Effect of Density, Moisture Content, and Feed Speed on the Surface Quality of Planed Pinewood Boards

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The main goal of this study was to verify the best combination of density, moisture content, and feed speed on the surface quality of *Pinus elliottii* boards aimed at deck manufacturing. The secondary goal was to compare three methods of surface quality assessment. Tangential boards were sampled and sorted by density (level 1: 414 kg·m^{-3} to 525 kg·m^{-3}; level 2: 526 kg·m^{-3} to 668 kg·m^{-3}) and moisture content (level 1: 13.5% to 17.5%; level 2: 17.6% to 20.0%). A four-side planer molder was used, at three levels of feed speed (15, 20, and 25 m·min^{-1}). Surface quality was assessed immediately after machining by visual-tactile analysis, stylus surface profilometer reading (parameters R_a, R_z, and R_t), and feed per tooth (f_z) measurement. The best surface quality results were obtained with denser (526 kg·m^{-3} to 668 kg·m^{-3}) and wetter boards (17.6% to 20.0% moisture content) at feed speed 20 m•min^{-1}. This recommendation represents an optimal balance between the quality standard of the deck boards and high productivity. Because of the low cost and because it has some correspondence with the stylus surface profilometer readings, visual-tactile analysis is recommended to assess the surface quality.

DOI: 10.15376/biores.18.4.7587-7600

Keywords: Deck manufacturing; Surface roughness; Feed per tooth; Visual-tactile analysis; Stylus surface profilometer

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INTRODUCTION

Data from the Associação Nacional dos Produtores de Pisos de Madeira (National Hardwood Flooring Association – Brazil 2011) indicate that 68% of Brazilian wood flooring production is concentrated only in the species *Hymenaea* spp. (jatobá), *Handroanthus* spp. (ipê), and *Dipteryx odorata* (Aubl.) Forsyth f. (cumaru). Considering environmental and economic aspects, it is important to have more species available for the manufacture of wood flooring, to reduce the impact on the few species that are traditionally used, as well as to diversify the production. These issues have led to the increasing use of wood-plastic composites for deck board manufacture (Machado *et al.* 2016).

Pinewood from fast-growing planted forests is the main raw material machined in Brazil to produce lumber, lathed veneers, and products made by secondary processing, such as plywood, doors, moldings, and furniture (Brazilian Association for Mechanically Processed Timber 2022). It has the potential for use as cladding and flooring, such as decks. With proper forest management, wood quality control, and processing, it is possible to make high-quality products that meet the requirements of demanding markets, such as those indicated in the European use classes (Wood Protection Association 2019).

Good surface quality in machining is achieved with wood having higher densities and lower moisture contents (Aguilera 2011), which was also reported by Silva *et al.* (2016) for eucalypt wood regarding density (15% moisture content). Out of three eucalyptus species (18 years old), Lopes *et al.* (2014) suggested *Eucalyptus urophylla* was the best for furniture manufacturing due to its higher density (690 kg·m^{-3}). Dias Júnior *et al.* (2013) suggested *Eucalyptus pellita* out of four eucalyptus species for solid products, although it was not the densest species. Other characteristics must also be considered, such as grain orientation (Hernández and Cool 2008; Coelho *et al.* 2011; Silva *et al.* 2016), as well as other anatomical features. Although it is an important factor regarding raw material quality, moisture content has not been frequently investigated.

For the cutting direction 90° to 0°, machining studies worldwide have mainly focused on feed speed (Malkoçoglu 2007; Hernández and Cool 2008; Dias Júnior *et al.* 2013; Lopes *et al.* 2014; Kvietková *et al.* 2015; Silva *et al.* 2016; Vanco *et al.* 2016; Andrade *et al.* 2018) because it is one of the most important parameters, along with cutting speed (Keturakis and Juodeikiené 2007; Braga *et al.* 2014; Silva *et al.* 2016; Vanco *et al.* 2016) and cutting depth (Hernández and Cool 2008; Aguilera 2011; Coelho *et al.* 2011). As a rule of thumb, better surface quality is achieved at a lower feed speed, but this leads to lower productivity. Thus, finding the most economically feasible balance between quality and productivity is one of the major challenges of wood machining, mainly when companies use machines of a lower level of technology.

Coelho *et al.* (2011) classified surface analysis methods as mechanical contact, artificial vision, pneumatic, friction, and visual-tactile. Among the objective methods, contact probing mechanical devices, such as the stylus contact profilometer (or roughmeter), are the most used globally. These devices commonly express the roughness in three parameters, R_a, R_z, and R_t, in which R_a (mean roughness) is most frequently used. However, in most cases, the qualitative and subjective visual-tactile method is the only test available in the wood industry.

