Analysis of the Parameters Affecting the Surface Sanding of *Pinus elliottii* and *Corymbia citriodora* Wood Species

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Wood is a versatile and renewable material. It features characteristic mechanical resistance, thermal and electrical insulation, easy workability, and low energy consumption during processing. These properties make it attractive compared with other materials, mainly in the manufacturing and civil construction industries. One of the most important processes in the logging industry is sanding, though it is treated empirically by companies without a systematic study of the influence of its parameters, and it incurs high costs in this sector. Therefore, this work analyzed the effects of the sandpaper parameters (grit size and type of abrasive), wood parameters (species and fiber direction), and contribution percentage thereof on the behavior of the surface roughness and removal rate of the material. The Taguchi method was applied, and tests were performed on a flat sander with a pneumatic circuit and monitoring system for data acquisition. The tests were analyzed statistically by analysis of variance. The results showed that the surface roughness and removal rate were significantly influenced by the sandpaper parameters, but not by the wood parameters. Also, the aluminum oxide sandpaper presented greater durability and resulted in lower roughness values.

Keywords: Surface quality; Roughness; Removal rate; Pinus elliottii; Corymbia citriodora

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INTRODUCTION

Wood is a notable ecological material because of its beauty and versatility, and is mainly applied in the building and construction industries. Wood obtained from sustainably managed forests is one of the most environmentally-friendly materials, and its manufactured products are fundamental in modern society (Ramage *et al.* 2017).

One of the most important processes in the forestry industry is sanding to adjust the dimensions and surface finish of the product (Bao *et al*. 2018). Sanding is a prerequisite for subsequent processes involving the application of coatings, such as varnish, paint, adhesive, glue, sealant, or even a colorless varnish to improve the appearance of raw wood and highlight its visual appearance (Varasquim *et al*. 2012).

The main indicator of the surface quality of wood that undergoes sanding is the roughness (Ugulino and Hernandez 2018). The roughness characteristic includes micro geometric irregularities. This can be measured through the surface roughness (R_a), and the value represents the arithmetic mean of the absolute values of the deviations found from the surface measurement (Gottlöber 2014). According to Kilic *et al.* (2006), the pen method using one of the measures R_a can be used to evaluate and distinguish variations on the surface of the wood in the sanding process.

The roughness directly influences the quality of the wood surface finish. According to Xavior *et al.* (2017), the roughness and residual stress are the main problems of surface integrity and affect the quality and useful life of a product. De Moura *et al.* (2010) stated that low roughness values reduce the area available for adhesion in processes involving gluing of wood. Cool and Hernández (2011) advocated for a minimum level of fibrillation of the cell wall to improve the coating performance. Rough surfaces, which have high roughness values, hinder the adhesion of the coating, requiring a greater product quantity and interfering with the finish quality (Tiryaki *et al.* 2014).

Because of the large number of factors present in the sanding process related to the wood, sandpaper, and machines, it is necessary to apply an experimental planning method to minimize the number of experimental conditions that need to be investigated. The Taguchi method provides such an approach (Zhang *et al*. 2015). According to Hamzaçebi (2016) the Taguchi method is an effective and robust experimental design technique that determines the most important factors and their impact on the optimization of process parameters through the reduction of number of experiments performed. Works applying the Taguchi method in experimental timber planing include Hamzaçebi (2016), Ke *et al.* (2016), and Denes *et al.* (2006). For the application of this method, the following steps are performed: (a) identifying the factors that interfere with the product quality; (b) choosing the factor levels; (c) choosing the orthogonal matrix; (d) performing the tests; and (e) analyzing the results using the signal-to-noise (S/N) ratio and a variance analysis (Denes *et al.* 2006). After identifying the number of factors to be investigated, the factor values are specified as levels. Then, the orthogonal matrix is chosen to be described by *Ln*, where *n* is the number of conditions tested (Mertol 1995). The Taguchi method involves analysis of the average response for each combination in the arrangement using the S/N ratio, which can be categorized into three types: smaller is better, greater is better, and nominal. These S/N ratio categories can be calculated according to Eqs. 1, 2, and 3, respectively,

$$S/N = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

$$S/N = -10\lg\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \tag{2}$$

$$S/N = -10\lg\left(\frac{1}{ns}\sum_{i=1}^{n} y_i^2\right) \tag{3}$$

where *y* is the value of the response, *n* is the number of repetitions, and *s* is the standard deviation (Gu *et al*. 2014).

