Aldo Rolleri , Francisco Burgos, Alfredo Aguilera[1]

Surface Roughness and Wettability Variation: The effect of Cutting Distance during Milling of Pinus Radiata Wood

Promjene hrapavosti i svojstva kvašenja površine: utjecaj duljine rezanja tijekom blanjanja borovine

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ABSTRACT • *The variation of the machined surface properties is usually described in terms of changes in cutting parameters. However, the effect of the cutting distance should be considered, as it further shows the influence of the cutting tool wear. In order to assess the effect of the cutting distance on roughness and wettability of Pinus radiata wood surfaces, three conditions of feed speed and cutting speed were applied on cutting distance of 0 to 10000 meters. This study describes the effect of machining parameters on the behavior of roughness and wettability through the cutting distance, and the interaction of both surface properties is also discussed. The variation of surface roughness in function of the cutting distance is not directly related to variations in the surface wettability. It was, therefore, concluded that is was not reliable to consider only the surface roughness to explain the wetting behavior of a heterogeneous surface such as wood.*

Key words: *cutting distance, roughness, wettability, contact angle, wood, milling*

SAŽETAK • *Varijacije svojstava obrađene površine drva obično se opisuju kao posljedica promjene parametara obrade. Međutim, treba uzeti u obzir i učinak duljine rezanja jer to dodatno pokazuje utjecaj istrošenosti reznog alata. Kako bi se procijenio učinak duljine rezanja na hrapavost i svojstvo kvašenja površine drva bora (Pinus radiate), pri blanjanju na duljini od 0 do 10 000 metara primijenjene su tri različite posmične brzine i brzine rezanja. U radu se opisuje utjecaj parametara obrade na hrapavost i svojstvo kvašenja obrađene površine u ovisnosti o duljini rezanja, a objašnjena je i interakcija tih dvaju svojstava obrađene površine. Varijacije hrapavosti površine u ovisnosti o duljini rezanja nisu izravno povezane s varijacijama svojstva kvašenja površine. Zaključeno je da za određivanje svojstva kvašenja heterogene površine materijala kao što je drvo nije pouzdano uzimati u obzir samo hrapavost njegove površine.*

Ključne riječi: *duljina rezanja, hrapavost, svojstvo kvašenja, kontaktni kut, drvo, blanjanje*

[1] Authors are assistant proffesors and associate professor at the Forest Product Laboratory, Institute of Forests and Society, Faculty of Forest Science and Natural Resources, Austral University of Chile, Campus Isla Teja, Casilla 567, Valdivia, Chile.
[1] Autori su docenti i izvanredni profesor Laboratorija za šumske proizvode, Fakultet znanosti o šumama i prirodnim resursima, Južno sveučilište u Čileu, Valdivia, Čile.

1 INTRODUCTION
1. UVOD

The characterization of wood cutting surfaces is very important as it normally interacts with adhesives, paints and varnishes. Roughness and wettability are surface properties that are normally used to assess surface quality. The characterization of surface quality depends on many influencing factors and can be related both to wood properties and machining conditions (Magoss, 2008). Dundar *et al*., (2008) and Magoos (2008) found that an increase in cutting speed decreased the surface roughness. On the other hand, by the increasing of the feed speed, the surface roughness is increased (Keturakis and Juodeikienė, 2007; Hernandez and Cool, 2008). Walinder (2000) explained that the intrinsic wood surface structure combined with the irregular surface structure resulting from different machining processes might cause variation in wood wettability. Hernandez and Cool (2008) found that an increment in feed speed affected the wetting of a surface. The authors considered that better wetting was associated with higher surface roughness. In a comparison of different types of wood surface machining, planed, sanded and disc sawn surfaces, Santoni and Pizzo (2011) found that the high roughness, produced in the sanding process made more wettable the sanding surfaces. Cool and Hernandez (2011) also measured better wettability on rough surfaces compared to smoother ones.