The main goal of this work was to verify the best combination of density, moisture content, and feed speed on the surface quality of *Pinus elliottii* Engelm. boards, aimed at deck manufacturing. The secondary goal was to compare three methods of surface quality assessment.

EXPERIMENTAL

Boards Sampling and Sorting: Definition of the Qualitative Levels

Flatsawn boards of *Pinus elliottii* Engelm., from planted forests (no record of age), were sampled from air-drying stacks available for industrial processing, having nominal dimensions of 30 x 100 x 3000 mm (thickness x width x length). The boards were sorted by density and moisture content, both at two levels. The density was assessed by direct measurement of the dimensions of the boards, using a digital caliper (0.01 mm accuracy) for thickness and width and a measuring tape (1 mm accuracy) for length. The mass was measured with a digital scale (30 kg capacity) to the nearest 0.001 kg. The density of the wood (kg·m^{-3}) was calculated by dividing the mass by the volume, and the boards were sorted as level 1 (ranging from 414 to 525 kg·m^{-3}) or level 2 (ranging from 526 to 668 kg·m^{-3}).

A Hydromette HT 65 resistive moisture meter (Gann, Gerlingen, Germany) was used to sort the boards by moisture content, which were measured at the length midpoint. The moisture of the boards sorted as level 1 ranged from 13.5% to 17.5%, while for level 2 it ranged from 17.6% to 20.0%. The boards were machined immediately after the sorting, to ensure that the wood does not dry and, consequently, variations in density occur, resulting in a loss of the qualitative levels indicated above.

Deck Boards Manufacture and Statistical Treatments

The deck boards were manufactured in a PMM-220 5° E four-side planer molder (Omil, Ibirama, Brazil), at a rotation speed (n) of 5200 min^{-1}, cutting direction of 90°-0°, and a cutting depth of 1.5 mm. The boards were fed manually, and to minimize the bluntness effect of the cutting edges on the surface quality, the boards of the different statistical treatments were fed alternately, three by three. Only one surface was assessed, machined by a model 77 helical head (Fepam Tools, São Leopoldo, Brazil) with 125 mm diameter and z equal to 8 (Fepam Tools 2022), which had been freshly sharpened.

The feed speed was analyzed at three nominal levels, established based on the standard used by the company: 20 $\text{m}\cdot\text{min}^{-1}$ and two other levels, 5 $\text{m}\cdot\text{min}^{-1}$ above and below the standard. These feed speeds resulted, respectively, in feed per tooth (f_z) equal to 2.88 mm, 3.85 mm, and 4.81 mm. The calculated cutting speed was 34 $\text{m}\cdot\text{s}^{-1}$.

The interaction between the variables moisture content (two levels), density (two levels), and feed speed (three levels) resulted in 12 statistical treatments. From now on, treatment means the same as “statistical treatments”. Fifteen boards were machined per treatment, resulting in 180 boards assessed.

Surface Quality

Surface quality was assessed immediately after machining by visual-tactile analysis, stylus surface profilometer reading, and feed per tooth (f_z) measurement. These methods were adopted because they are widely used in industry (Coelho *et al.* 2011) and by researchers (Andrade *et al.* 2018; Braga *et al.* 2014; Dias Júnior *et al.* 2013; Malkoçoglu 2007; Martins *et al.* 2011; Ramananantoandro *et al.* 2014; Silva *et al.* 2016) to assess surface quality. For all methods, the analyses were carried out at the same points, in three different positions of the boards: at half-length and 100 mm from each end). The three measurements for each method were used to compute the arithmetic mean per board.

For f_z measurement, a 25 mm line was marked on the boards with a ruler and a pencil in the feed direction, and the number of marks caused by the cutting tool was counted with a magnifying glass (15 x), similar to what is described by Aguilera (2011). The larger the distance between the marks, the more visible they are, representing a worse surface quality and vice versa. Three evaluators were used in the visual-tactile analysis, who classified the decks in grades from 1 (best quality= “excellent”, defect-free) to 5 (worst quality= “very poor”), according to the standard D 1666-87 (American Society for Testing and Materials 1999).

The surface roughness was measured using a stylus surface profilometer model TR200 (Digimess, São Paulo, Brazil), according to the technical procedures described in the device’s manual, which has as reference NBR ISO 4287 (Brazilian Association of Technical Standards 2002). A cut-off length of 2.5 mm combined with a Gaussian filter was used at a measurement length of 12.5 mm. The equipment measured the roughness parameters R_a (mean roughness), R_z (mean peak-to-valley height or total roughness), and R_t (maximum roughness).

Statistical Analysis

The significance level was up to 5% for all tests. The R_a, R_z, and R_t data were analyzed in a completely randomized design in a 2 x 2 x 3 factorial arrangement: The factors were density (two levels), moisture content (two levels), and feed speed (three levels), with 15 repetitions.