The Taguchi method was applied in this work to analyze the contribution percentage of the sandpaper and wood parameters to the removal rate and surface roughness during sanding of *Pinus elliottii* and *Corymbia citriodora*.

These species were chosen because Brazil has promoted a progressive substitution of native forests for forestry to supply the timber industry, opting for the production of young, short cycle, and fast growing forests, especially *P. elliottii* and *C. citriodora*; these species are adapted to the soil and Brazilian climate, presenting a rapid growth, besides easy handling, attractive that made them important raw materials in the supply of timber industries, and therefore, are present in the coverage of the forest stand (Merry *et al.* 2009).

EXPERIMENTAL

Materials

For the sanding tests, aluminum oxide sandpaper from Norton Saint-Gobain (Paris, France) and silicon carbide sandpaper from DEERFOS Co., Ltd. (Incheon, South Korea) were used. These sandpapers were properly heated and packed to meet the ideal use conditions, according to ABNT NBR 14960 (2003).

The selected wood species were *P. elliottii* and *C. citriodora*, from a planted forest in the southeast of the state of São Paulo, and both species had a diameter at breast height of 50 cm and apparent density of 355.9 and 463.8 kg/m^3. The samples were packed at 40 °C and a maximum relative humidity of 70% to stabilize the equilibrium moisture content (EMC) at 12%, according to ABNT NBR 7190 (1997). The final dimensions of the samples were 54 mm, 30 mm, and 23 mm in the longitudinal (length), tangential (width), and radial (thickness) wood directions, respectively.

Structure of the Test System

For the experiments, a flat sander (LFH-2, Baldan, Guariba, Brazil) was used with support and pressure control from a pneumatic cylinder, which had a rod that affixed the wood samples during the sanding process. To determine the power consumed by the engine, a sensor (LEM AT5B10, LEM International SA, Geneva, Switzerland) was used, which collected and transmitted the engine current to a data acquisition plate (NI PCI 6220, National Instruments, Austin, TX, USA). The data was analyzed by a program developed in LabVIEW software (version 2014, National Instruments, Austin, TX, USA), which was installed on a microcomputer. All of the collected data was stored in individual files according to the parameters measured by the sensors.

Experimental Procedure

The orthogonal matrix arrangement chosen for the experiment was L8 $(2)^3$ because the combinations were stipulated in relation to the grit size and the other three factors each had two levels, which resulted in eight different sanding conditions. The parameters of the sandpaper and wood were considered for the application of the Taguchi method. The sandpaper parameters were the grit size and type of abrasive. The grit size was divided into Level 1 (80 grit size), Level 2 (100 grit size), Level 3 (100 grit size), and Level 4 (220 grit size), and the type of abrasive factor was divided into Level 1 (aluminum oxide) and Level 2 (silicon carbide). The wood parameters were the fiber direction and wood species. The fiber direction was divided into Level 1 (parallel) and Level 2 (perpendicular), and the wood species was divided into Level 1 (*P. elliottii*) and Level 2 (*C. citriodora*).

The eight combinations of the factors were repeated three times each, and the average y value was calculated for use in Eq. 1. The calculations and analysis of variance (ANOVA) were performed using the Minitab statistical analysis program (Pennsylvania State University, University Park, USA) with a 5% significance level.

