer sides under the process of thermal compression, which directly influence the bonding quality of veneer-based composites. Veneer may be used not only in the production of plywood or LVL, but also for veneering of particleboards and MDF in the furniture industry. It is essential to gain specific data on surface characteristics of thermally compressed birch veneer, including its wettability, to optimise gluing or coating processes. Therefore, the objective of this study was to investigate the effect of thermal compression treatment at various temperatures and pressures and the treated veneer side (loose and tight) on dynamic contact angle of birch veneer to provide guidelines for an appropriate application of compressed veneer in veneer-based composites.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood veneer samples
2.1. Uzorci furnira

Birch is one of the most commonly used raw materials for plywood production in Ukraine. Therefore, rotary-peeled birch (*Betula verrucosa* Ehrh.) wood veneer with the nominal thickness of 1.5 mm and moisture content of 5 % were used in this study. Defect free tangential sheets of veneer were cut in 300 mm by 300 mm pieces for thermo-mechanical densification and subsequent measurements.

2.2 Short-term thermo-mechanical compression
2.2. Kratkoročna toplinsko-mehanička kompresija

Veneer sheets were compressed using an automatically controlled single-opening hot press. To avoid surface contamination during compression, veneer samples were placed between smooth and cleaned thin stainless steel press caul. Then, the veneer samples held between steel sheets were placed between heated press plates and when the pressure reached 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 or 3.5 MPa, it was held under compression perpendicular to the grain (thickness direction) at the temperatures of 150 or 180 °C for 1 min. After this period, the press was opened, the densified veneer was removed from the press and allowed to cool at room temperature. The weight and dimensions of the samples were measured before and after compression. Afterwards, each veneer sheet was cut to strips of 100 mm in length and 15 mm in width for dynamic contact angle measurements. Ten replications for each variant of short-term thermo-mechanical compression were prepared.

2.3 Dynamic contact angle measurements
2.3. Mjerenje dinamičkoga dodirnog kuta

Droplets having distilled water volume V=3.5 μL, were placed on the loose and tight side of birch veneer using the sessile drop method and were determined using a PG-3 goniometer. The measurements were conducted at a temperature of 20±1 °C and relative humidity of 65±2 %. Fifteen images per second of the liquid drop shape on the veneer surface along the grain were captured by a camera. The contact angles were measured directly from the images using an integrated imaging software package. Twenty contact angle measurements were taken per droplet for each birch veneer sample.

2.4 Analysis of variance (ANOVA)
2.4. Analiza varijance (ANOVA)

Analysis of variance (ANOVA) at a 0.05 significance level was carried out using IBM SPSS Statistics software to estimate the relative importance of the effects of the experimental variables, such as compression temperature and pressure, on the dynamic contact angle of veneer. Duncan's multiple range tests were also conducted for multiple comparisons between the means of the measured properties for different sides of veneer and various compression temperature and pressure. ANOVA analysis and Duncan test were carried out at 60 s deposition because water droplets fully penetrate across the surface of veneer on the loose side after 60 s deposition for certain thermal compression conditions.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The behaviour of the contact angle in both loose and tight sides as function of time of non-densified and densified veneer for different thermal compressions is shown in Figs.1 and 2. As can be seen in these figures, the contact angle decreased as a function of wetting time. Spreading is the dominant process on the tight side for non-densified veneer, while penetration is the dominant process on the loose side of veneer (Fig. 1). After about 60 seconds, a drop of water completely penetrates into the wood surface on the loose side. As can be seen in Fig. 1, there is a distinct and substantial difference between the loose and tight sides of non-densified veneer. Therefore, in practice, this is usually taken into account and adhesive is applied on the loose side of veneer and its loose side is turned in the middle position in the process of forming a veneer package.

Similar behaviour of a drop of water on the surface of wood is observed for densified veneer (Fig. 2). However, the time required to penetrate the drop into the wood surface on the loose side of veneer increases to 60-80 seconds. In addition, under certain compression pressures, the drop of water on the loose side spreads without penetration into the wood, similar to the tight side of the samples, especially those compressed at the temperature of 180 °C. However, no clear dependence on the behaviour of a drop of water on the surface of wood, depending on the compression pressure, was established. Probably, this is because it is very difficult to pick up veneer sheets that would have identical properties such as morphology, porosity, roughness, density, hardness, and moisture content.