The effect of the factors and the interaction between them was verified by analysis of variance (ANOVA). When the null hypothesis was confirmed ($P<0.05$), the Tukey test was applied to compare the means of the treatments. In cases where there was a significant interaction ($P<0.05$) between the factors, Pearson's correlation matrix was used.

The mean grades of the visual-tactile analysis and the f_z counts were transformed into ranks and analyzed by the Kruskal-Wallis H-test, according to the same 12 treatments of the factorial analysis. When the null hypothesis was confirmed ($P<0.05$), Bonferroni's test was applied to compare the mean ranks of the treatments.

RESULTS AND DISCUSSION

Roughness Parameters

Table 1 shows the means of R_a, R_z, and R_t by treatment, as well as the means of density and moisture content.

Table 1. Studied Factors and Roughness Parameters R_a, R_z, and R_t by Treatment

Treatment	Density (kg·m^{-3})	Moisture content (%)	Feed speed (m·min^{-1})	R_a (μm)	R_z (μm)	R_t (μm)
1	484 (3.8%)	15.9 (5.2%)	15	4.921 (17.5%)	28.99 (19.0%)	41.57 (25.7%)
2	480 (5.6%)	17.8 (2.8%)		5.154 (16.1%)	31.02 (16.5%)	43.75 (18.7%)
3	587 (7.6%)	15.6 (7.9%)		4.308 (16.0%)	26.69 (20.0%)	37.22 (23.3%)
4	547 (3.9%)	18.5 (4.7%)		5.192 (16.9%)	30.67 (16.6%)	42.84 (18.9%)
5	484 (5.1%)	16.2 (7.3%)	20	5.081 (15.5%)	30.70 (18.0%)	45.15 (20.2%)
6	495 (4.8%)	18.3 (2.5%)		5.066 (14.1%)	30.54 (18.4%)	44.55 (26.2%)
7	579 (6.3%)	16.4 (6.2%)		4.941 (23.3%)	28.45 (25.3%)	40.11 (25.0%)
8	565 (5.9%)	18.8 (3.7%)		4.723 (17.2%)	27.99 (20.0%)	40.10 (25.0%)
9	474 (5.4%)	16.5 (3.9%)	25	5.616 (9.0%)	32.74 (9.6%)	45.63 (8.2%)
10	474 (5.8%)	18.5 (3.4%)		5.435 (16.2%)	32.17 (17.0%)	45.80 (22.8%)
11	573 (8.3%)	15.5 (5.1%)		4.913 (15.0%)	28.19 (18.8%)	39.39 (17.8%)
12	616 (13.2%)	18.0 (2.9%)		5.131 (16.1%)	29.61 (17.8%)	41.78 (18.0%)

Note: Results in parentheses are the coefficients of variation (%).

The discussion is presented initially in terms of absolute means. Treatment 3 (density level 2, moisture content level 1, and feed speed equal to 15 m·min^{-1}) had the lowest means of R_a (4.308 µm), R_z (26.69 µm), and R_t (37.22 µm). In contrast, treatment 9 (density level 1, moisture content level 1, and feed speed equal to 25 m·min^{-1}) had the highest means of R_a (5.616 µm), R_z (32.74µm), and R_t (45.63 µm). The roughness amplitudes between the highest and lowest absolute means were 1.308 µm, 6.05 µm, and 8.41 µm, respectively, for R_a, R_z, and R_t.

Table 2 summarizes the ANOVA results of the parameters R_a, R_z, and R_t in a factorial arrangement. In these analyses, the effect of the individual factors was verified, as well as the interactions (double and triple). There was no significant double or triple interaction ($P>0.05$) for any of the three roughness parameters. Only the effect of density was significant ($P<0.05$) for the three parameters. Additionally, the effect of feed speed was significant ($P <0.05$) only for R_a. Thus, the roughness parameters were analyzed for every individual factor and the results for density, feed speed, and moisture content are presented in Tables 3, 4, and 5, respectively.

The effect of density was the same for all roughness parameters, where the roughness was lower for the highest level of density, meaning better surface quality. The absolute amplitudes between the means were 0.347, 2.44, and 4.19 µm for R_a, R_z, and R_t, respectively. These results are depicted in Fig. 1.