Surface Roughness and Removal Rate

To acquire the roughness data, nine measurements were collected along the surface of each sample with a rugosimeter (M300 C-RD 18C2, Mahr, São Paulo, Brazil). From these values, the average of the surface roughness was calculated. Additionally, a robust Gaussian filter was used in the rugosimeter to obtain the roughness characteristics and sampling length (Le) or cut-off (λ_c) of 2.5 mm.

The removal rate was calculated by dividing the volume of the wood sanded by the time. All of the samples had 2 mm removed from the thickness. Therefore, because of the defined dimensions of the samples, it was calculated that 2 mm × 30 mm × 54 mm (3240 mm^3) of the wood was removed. The time was obtained by analysis of the power behavior during the sanding process.

RESULTS AND DISCUSSION

Table 1 presents the orthogonal matrix with the eight conditions established by the Taguchi method and their average roughness (µm) and removal rate values (mm^3/s).

Table 1. Sanding Conditions with Mean Values of Roughness and Removal Rate

Condition				Average Roughness (µm)	Removal Rate (mm^3/s)
Grit Size	Type of Abrasive	Fiber Direction	Species		
80 mesh	Oxide	Parallel	*P. elliottii*	8.16	254.70
80 mesh	Carbide	Perpendicular	*C. citriodora*	11.70	200.98
100 mesh	Oxide	Perpendicular	*P. elliottii*	7.11	159.83
100 mesh	Carbide	Parallel	*C. citriodora*	8.97	137.78
120 mesh	Oxide	Parallel	*C. citriodora*	6.25	128.62
120 mesh	Carbide	Perpendicular	*P. elliottii*	7.02	115.45
220 mesh	Oxide	Perpendicular	*C. citriodora*	3.65	84.34
220 mesh	Carbide	Parallel	*P. elliottii*	5.23	46.45

Figure 1 shows the Taguchi chart and behavior of the roughness in relation to the factor levels established during the sanding process.