The difference between the contact angles on the loose and tight side was significant for non-densified veneer (Table 1). As can be seen in Fig. 1, contact angle decreased more rapidly on the loose side than on the tight side. This difference is largely due to the deeper lathe checks on the loose side of veneer. As a result, water will easily penetrate the wood surface on the loose side, increasing wettability. Therefore, the loose

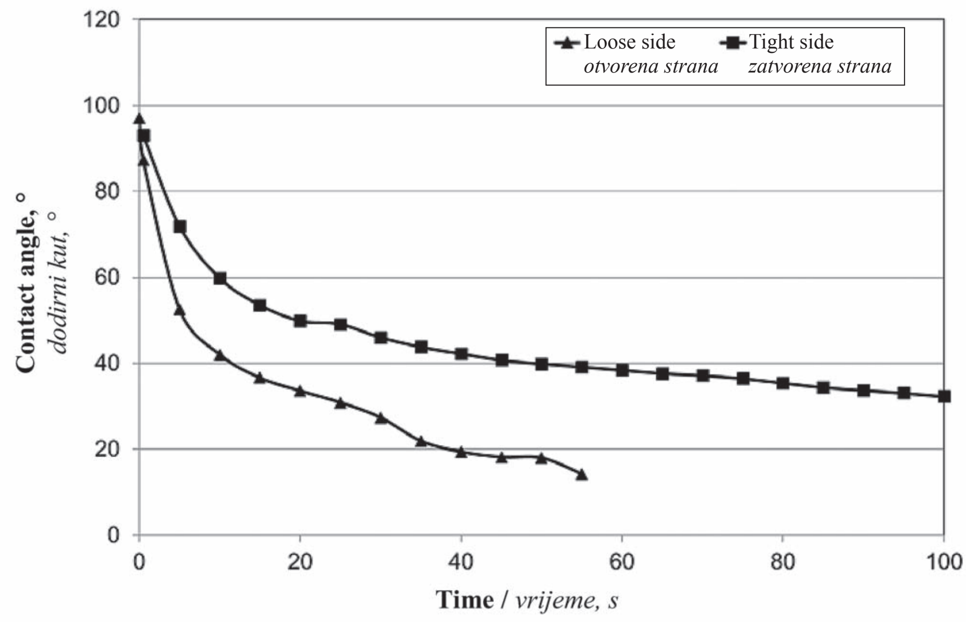


Figure 1 Changes in dynamic contact angle of distilled water as a function of time on non-densified veneer surfaces
Slika 1. Promjene dinamičkoga dodirnog kuta destilirane vode kao funkcija vremena na nekomprimiranim površinama furnira