Table 2. Summary of ANOVA in a Factorial Arrangement of Roughness Parameters

Variation Source	**R_a**		**R_z**		**R_t**	
	Fc	P-value	Fc	P-value	Fc	P-value
Density (D)	8.035	0.0052*	9.069	0.0030*	9.664	0.0022*
Moisture content (MC)	1.571	0.2118^{ns}	1.667	0.1984^{ns}	1.481	0.2253^{ns}
Feed speed (Vf)	3.762	0.0252*	1.167	0.3138^{ns}	0.628	0.5351^{ns}
D X MC	1.263	0.2628^{ns}	0.514	0.4746^{ns}	0.552	0.4585^{ns}
D X Vf	0.387	0.6799^{ns}	0.609	0.5452^{ns}	0.319	0.7271^{ns}
MC x Vf	2.866	0.0597^{ns}	1.551	0.2152^{ns}	1.551	0.4346^{ns}
D x MC x Vf	1.103	0.3344^{ns}	0.230	0.7950^{ns}	0.095	0.9090^{ns}

*: Significant (95% confidence level); ns: not significant (95% confidence level).

Table 3. Results for R_a, R_z, and R_t as a Function of Density Level

Density Level	**Density (kg·m^{-3})**			**R_a (µm)**	**R_z (µm)**	**R_t (µm)**
	Minimum	Mean	Maximum			
1	414	483 (5.2%)	525	5.217 a (15.1%)	31.03 a (16.5%)	44.41 a (20.6%)
2	526	577 (8.7%)	668	4.870 b (18.1%)	28.59 b (19.6%)	40.22 b (21.3%)

Note: Means followed by the same letter in the column do not differ statistically by the Tukey test ($P>0.05$). Numbers in parentheses correspond to the coefficient of variation.

This inversely proportional relationship between density and roughness has been found in other experiments (Lopes *et al.* 2014; Silva *et al.* 2016). Denser wood has higher mechanical resistance, which leads to a good relationship with cutting direction 90° to 0° due to less surface damage and defects, resulting in better surface quality. According to Silva *et al.* (2016), low-density woods have more fragile tissues, and after machining, the cells pull out, resulting in fuzzy surfaces. Hence, to improve the surface quality of deck boards, companies should improve quality control regarding density. This is also an important aspect to produce deck boards with higher mechanical resistance.

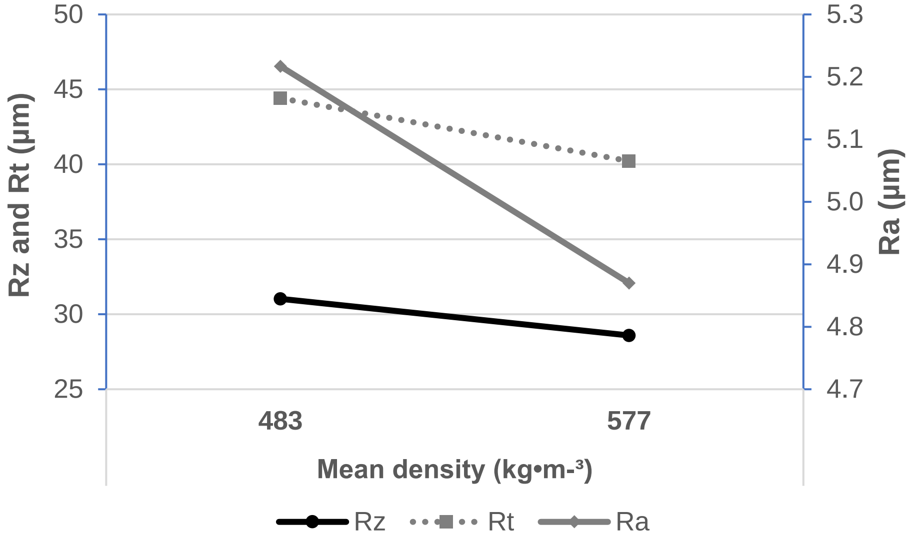

Fig. 1. Trend lines of the roughness parameters in function of density

As previously mentioned, only R_a was significantly influenced by feed speed, in which the lower the feed speed, the higher the surface quality was (lower mean), as shown in Table 4. R_z and R_t had the same effect, but only in terms of absolute means, which can be seen in Fig. 2. Since there was no significant difference between the means of R_z and R_t as a function of the different levels of feed speed, there was no increase or decrease in the distances between the peaks and valleys of the analyzed profiles. Malkoçoglu (2007) also reported a non-significant effect of feed speed (7.6, 12.6, and 20.0 m•min^{-1}) on R_z for *Pinus sylvestris* and *Picea orientalis*, as well as three other hardwood species.

Pinheiro (2014) concluded that R_t was more sensitive than R_a for some machining parameters (feed speed was not analyzed by that author), which is opposite the result shown in Table 4. On the other hand, Ramananatoandro *et al.* (2014) stated that R_a is by far the most common parameter for surface quality ranking. Indeed, some authors have used only this roughness parameter (Hernández and Cool 2008; Dias Júnior *et al.* 2013; Lopes *et al.* 2014; Kvietková *et al.* 2015; Andrade *et al.* 2018; Darmawan *et al.* 2020). The reason is that R_a is displayed on most stylus surface profilometers, as well as other devices, and is easily interpreted (representing the arithmetic mean roughness).