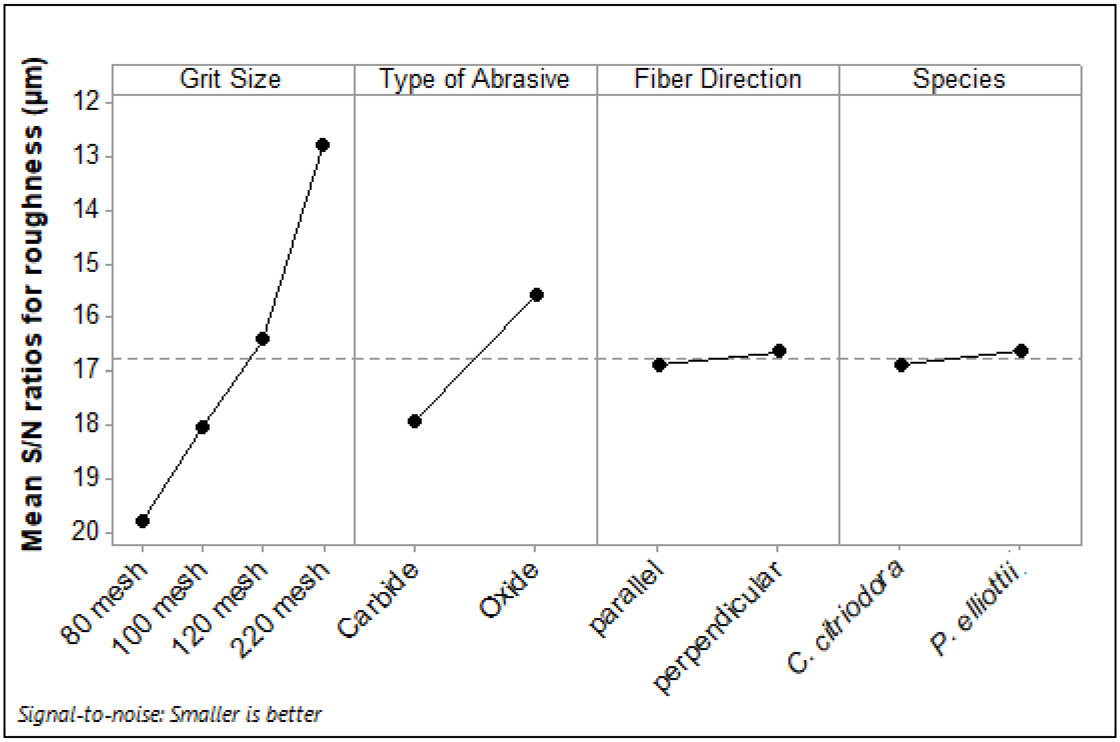

Fig. 1. Behavior of the surface roughness of the sanding process in relation to the grit size, type of abrasive, direction of the fibers, and species

When analyzing Fig. 1, the smallest roughness was obtained with the combination perpendicular sanding of *P. elliottii* with aluminum oxide and a 220-grit size, while the greatest roughness was observed with the combination parallel sanding of *C. citriodora* with silicon carbide and an 80-grit size). The influence of the average roughness factors is shown in Table 2, and was represented by the influence percentage for each factor that was obtained after the variance analysis of the S/N ratio.

Table 2. ANOVA of the S/N Ratio for the Roughness

Factor	Sum of Squares	Degree of Freedom	Mean of Squares	Variance Ratio (F-value)	Pr(>F)	Percentage (1- Pr(>F))
Grit Size	51.16	3	17.05	12.83	0.20	0.80
Type of Abrasive	10.21	1	10.21	7.68	0.22	0.78
Fiber Direction	0.13	1	0.13	0.10	0.81	0.19
Species	0.22	1	0.22	0.17	0.75	0.25
Residual Error	1.33	7	1.33			
Total	63.05	(1)				

R^2 = 97.9%; significance level of 5%

Table 2 shows that 97.9% of the factors were responsible for influencing the roughness. The values Pr (> F) of Table 2 were arranged as a percentage to quantify the significant percentage influence of the factors in relation to surface roughness. Among the presented factors, the grit size and type of abrasive, whose percentages were 80% and 78%, respectively, had the greatest influence and explanatory value.

Figure 1 shows that the grit size had an inverse behavior with the roughness. When the size of the sandpaper increased, the surface roughness decreased. This behavior was because as the size of the sandpaper increased, the length of the abrasive grains decreased; therefore, material was removed with less depth. The aluminum oxide resulted in a lower roughness than the silicon carbide.

Table 2 shows that the fiber direction and wood species contributed little to the surface finish, at 19% and 25%, respectively. Figure 2 shows the behavior of the removal rate in relation to the factors and levels stipulated in the sanding process.