Nevertheless, the effect of those cutting parameters on surface properties is not constant due to the wear on the cutting tool by the effect of the cutting distance. This cutting distance was considered for limited cutting distances or the wear was reproduced artificially. The wood milling tools undergo wear during the cutting process, the mass of the tools decreases and the geometrical parameters change (Keturakis and Lisauskas, 2010). Surface quality is particularly sensitive to the changes in wear profile geometry (Sheikh and McKenzie, 1997). Itaya and Tsuchiya (2003) cited by Aknouche *et al*. (2009) concluded that the direct consequence of the cutting edge wear is the gradual loss of its ability to cut the machined material. These conditions also result in a poor wood surface quality. Keturakis and Juodeikienė (2007) modelled artificially the cutting edges of the knives and found that a decrease on tool edge blunt radius and feed rate during milling decreases the surface roughness of birch wood. Gilewicz *et al*. (2010), evaluated the wear by the effect of the cutting distance until 6000 meter on the surface properties and found almost a linear increase of R_z together with the tool wear. This study is intended to provide information on the variation of surface properties depending on the cutting distance in order to support decisions as to when to renew the cutting tool.

Therefore, the main objective of this study was to describe the behavior of roughness and wettability on *Pinus radiate* wood surfaces in function of the cutting distance during its machining.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

In this study, *Pinus radiata* D. Don samples, see table 1, with a mean EMC of 10.9 % (NCh176/1) and a mean density of 470 kg·m^{-3} (NCh176/2) according to Chilean standard, were machined using a single-spindle shaper (milling) machine with variable cutting speed and feed, with three hydro centered mounting cutter-heads of 6 knives HS6-5-2 (High Speed Steel type M2) with 26° clearance angle and 15° of rake angle each.

The machining takes into account a tool wear at a cutting distance of 0 to 10000 meters (linear cutting meters of material to be cut), with specific wear conditions, see Table 1.

Also in order to control and measure the tool wear, the cutting edge recession was measured with the help of a magnifying glass and software. Each 2000 meters of cutting distance, the machining conditions were adjusted, see Table 1, to assess the surface quality through the roughness and wettability surface properties. The mean peak-to-valley height (R_z) parameter, in accordance with ISO 4287 (1997) standard, was used to measure the roughness surface using a Mitutoyo SJ-201 apparatus. On the other hand, wettability was measured by the principle of contact angle using a DSA25 Krüss device.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2, below, shows the variation of average surface roughness in function of the cutting distance associated with the machining parameters. Independent of the

Table 1 Experimental conditions
Tablica 1. Uvjeti eksperimentalnih mjerenja

Factors *Činitelji*	**Wood** *Drvo*	**Tool Wear** *Trošenje alata*	**Surface quality measuring** *Mjerenje kvalitete površine*
Density / *gustoća*	470 kg·m^{-3}		
Equilibrium Moisture content (EMC) *ravnotežni sadržaj vode (EMC)*	10.9 %		
Tool diameter / *promjer alata*		192 mm	
Rake angle / *prsni kut*		15°	15°
Feed speed, v_f / *posmična brzina,* v_f		26 m·min^{-1}	22, 30, 38 m·min^{-1}
Cutting speed, v_c / *brzina rezanja,* v_c		50 m/s	44, 50, 56 m/s
Cutting distance, *L* / *duljina rezanja, L*		0 to 10000 meters	each 2000 meters

Table 2 Variation of the average roughness R_z (μm) during *Pinus radiata* wood machining
Tablica 2. Varijacije srednje vrijednosti hrapavosti R_z (μm) tijekom obrade borovine