Table 4. Results for R_a, R_z, and R_t as a Function of Feed Speed

Feed speed (m·min^{-1})	**R_a (µm)**	**R_z (µm)**	**R_t (µm)**
15	4.893 b (17.8%)	29.34 a (18.4%)	41. 34 a (22.0%)
20	4.952 ab (17.6%)	29.42 a (20.4%)	42.48 a (24.2%)
25	5.276 a (14.8%)	30.70 a (16.7%)	43.18 a (18.2%)

Note: Means followed by the same letter in the column do not differ statistically by the Tukey test (P>0.05). Numbers in parentheses correspond to the coefficient of variation.

The cause-effect relationship between feed speed and surface quality is strongly consolidated in the literature (Aguilera 2011), making feed speed one of the most important factors in wood machining. The effect shown in Fig. 2 is the same as reported by Vanco *et al.* (2016) for another pinewood species (*Pinus sylvestris*) at lower levels of feed speed (6, 10, and 15 m•min^{-1}). However, feed speed was significant for R_a, R_z, and R_t only with a difference of 10 m•min^{-1} between the lowest (15 m•min^{-1}) and highest level (25 m•min^{-1}), since the average level (20 m•min^{-1}) did not differ significantly from the other levels (Table 4).

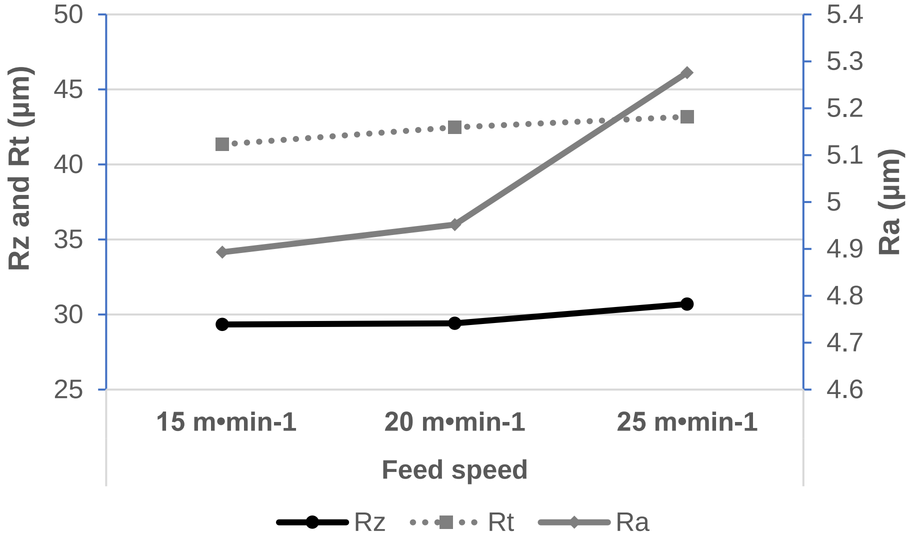

Fig. 2. Trend lines of roughness parameters in function of feed speed

The literature reports different effects of feed speed on R_a for feed speed higher than 15 m•min^{-1}. Hernández and Cool (2008) reported significant improvement in surface quality (R_a) for *Betula papyrifera* from 36.8 m•min^{-1} to 15.7 m•min^{-1}. On the other hand, a non-significant effect was reported by Silva *et al.* (2016) for five eucalyptus species when changing feed speed from 15 to 30 m•min^{-1}. Besides the different wood species, other machining parameters might have influenced these contrasting results, such as the cutting speed and the cutting depth, as well as the method used for measuring R_a.

Despite this discussion and the statistical tests, the absolute amplitudes between the highest (feed speed = 25 m•min^{-1}) and lowest (feed speed = 15 m•min^{-1}) means were 0.383, 1.36, and 1.84 µm, respectively for R_a, R_z, and R_t. It is necessary to verify whether such amplitudes represent different deck board quality regarding surface roughness.

As previously discussed, the roughness parameters were not significantly influenced by moisture content, as can be seen in Table 5. However, there was a trend of lower roughness for lower moisture content (Fig. 3). The amplitudes between the highest (level 2) and lowest (level 1) means were 0.254, 1.04, and 1.64 µm, respectively, for R_a, R_z, and R_t.

The trend lines presented in Fig. 3 are in agreement with those presented by Pinheiro (2014), who also reported for milled *Pinus elliottii* that R_a and R_t increased with increasing moisture content. Pinheiro (2014) studied three moisture content levels, at shorter ranges ($8\% \leq x < 12\%$; $12\% \leq x < 16\%$; and $16\% \leq x < 20\%$). In general, increasing moisture content reduces the mechanical resistance of wood, resulting in less resistant cells to the cutting forces. At certain levels, this effect can reduce surface quality, but no significant effect was verified in this work, even in a wide range of moisture content values (from 13.5% to 20.0%).