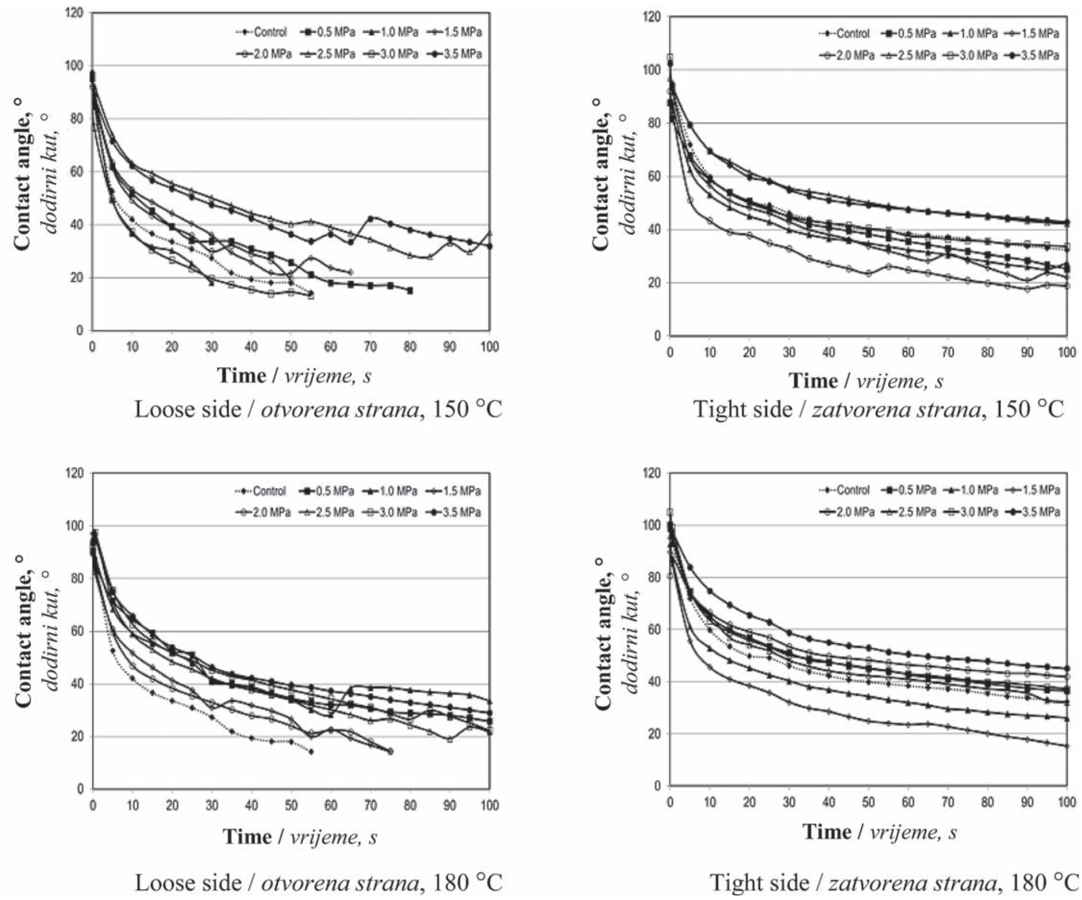


Figure 2 Changes in dynamic contact angle of distilled water as a function of time on densified surfaces of birch veneer at various compression temperature and pressure values
Slika 2. Promjene dinamičkoga dodirnog kuta destilirane vode kao funkcija vremena na površinama bukova furnira komprimiranoga pri različitim temperaturama i tlakovima

Table 1 Duncan's test results for main effects
Tablica 1. Rezultati Duncanova testa za glavne utjecajne činitelje

Variable / *Varijable*	**Contact angle (degrees)** / *Dodirni kut (u stupnjevima)*			
	Loose side / *Otvorena strana*		**Tight side** / *Zatvorena strana*	
	Mean	SG	Mean	SG
Temperature / *temperatura*, °C				
non-densified (control) / *nekomprimirani kontrolni uzorak*	39.56	aA	57.28	abB
150	47.61	bA	55.91	aB
180	54.51	cA	59.08	bB
Pressure / *tlak*, MPa				
non-densified (control) / *nekomprimirani kontrolni uzorak*	39.56	aA	57.28	cB
0.5	52.49	cA	58.80	cB
1.0	46.97	bA	50.60	abA
1.5	48.34	bA	48.77	aA
2.0	45.37	bA	52.85	abB
2.5	58.11	dA	63.69	dB
3.0	46.63	bA	59.08	cB
3.5	59.48	dA	68.63	eB

Different letters denote a significant difference. The means followed by the same letter do not statistically differ from each other ($p \leq 0.05$). Lower case letters regard the analysis between temperatures and pressures within each loose and tight side and capital letters regard the analysis (*t*-test) between the loose and tight sides within each temperature and pressure. SG: statistical group.

Različita slova označavaju značajnu razliku. Srednje vrijednosti obilježene istim slovom međusobno se statistički ne razlikuju (p ≤ 0,05). Mala slova znače da je uzeta u obzir analiza između vrijednosti dobivenih na svakoj strani furnira pri različitim temperaturama i tlaku a velika znače da je uzeta u obzir analiza (t-test) između srednjih vrijednosti za različite strane furnira pri svakoj temperaturi i tlaku kompresije; SG – statistička skupina.