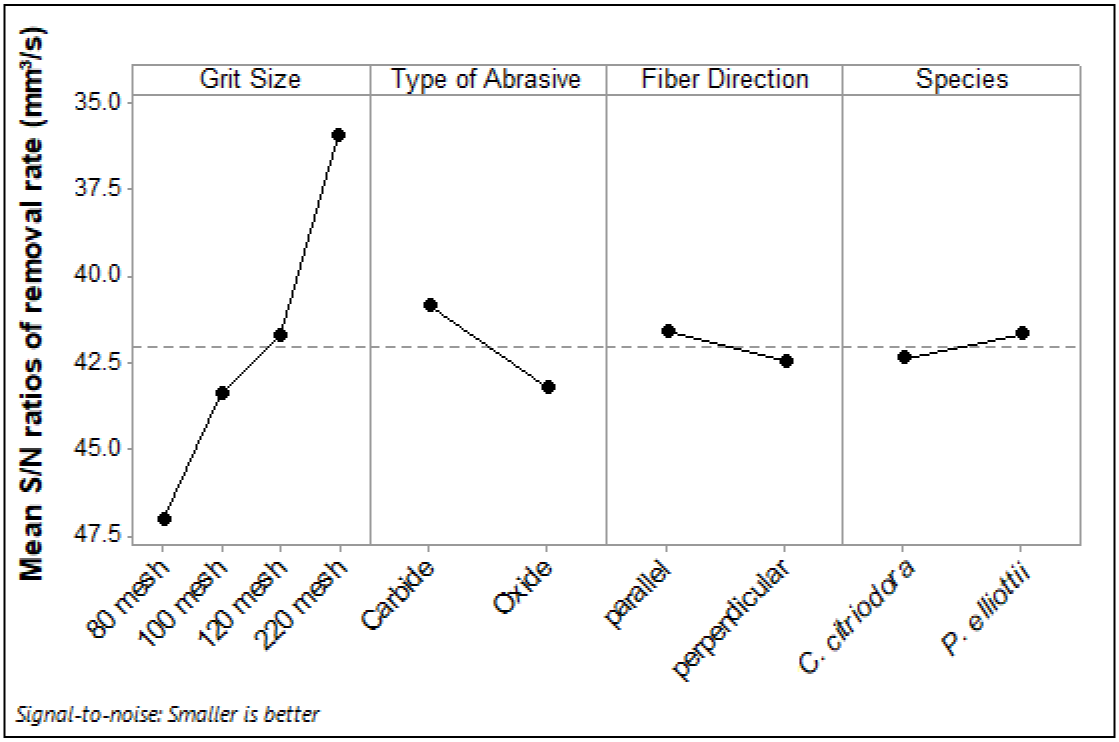

Fig. 2. Behavior of removal rate in relation to grit size, type of abrasive, fiber direction, and species

Considering the interaction of the variables in Fig. 2, the lowest removal rate occurred with the combination parallel sanding of *P. elliottii* with silicon carbide and a 220-grit size, and the largest removal rate occurred with the combination parallel sanding of *C. citriodora* with aluminum oxide and an 80-grit size.

The influence of the factors on the average removal rate is shown in Table 3, which gives the influence percentage of each factor obtained after the variance analysis of the S/N ratio.

Table 3. ANOVA of the S/N Ratio for the Removal Rate

Factor	Sum of Squares	Degree of Freedom	Mean of Squares	Variance Ratio (F-value)	Pr(>F)	Percentage (1- Pr(>F))
Grit Size	91.50	3	30.50	2.95	0.40	0.60
Type of abrasive	16.68	1	16.68	1.61	0.42	0.58
Fiber Direction	1.17	1	1.17	0.11	0.79	0.21
Species	9.80	1	9.85	0.95	0.50	0.50
Residual Error	10.35	7	10.35			
Total	129.50	(1)				

R^2 = 92.0%; significance level of 5%

Table 3 shows that 92% of the combined factors were responsible for influencing the removal rate. The Pr (> F) values of Table 3 were set out in percentage form to quantify the significant percentage influence of the factors in relation to the removal rate. The grit size, type of abrasive, and wood species showed greater influences and explanatory values, with influence percentages of 60%, 58%, and 50%, respectively.

Table 3 shows that 21% of the removal rate was significantly influenced by the fiber direction. The direction parallel to the wood fibers favored a lower removal rate compared with the perpendicular direction, which is illustrated in Fig. 2.

Aluminum Oxide *versus* Silicon Carbide

Figures 1 and 2 show that aluminum oxide resulted in a higher removal rate and lower roughness. This result was because of the shape of the grain. The aluminum oxide grain had a spherical shape. It did not sharply strike the surface and presented a greater resistance to fracture, which meant that it retained its cutting power for longer. In contrast, the silicon carbide had a sharp shape that made it easier to penetrate the wood and remove material with a greater cutting depth, and had better cooling by quickly eroding.

However, different results can be obtained depending on the wood species. De Moura and Hernández (2006) found that surfaces sanded with silicon carbide were softer and less damaged than surfaces sanded with aluminum oxide when using sugar maple.