Table 5. Results for R_a, R_z, and R_t as a Function of Moisture Content Level

Moisture Content Level	Moisture Content (%)			R_a (µm)	R_z (µm)	R_t (µm)
	Minimum	Mean	Maximum			
1	13.5	16.0 (6.1%)	17.5	4.867 a (16.5%)	29.30 a (18.1%)	41.51 a (20.3%)
2	17.6	18.3 (3.6%)	20.0	5.121 a (17.3%)	30.34 a (18.8%)	43.15 a (22.6%)

Note: Means followed by the same letter in the column do not differ statistically by the Tukey test (P>0.05). Numbers in parentheses correspond to the coefficient of variation.

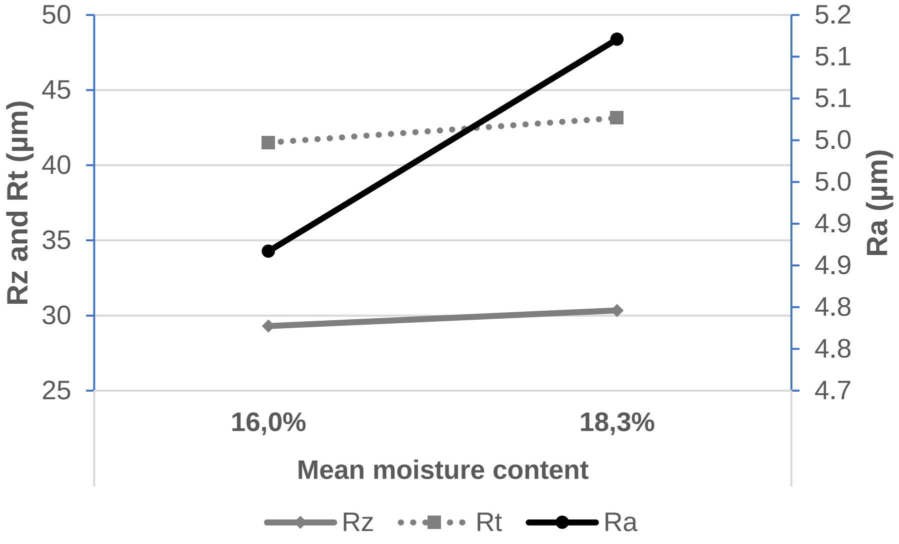

Fig. 3. Trend lines of the roughness parameters in function of moisture content

The results found for moisture content were interesting regarding industrial production because moisture content did not affect surface roughness in a mean range from 16.0% to 18.3%. This indicates that it is possible to process boards at a higher mean level without compromising surface quality, which is particularly important in the case of fast-drying species such as *Pinus elliottii*, enabling a shorter air-drying cycle. However, it is necessary to verify the equilibrium moisture content of the place where the deck boards will be installed to understand the behavior regarding dimensional stability and the possibility of associated defects, such as warping and cracks.

Visual-tactile Analysis

Table 6 shows the results of the visual-tactile analysis. Lower mean grades and their respective mean ranks represent better surface quality. According to the H-test of Kruskal-Wallis (H_c= 31.28), there was a significant difference (P<0.05) between at least one of the mean ranks analyzed. Hence, the mean ranks were differentiated according to the Bonferroni test.

Treatment 7 (density level 2, moisture content 1 and feed speed equal 20 m•min^{-1}) had the lowest absolute mean rank, but it did not differ significantly from treatment 11 (density level 2, moisture content level 1 and feed speed= 25 m•min^{-1}). Hence, these treatments produced the best surface quality among all treatments.

Treatment 1 (density level 1, moisture content level 1, and feed speed equal to 15 m•min^{-1}) had the highest absolute mean rank, but it did not differ significantly from the other seven treatments (2, 4, 5, 6, 9, 10 and 12). This indicates these treatments had the worst surface quality. Furthermore, there was no significant difference between treatments represented by all levels of density, moisture content, and feed speed.

Table 6. Results of the Visual-tactile Analysis by Treatment

Treatments	Density (kg·m^{-3})	Moisture Content (%)	Feed Speed (m•min^{-1})	Mean Grades	Mean Ranks
1	484	15.9	15	2.00	113 a
2	485	17.8		1.93	106 ab
3	587	15.6		1.67	84 bc
4	547	18.5		1.93	106 ab
5	484	16.0	20	1.80	95 ab
6	495	18.3		1.73	90 ab
7	579	16.4		1.30	54 d
8	565	18.8		1.67	84 bc
9	474	16.5	25	1.73	90 ab
10	474	18.5		1.87	101 ab
11	573	15.5		1.40	60 cd
12	616	18.0		1.86	99 ab

Note: Mean ranks followed by at least one same letter in the column do not differ statistically by the Bonferroni test (P>0.05).