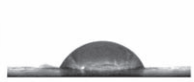
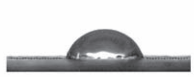
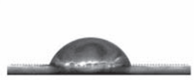
side of non-densified veneer surface is more wettable. Shupe *et al.* (1998) found that loose-side values were much smaller than tight-side values for both earlywood and latewood. Vazquez *et al.* (2003) also showed that the presence of lathe checks on the loose sides favours wettability, with the contact angle decreasing more rapidly on these sides than on tight sides.

According to Fig. 2, the contact angle of birch veneer changed after the thermal compression process. The statistical analysis identified that significant changes ($p<0.05$) occurred at various compression temperatures and pressures on both loose and tight sides. It was found that, with an increase of compression temperature and pressure, the contact angle increased on the loose and tight sides of veneer compared to the loose and tight sides of non-densified veneer. For example, the compression at 150 °C caused an average increase of 16.9 % and compression at 180 °C caused an average increase of 27.4 % in the contact angle of the loose side, respectively. However, insignificant difference in the contact angle values was observed between samples compressed at temperatures of 150 and 180 °C for the tight side (Table 1).

The change in contact angle values especially on the tight side for the investigated pressure range of 0.5-3.5 MPa was irregular probably because of the complex morphology of the veneer surface. As mentioned above, it is very difficult to pick up veneer sheets that would have identical characteristics.

Factor analysis showed that the effect of compression temperature and pressure on changes in contact angle was significant ($p<0.05$) for both sides of veneer. Regarding the temperature, a clear dependence was found on the effect of compression temperature on wettability. In particular, if the compression temperature increases, wettability worsens. With respect to the compression pressure, no clear dependence of the effect of this factor on wettability was found. Contact

Table 2 Drop shape changing on non-densified and densified surfaces of birch veneer specimens as a function of time at different thermal compression
Tablica 2. Promjena oblika kapljice na površini uzoraka nekomprimiranoga i komprimiranog furnira kao funkcija vremena pri različitim toplinskim kompresijama

Side of veneer and compression conditions *Strana furnira i uvjeti kompresije*	**Wetting period** / *Vrijeme kvašenja* 5 sec	30 sec	60 sec
Loose side (non-densified) *otvorena strana (nekomprimirana)*			
Tight side (non-densified) *zatvorena strana (nekomprimirana)*			
Loose side (densified at 150 °C/0.5MPa) *otvorena strana (komprimirana pri 150* °C / *0,5* MPa*)*			
Tight side (densified at 150 °C/0.5MPa) *zatvorena strana (komprimirana pri 150* °C / *0,5* MPa*)*			
Loose side (densified at 150 °C/3.5MPa) *otvorena strana (komprimirana pri 150* °C / *3,5* MPa*)*			
Tight side (densified at 150 °C/3.5MPa) *zatvorena strana (komprimirana pri 150* °C / *3,5* MPa*)*			
Loose side (densified at 180 °C/0.5MPa) *otvorena strana (komprimirana pri 180* °C / *0,5* MPa*)*			
Tight side (densified at 180 °C/0.5MPa) *zatvorena strana (komprimirana pri 180* °C / *0,5* MPa*)*			
Loose side (densified at 180 °C/3.5MPa) *otvorena strana (komprimirana pri 180* °C / *3,5* MPa*)*			
Tight side (densified at 180 °C/3.5MPa) *zatvorena strana (komprimirana pri 180* °C / *3,5* MPa*)*			

angle values on the tight side are higher than on the loose side for the same thermal compression conditions. Therefore, the tight side presents lower wettability than the loose side. Moreover, contact angle values of densified veneer are higher than those of non-densified veneer. This difference is significant for the loose side (Table 1). For the tight side, this difference is not clear as displayed in Table 1. The changes in the contact angle values for a tight side of veneer densified at temperature levels of 150 and 180 °C, as compared to non-densified veneer, are negligible. The contact angles on the tight side of veneer thermally compressed at 150 and 180 °C were found as 55.91° and 59.08°, respectively. It appears that these values were close to 57.28°, which was found on the tight side of non-densified veneer. However, this difference in the contact angle values on the tight side between compression temperatures of 150 and 180 °C was significant (Table 1).