Saloni *et al.* (2005) reported that the material removal rate increased with the use of aluminum oxide compared with silicon carbide. However, the aluminum oxide was responsible for creating surfaces with more roughness for hard maple (*Acer saccharum*) and white pine (*Pinus strobus*). Juan (1992) showed that silicon carbide produced surfaces with a small roughness value and produced deeper, more narrow cuts compared with aluminum oxide.

Corymbia citriodora versus Pinus elliottii

Figures 1 and 2 show that *C. citriodora* presented a greater roughness and higher removal rate, while *P. elliottii* presented less roughness and a lower removal rate during the sanding process. Table 2 shows that the wood species factor did not have a good explanatory value for the roughness (25%), only for the removal rate (50%) (Table 3).

P. elliottii, being a conifer, releases resin during the sanding process, which penetrates the abrasives of the sandpaper, making it difficult to cut the grain. Therefore, it presents a lower removal rate and a lower surface roughness value. *C. citriodora* is a hardwood species, which has in its structure fibers, long cells that are easy to remove and whose rupture causes greater irregularities in the surface, thus presenting higher rate of removal and greater roughness (Pertuzzatti *et al.* 2018).

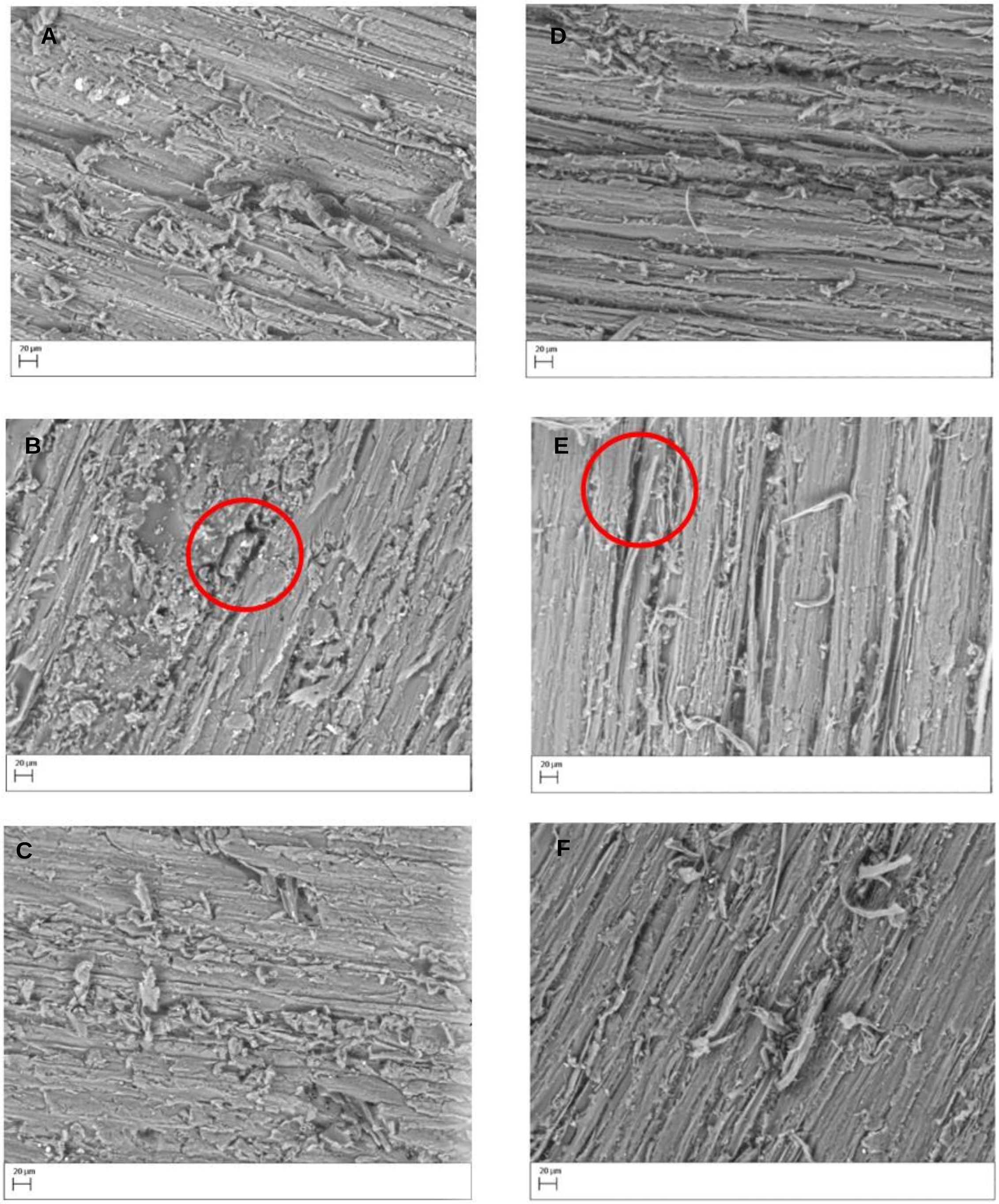

Fig. 3. Microscopic images (500x magnification) of the surface of the P. elliottii wood sanded with aluminum oxide with a 100-grit size (A), 120-grit size with emphasis on the sandpaper grain stuck to the surface of the wood (B), and 220-grit size (C); microscopic images (500x magnification) of the surface of C. citriodora wood sanded with aluminum oxide sandpaper with a 100-grit size (D), 120-grit size with emphasis on a micro crack (E), and 220-grit size (F)

Scanning Electron Microscopy

In order to analyze the surface of the wood after sanding, the images were taken with scanning electron microscopy (EVO LS-15, Zeiss, Zaventem, Belgium) in the N2 atmosphere configurations to 5 kV at pressures of the order of 60 Pa, collecting the scattered retro-electron signal. Figure 3 shows the images obtained from the surfaces of