Despite the discussion based on the statistical tests, the amplitude between the highest (treatment 1) and the lowest (treatment 7) mean grade was 0.70, for a scale from 1 (“excellent” quality) to 5 (“very poor” quality). This is a small amplitude, and all treatments were classified from “excellent” (grade 1) to “good” (grade 2), according to the American Society for Testing and Materials (1999) standard.

Feed per tooth (f_z) Analysis

Table 7 shows the results of the f_z analysis. Lower means (mm) and their respective mean ranks represent better surface quality. According to the Kruskal-Wallis H-test (H_c= 114.19), there was a significant difference ($P<0.05$) between at least one of the mean ranks analyzed. Hence, they were differentiated according to the Bonferroni test.

Treatment 2 (density level 1, moisture content level 2, and feed speed equal to 15 m•min^{-1}) had the lowest mean rank of f_z, but it did not differ significantly from the other treatments with the same feed speed, *i.e.*, treatments 1, 3, and 4. This indicates that the factors density and moisture content did not affect the surface quality according to the fz method. This result is consistent since the measured f_z has a stronger relationship with the machining conditions than with the raw material (expressed by density and moisture content).

Treatment 9 (density level 1, moisture content level 1, and feed speed equal to 25 m•min^{-1}) had the highest mean rank, but it did not differ significantly from treatments 11 (density level 2, moisture content level 1, and feed speed equal to 25 m•min^{-1}) and 12 (density level 2, moisture content level 2 and feed speed equal to 25 m•min^{-1}), both with the same feed speed as treatment 9. Likewise, for the treatments with the best surface quality, density, and moisture content did not affect this quality according to the f_z method.

Table 7. Results of the Feed per Tooth (f_z) Analysis by Treatment

Treatments	Density (kg·m⁻³)	Moisture Content (%)	Feed Speed (m•min^{-1})	Mean f_z (mm)	Mean Rank
1	484	15.9	15	2.8	33 d
2	485	17.8		2.8	27 d
3	587	15.6		2.9	40 d
4	547	18.5		2.8	33 d
5	484	16.0	20	3.6	97 c
6	495	18.3		3.6	88 c
7	579	16.4		3.6	90 c
8	565	18.8		3.6	92 c
9	474	16.5	25	4.4	155 a
10	474	18.5		4.1	138 b
11	573	15.5		4.3	145 ab
12	616	18.0		4.2	146 ab

Note: Mean ranks followed by at least one same letter in the column do not differ statistically by the Bonferroni test (P>0.05).

The treatments could be divided into three groups of average f_z ranks according to feed speed (Fig. 4). Thus, the treatments with the lowest feed speed (15 m•min^{-1}, light gray bars) had the best surface quality.

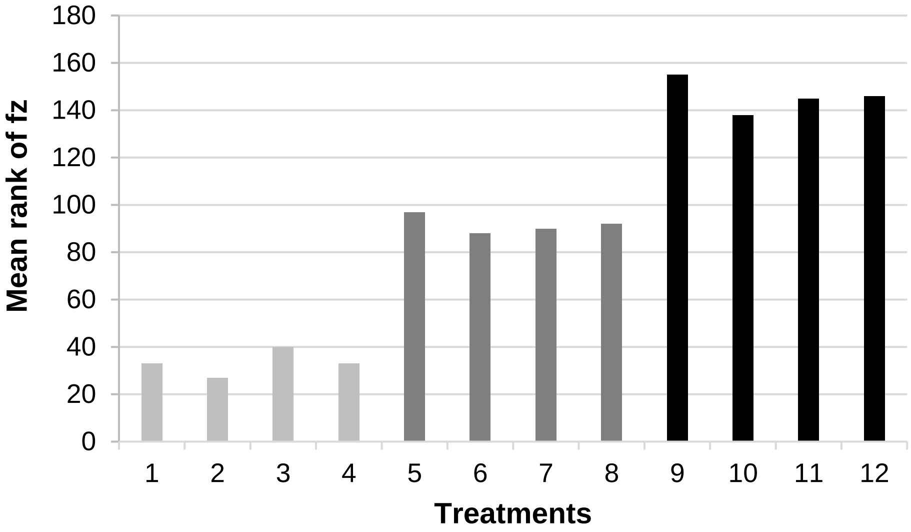

Fig. 4. Mean ranks of feed per tooth (fz): light gray bars feed speed= 15 m•min^{-1}.; gray bars feed speed= 20 m•min^{-1}; black bars feed speed= 25 m•min^{-1}.