Feed speed v_f *Posmična brzina, v_f* m·min^{-1}	**Cutting speed v_c** *Brzina rezanja, v_c* m·s^{-1}	**Cutting distance, m** / *Duljina rezanja,* m					
		0	2000	4000	6000	8000	10000
22	44	21.0	20.3	26.5	27.8	27.3	25.2
	50	21.9	20.5	25.5	27.0	25.9	24.3
	56	19.9	19.3	23.8	23.9	25.5	23.9
30	44	22.4	20.7	26.8	29.5	32.2	26.9
	50	20.5	21.2	25.6	26.7	28.4	24.7
	56	18.6	18.6	24.0	25.6	26.5	24.2
38	44	20.7	19.8	26.9	25.7	25.1	26.2
	50	20.5	19.6	26.3	27.4	28.6	28.4
	56	20.7	19.4	27.3	28.7	25.5	25.4

machining conditions, the average roughness decreases from its initial level at 0 meters until 2000 meters and then increases again until the cutting distance of 8000 meters; then it shows a gentle tendency to diminish.

When the roughness is compared in function of the cutting speed, roughness tends to diminish as the cutting speed v_c increases. On the other hand, when the comparison is related to feed speed, there is a slight increase of the roughness as feed speed v_f increases. These trends become more consistent when the comparison is made among conditions of v_f (22 to 38 m·min^{-1}) and as the cutting distance increases. Table 3 shows the average contact angle in function of the cutting distance and machining conditions. In general, it does not show a clear trend through the cutting distance, or with the cutting speed. However, when comparison is made based on the cutting distance of 0 meter and 10000 meter, the contact angle changes depending on the feed speed. In case of feed speed of 22 and 38 m·min^{-1}, the surface wetting tends to decrease with the cutting distance, i.e. higher contact angle at 10000 meters than 0 meters.

The statistical analysis, ANOVA, see Table 4, shows that the cutting distance (*L*) is the most significant factor for roughness (R_z). It is followed in importance by the cutting speed (v_c), and only then by the feed speed (v_f). In the case of wettability (contact angle), the most significant factor of variance is the feed speed (v_f) followed by the cutting distance (*L*) and the cutting speed (v_c) as the least important.

Table 3 Variation of average contact angle θ (°) during *Pinus radiata* wood machining
Tablica 3. Varijacije srednjega kontaktnog kuta kvašenja površine θ (°) tijekom obrade borovine

Feed speed v_f *Posmična brzina, v_f* m·min^{-1}	**Cutting speed v_c** *Brzina rezanja, v_c* m·s^{-1}	**Cutting distance, m** / *Duljina rezanja,* m					
		0	2000	4000	6000	8000	10000
22	44	31.8	50.6	37.9	90.1	60.3	61.5
	50	30.2	47.9	25.5	90.1	48.6	61.9
	56	31.9	47.7	32.3	85.0	55.1	55.2
30	44	28.6	21.2	19.8	46.7	22.4	20.6
	50	29.2	21.3	25.5	23.2	28.3	15.7
	56	35.1	25.1	24.9	26.7	24.8	18.5
38	44	34.3	32.5	36.5	31.0	35.4	46.4
	50	33.6	25.4	39.8	19.0	34.8	29.8
	56	28.9	20.9	26.6	20.3	29.3	40.9

Table 4 ANOVA of surface properties in function of cutting conditions and distance
Tablica 4. ANOVA analiza svojstava obrađene površine u ovisnosti o parametrima obrade i duljini rezanja

Roughness *Hrapavost*	***Df***	**Sum *Sq***	**Mean *Sq***	***F* value**	**Pr (>*F*)**
L	5	8153.45	1630.69	110.22	0.0000
v_c	2	503.30	251.65	17.01	0.0000
v_f	2	126.28	63.14	4.27	0.0143
Residuals	960	14203.16	14.79		
Contact angle *Kontaktni kut*					
L	5	31494.08	6298.82	31.22	0.0000
v_c	2	2467.21	1233.60	6.11	0.0023
v_f	2	137211.76	68605.88	340.02	0.0000
Residuals	960	194103.55	201.77		

Table 5 Pearson correlation matrix between studied factors
Tablica 5. Pearsonova korelacijska matrica između istraživanih utjecajnih činitelja

	L	v_c	v_f	R_z	θ
L	1.00	0.00	0.00	0.46	0.17
v_c		1.00	0.00	-0.14	-0.07
v_f			1.00	0.06	-0.44
R_z				1.00	0.00
θ					1.00

Moreover, Pearson correlation shows similar tendencies. R_z behavior is most related to the effect of the cutting distances (L) followed by the cutting velocity (v_c) and only then by the feed speed (v_f). In the case of contact angle θ, the most related factor is the feed speed (v_f) followed by the cutting distance and only then by the cutting velocity, see Table 5.