Table 2 shows the reduction in drop volume as a function of time due to the penetration of water into the porous structure of wood. Slower absorption of water by capillaries on a smooth (tight) surface justifies the observed differences. At higher compression temperature, the shape of water drop on the loose and tight sides of veneer surface remains unchanged.

For non-densified veneer, the surface on the tight side is more homogeneous than on the loose side. The penetration of water into the tight side is more homogeneous, with the exception of penetration into the area of veneer heterogeneous, while penetration into the loose side is both deeper and less homogeneous. Compression of veneer homogenises the surface and reduces the influence of wood anatomical characteristics on wetting behaviour. After compression, the surface characteristics of the loose and tight sides become comparable. The difference between the loose and tight sides of densified veneer is reduced, although it still remains significant. The difference between the values of the contact angle for the loose and tight sides is 30.9 % for non-densified veneer, 14.8 % for the veneer densified at 150 °C and 7.7 % for the veneer densified at 180 °C (Table 1).

The contact angle decreases faster on the loose side than on the tight side of the veneer (Table 3). On the loose side, due to the existence of lathe checks, the horizontal flow on the veneer surface was mainly responsible for decreasing the contact angle (Vazquez *et al*., 2003). On the tight side, the speed of changing the values of the contact angle for non-densified veneer and veneer compressed at different temperatures remains practically the same. This may indicate that the tight side surface, both in non-densified and densified veneer, is homogeneous. The speed with which the contact angle changes for non-densified veneer is greater than for the veneer compressed at different temperatures. The smallest rate of changes in the contact angle was observed at the compression temperature of 180 °C.

There are several possible reasons for the decreased wettability of surface densified wood veneers.

Table 3 Contact angle changes on non-densified and densified birch veneer specimens at different wetting period (T – compression temperature; P – compression pressure; LS – loose side; TS – tight side)
Tablica 3. Promjene dodirnih kutova na uzorcima nekomprimiranoga i komprimiranog bukova furnira pri različitom vremenu kvašenja (*T* – temperatura kompresije, *P* – tlak kompresije, LS – otvorena strana, TS – zatvorena strana)

***T*, °C**	***P*, MPa**	**Initial angle** *Početni kut*		**Angle after 30 s** *Kut nakon 30* s		**Angle after 60 s** *Kut nakon 60* s		**Percent decrease of angle after 30 s** *Postotno smanjenje dodirnog kuta nakon 30* s		**Percent decrease of angle after 60 s** *Postotno smanjenje dodirnog kuta nakon 60* s	
		LS	TS	LS	TS	LS	TS	LS	TS	LS	TS
Control (non-densified) *Kontrolni nekomprimirani uzorak*		87.2	93.1	27.3	46.0	13.0	38.4	68.7	50.6	85.1	58.7
150	0.5	86.0	81.6	37.2	44.6	18.1	35.5	56.8	45.4	78.9	56.5
	1.0	84.6	87.9	18.1	39.8	-	32.4	78.6	54.7	-	63.2
	1.5	87.4	91.9	36.1	42.8	23.7	29.9	58.7	53.4	72.9	65.7
	2.0	89.5	85.0	29.9	32.8	17.0	24.8	66.6	61.5	81.0	70.9
	2.5	92.4	93.6	50.1	55.6	39.1	47.6	45.8	40.6	57.7	49.1
	3.0	76.6	93.5	19.7	45.1	12.5	37.7	74.4	51.8	83.7	59.7
	3.5	88.9	94.5	47.6	54.9	36.4	47.7	46.5	41.9	59.1	49.8
180	0.5	85.6	96.0	41.0	51.0	32.1	42.8	52.1	46.9	62.5	55.5
	1.0	88.5	87.1	41.3	40.3	28.2	32.0	53.4	53.7	68.2	63.3
	1.5	82.3	85.3	30.9	32.1	22.7	23.5	62.4	62.3	72.5	72.5
	2.0	84.9	88.1	33.0	53.5	22.5	46.5	61.2	39.3	73.5	47.3
	2.5	97.7	94.6	42.0	48.3	30.1	41.0	57.0	49.0	69.2	56.7
	3.0	97.5	99.3	45.2	50.1	34.3	42.9	53.7	49.5	64.8	56.8
	3.5	95.2	97.8	46.3	58.8	37.2	50.5	51.4	39.8	60.9	48.3