According to the classification of the Serviço Nacional de Aprendizagem Industrial (National Industrial Apprenticeship Service 1995), planed boards with f_z from 2.5 mm to 5.0 mm are classified as having a “coarse” texture. The mean f_z ranged from 2.8 mm (treatments 1, 2, and 4) to 4.4 mm (treatment 9), so based on this classification, all treatments were ranked as “coarse” textures. These measurements of f_z are similar to the calculated (theoretical) ones, with respectively 2.88, 3.85, and 4.81 mm for feed speeds 15, 20, and 25 m•min^{-1}.

Comparison of the Methods

For this comparison, common patterns were identified among the results of the three methods. According to the roughness parameters (stylus surface profilometer) and the visual-tactile analysis, the denser and drier boards had higher surface quality. For roughness, there was a tendency for better quality at the lowest feed speed (15 m•min^{-1}), but for the visual-tactile analysis, better results were obtained at the higher feed speed values (20 and 25 m•min^{-1}). That is, there was a divergence between the methods regarding feed speed, but they agreed regarding density and moisture content.

The f_z method discriminated surface quality strictly by the feed speed, not allowing detection of any relation with density or moisture content. This result was expected because f_z is a count of marks of the cutting edges in a given linear length. However, f_z had good correspondence with R_a regarding feed speed, where better surface quality was obtained at lower feed speed in both methods.

It was expected that the visual-tactile method would detect the sensorial perception of f_z, due to the wavy surfaces. However, this did not occur, because the best results of the visual-tactile method were not at the lowest feed speed, as indicated by f_z. Thus, the analysis of f_z complements the other methods.

The stylus surface profilometer has the advantage of generating quantitative rather than subjective data, unlike the visual-tactile analysis, which depends totally on the evaluators’ perception. This gives greater accuracy to the former method, which can be useful in some types of markets, especially international one, which demands objective and universal measurements. However, it is very time-consuming and requires a higher initial investment compared to other methods. This creates a disadvantage for industrial production, which requires fast decisions and operations, aiming at reducing costs.

The visual-tactile analysis does not require investment in equipment to be performed, but it does require greater experience from the workers than required to operate the stylus surface profilometer. This analysis is quite comprehensive because it considers aspects beyond surface roughness, such as machining defects. The use of this method by more experienced workers would reduce errors resulting from inherent subjectivity. In addition to the lower initial investment and the quick evaluation, a visual-tactile classification can be more easily interpreted and even carried out by consumers, especially if the product does not have subsequent finishing (sanding and surface coating). This can be advantageous from a commercial standpoint.

For scientific purposes, all three methods should be used to support decisions because they have different perspectives, advantages, and disadvantages. For example, if only f_z is used, the conclusion would be that the best surface quality is obtained at feed speed= 15 m•min^{-1}. If only R_a is used, the best surface quality would be obtained at both 15 m•min^{-1} and 20 m•min^{-1}. For the visual-tactile analysis, “excellent” to “good” surface quality can be achieved even at a feed speed equal to 25 m•min^{-1}.

CONCLUSIONS

1. It is better to use denser (526 to 668 kg·m^{-3}) and wetter boards (17.6% to 20.0% moisture content) at a feed speed of 20 m•min-^{1} to achieve better surface quality in planning pinewood (*Pinus elliottii* Engelm.). This recommendation represents an optimal balance between the quality standard of the deck boards and higher productivity.
2. The effect of density was significant on the surface roughness, in which better surface quality was obtained at the highest level (526 kg·m^{-3} to 668 kg·m^{-3}, mean equal to 577 kg·m^{-3}). The effect of feed speed was significant on the roughness parameters, and the best surface qualities were obtained at 15 m•min^{-1} and 20 m•min^{-1}.
3. The effect of the different levels of moisture content (13.5% to 17.5% and 17.6% to 20.0 %) was not significant on the surface roughness. Regarding the surface roughness parameters R_a, R_z, and R_t, there was no significant interaction (double or triple) between the factors density, moisture content, and feed speed.
4. Because of the low cost and some correspondence with the stylus surface profilometer (quantitative measurements), the visual-tactile analysis is recommended to assess the surface quality. However, for better decisions, other methods should also be applied. It is also necessary to check market requirements for quantitative and universally interpreted measurements, such as those obtained with the profilometer.
5. For future research, it is suggested to investigate the influence that boards classification exerts on the economic aspect of industries, making them more competitive, with higher-quality products.

ACKNOWLEDGMENTS

This work was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES) – Finance Code 001.

The present work was carried out with the support of the Research and Innovation Support Foundation of Espírito Santo (Fapes) - <Notice Number 05/2023>.

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Article submitted: May 4, 2023; Peer review completed: May 27, 2023; Revised version received: July 19, 2023; Accepted: July 21, 2023; Published: September 19, 2023.
DOI: 10.15376/biores.18.4.7587-7600