Based on the factor significance, the behavior of surface properties, roughness and wettability (contact angle), are presented below in function of the cutting distance. The figures 1 to 4 represent the values as (+ main, — median, ┬ ┴ min – max and ° outliers).

Figure 1 shows the general behavior of surface roughness parameter R_z in function of the cutting distance (L). As can be seen, the R_z values decrease from 0 meter to 2000 meters, and then increase until 8000 meters, to decrease again when the cutting distance of 10000 meters has been completed. The above is consistent with a Duncan test that identifies three different groups of roughness through the cutting distance (L), 0 to 2000, 4000 to 8000, and 10000 meters, at a significance level of 0.05 %. Second in importance is the influence of the cutting speed (v_c), Figure 2 shows the well known effect of the cutting speed on roughness; it decreases as the cutting speed increases.

This effect on roughness appears consistent throughout the cutting distance. Nevertheless, the values of roughness for the same machining conditions change as the cutting distance accumulates. For example, up to the cutting speed of 44 m/s, at the cutting distance of 0 meter, the R_z is slightly greater than 25 μm, but after the cutting distance of 8000 meters, the same machining conditions no longer generate the same level of roughness; it changes up to 25 μm.

The effect of cutting distance (L) and feed speed (v_f) on surface wettability (contact angle) of *Pinus radiate* wood throughout the cutting distance are shown in Figure 3 and 4. If the whole experiment design is considered, see Figure 3, it can be seen that the median and the average contact angle decrease until the minimum level when the cutting distance has reached 4000 meters, and then begin to rise steadily from 6000 meters on.

However, when the feed speed is plotted through the cutting distance, see Figure 4, its significance on wetting is evident.

Figure 4 shows how the contact angle evolves three different paths as the cutting distance increases. It could be said that the feed speed of 30 m·min^{-1} produced the most wettable surface, while the feed speed of 22 m·min^{-1} produced less wettable surface.

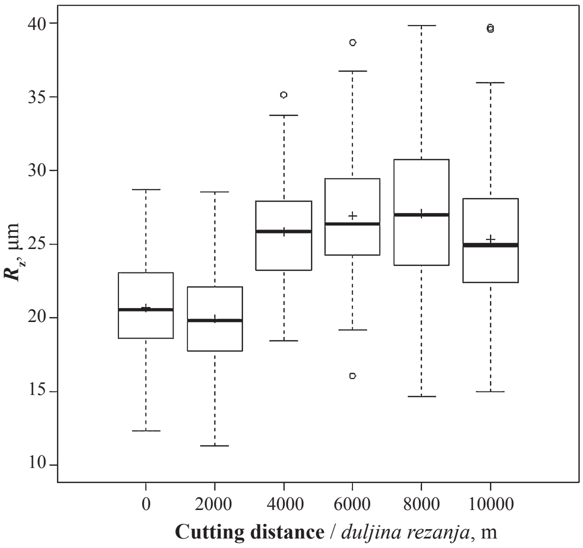

Figure 1 Surface roughness parameter R_z in function of cutting distance considering the whole experiment
Slika 1. Parametar hrapavosti površine R_z u ovisnosti o duljini rezanja tijekom cijelog eksperimenta