This may be attributed to surface roughness and chemical indices of wood surfaces that are changed with thermal compression (Diouf *et al.,* 2011; Fang *et al.,* 2012; Kutnar *et al.,* 2012; Arruda and Del Menezzi, 2013). When analysing the anatomical characteristics of densified veneer, it was shown that wood morphology changed significantly in the compression process. Earlier studies (Arruda and Del Menezzi, 2013; Bekhta *et al.,* 2014) indicated that thermo-mechanical densification improved surface quality of veneers with the surface becoming smoother, and roughness values decreasing significantly. Roughness is closely related to wettability: the higher the roughness, the higher the surface hydrophilicity (Piao *et al.,* 2010; Arnold, 2011). A contrary result was found by Stehr *et al.* (2001) in the case of southern pine. It was found that a smoother wood surface provided enhanced wetting and penetration properties for high-viscosity liquids such as adhesives. Our findings are in good agreement with the results obtained by Stehr *et al.* (2001). An increase in contact angle values on the loose side of densified veneer was also due to the decreased wood surface porosity during thermal compression. Smoother surfaces have lower porosity, which results in lower penetration characteristics. This increase was higher on the tight side of surface when compared to that of the loose side, since the loose surface (with more lathe checks) was more affected by compression compared to the tight side.

Liptakova *et al.* (1995) found that mechanical treatments not only change the morphological structure of wood, but also the chemical composition of the wood surface layer. The decreased wettability might also be caused by increased hydrophobicity. It has been reported that extractives that migrate to wood surface create hydrophobic properties and reduce its wettability (Nussbaum and Sterley, 2002). The degradation of the most hygroscopic components of wood, namely cellulose, hemicelluloses and lignin, which probably occurs during thermal compression (Kocaefe *et al.,* 2008; Diouf *et al.,* 2011; Bekhta and Krystofiak, 2016), reduces water absorption of wood. Changes in lignin occur at these temperatures. Lignin softens and blocks the cell pores contributing to the reduction in water absorption (Rowell *et al.,* 2000).

4 CONCLUSIONS
4. ZAKLJUČAK

Based on the findings presented in this paper, wettability of the loose and tight sides of veneer was decreased significantly by thermal compression treatment at all studied temperatures and pressures. For non-densified veneer, the dynamic contact angle values for the loose-side were much smaller than for the tight-side. It was also observed that, in the case of distilled water, there was no clear trend distinguishing the loose and tight sides of veneer after thermal compression treatment, whose mean values, considering all the temperatures and pressures studied, were very similar. On the other hand, the loose side showed a slight trend towards better wettability than the tight side for densified veneer compared to non-densified veneer. Thermal compression of veneer homogenises the surface and, as a result, its wettability of the loose and tight sides is comparable. Based on the obtained results, it can be argued that the difference between the loose and tight sides of the veneer is significantly reduced due to the compression process. For example, the difference between mean values of the contact angle for the loose and tight sides of non-densified veneer is 30.9 %. For the veneer compressed at the temperature of 150 °C, this difference is already 14.8 %, and for the veneer compressed at the temperature of 180 °C, this difference is only 7.7 %. In general, at the higher compression temperature, the wettability on the densified wood surface worsens as compared to non-densified veneer. At the same time, however, the difference between the loose and tight sides of the veneer is reduced. It seems that the main reason for the changes in dynamic contact angle are connected with the difference in the anatomical structure of loose and tight sides of veneer, since the thermal compression time was only 1 min. However, an accurate explanation of this phenomenon requires further study.

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