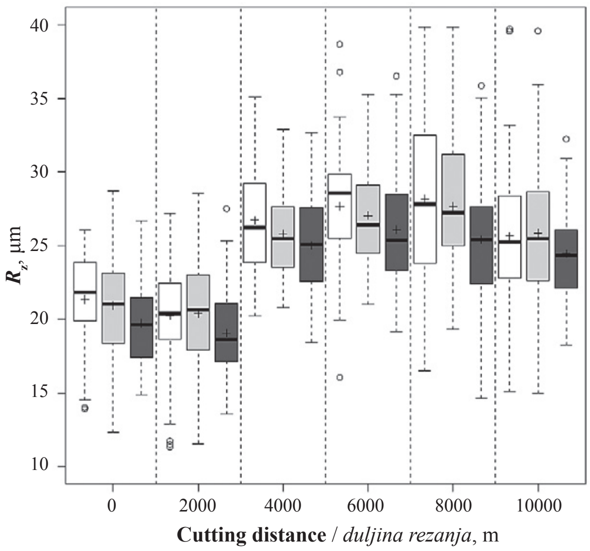

Figure 2 Surface roughness parameter R_z in function of cutting distance and cutting speed v_c (white 44 m/s, grey 50 m/s and black 56 m/s) considering the whole experiment
Slika 2. Parametar hrapavosti površine R_z u ovisnosti o duljini i brzini rezanja v_c (bijela 44 m/s, siva 50 m/s, crna 56 m/s) tijekom cijelog eksperimenta

Regarding the wear of the cutting tool, Figure 5 shows a comparison of cutting edges at the cutting distance of 0 meters and a dull condition of the knives after 10000 meters. The total average accumulated wear was of 3.5 μm. Both the Rake Face and the Clearance Face showed modifications to its original geometry. As shown in Figure 5, the most variable region is the so called land wear located on the Clearance Face. Future studies should focus on measuring this region through the cutting distance.

In this study, the behavior of roughness and wetting is described through the cutting distance. As it is well known, wettability is a thermodynamic response

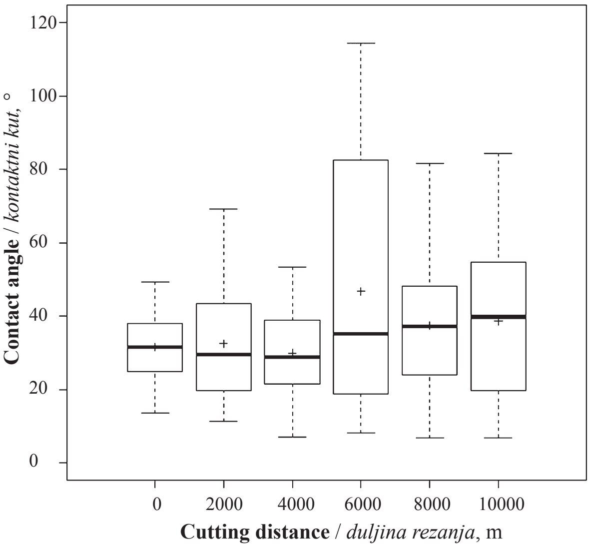

Figure 3 Contact angle θ in function of cutting distance considering the whole experiment
Slika 3. Kontaktni kut kvašenja površine θ u ovisnosti o duljini rezanja tijekom cijelog eksperimenta

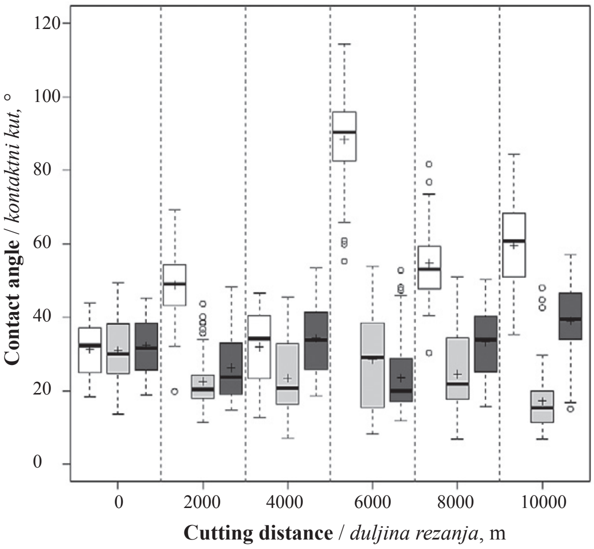

Figure 4 Contact angle θ in function of cutting distance and feed speed (white 22 m/min, grey 30 m/min and black 36 m/min) considering the whole experiment
Slika 4. Kontaktni kut kvašenja površine θ u ovisnosti o duljini rezanja i posmičnoj brzini v_f(bijela 22 m/min, siva 30 m/min, crna 36 m/min) tijekom cijelog eksperimenta

to physical and chemical properties of wood surfaces (Tshabalala, 2005). Apparently, chemical properties would be playing a more important role than physical properties, and their influence on wettability of a wood surface would be related in part to the wear of the cutting tool as a result of the cutting distance. This assumption is based on the null correlation found among roughness and wettability in this study. Hansson *et al*. (2011) indicate that surface roughness failed to correctly predict the contact angle on a heterogeneous surface with chemical or topological heterogeneities covered by the droplet. Frybort *et al*. (2014) explain that variability in wettability of a surface is largely determined by surface chemistry, besides other factors such as e.g. surface roughness, and conclude that differences in polarity between freshly cut cell walls and native inner lumen surfaces correlate with chemical heterogeneity. Apparently, the wear of the cutting tool, related to the cutting distance, produced a variation in the exposure of the chemical components of the wood ultrastructure and determined the thermodynamic behavior of the machined surface.

4 CONCLUSION
4. ZAKLJUČAK

The monitoring of the surface properties through the cutting distance has allowed a correlation to be

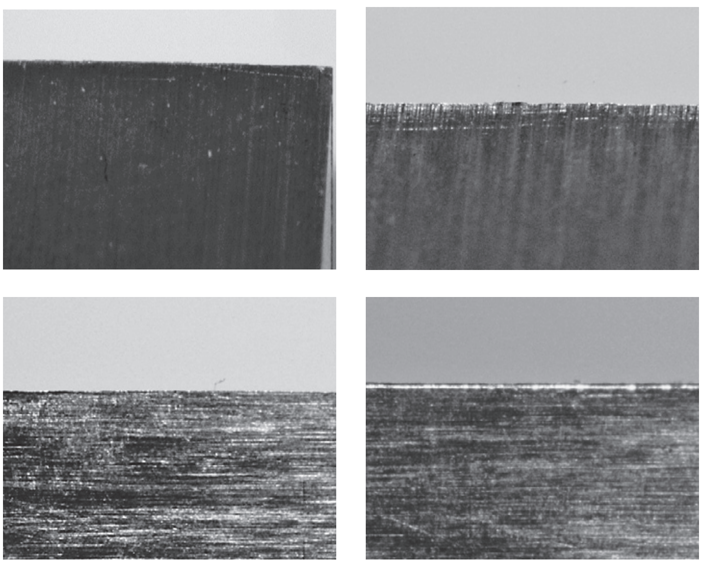

Figure 5 Cutting edge wear samples: cutting distance of 0 (left) to 10000 meters (right) Clearance Face (above) and Rake Face (below)
Slika 5. Primjeri trošenja oštrice alata: duljina rezanja 0 m (lijevo) i duljina rezanja 10 000 m (desno), leđna strana oštrice (gore) i prednja strana oštrice (dolje)

made between the wear of a cutting tool and the wettability of a machined surface. It is not reliable to explain the wettability of machined surfaces considering only the surface roughness on a heterogeneous surface such as wood. It is necessary to continue this study of the effect of the cutting distance with assessing changes in the surface chemistry and its relation with the thermodynamics of machined wood surfaces.

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Corresponding address:

Assist. Prof. ALDO ROLLERI S., Ph.D.

Forest Products Laboratory
Institute of Forest and Society
Faculty of Forest Science and Natural Resources
University Austral of Chile
Campus Isla Teja, Casilla 567, Valdivia
CHILE
e-mail: arolleri@uach.cl