P. elliottii and *C. citriodora* sanded with aluminum oxide grain with 100 grit, 120 grit, and 220 grit sizes.

When analyzing Figs. 3A, 3B, and 3C concerning the wood species *P. elliottii*, it was observed that the sandpaper grains compressed the surface of the wood. This was visible from the crushing aspect and presence of fragmented, compressed material. This species is a softwood and had long fibers and channels of resin, which affected the performance of the sandpaper because the fibers and channels overloaded the grains (mainly in larger sizes). This hindered the function of cutting, as can be seen in Fig. 3B, where the surface did not show the sanding aspect and had sandpaper grain attached to the wood surface.

CONCLUSIONS

1. This research showed that the roughness and removal rate of the sanding process were significantly influenced by the sandpaper parameters (grit size and type of abrasive), but not by the wood parameters (species and fiber direction).
2. The surface roughness and removal rate were inversely proportional to the grit size of the sandpaper, *i.e.*, a smaller grit size resulted in more surface roughness and a higher removal rate during the sanding process. Among the analyzed sandpapers, aluminum oxide provided the best surface finish compared with silicon carbide. It was observed that because of the tenacity of the aluminum oxide, it retained its cutting action for longer during the sanding process and created wood surfaces with less surface roughness.
3. The wood species and fiber direction did not significantly affect the roughness. Therefore, it was possible to infer that the aluminum oxide sandpaper with smaller grit sizes can provide a smoother surface finish, regardless of the wood species and direction of sanding.

ACKNOWLEDGMENTS

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES), the São Paulo Research Foundation (FAPESP), and the Mechanical Engineering Department of São Paulo State University (UNESP) for providing the facilities and inputs required for this study.

REFERENCES CITED

ABNT NBR 14960 (2003). "Safety requirements for abrading materials with coated abrasives systems," Brazilian Technical Standards Association, Rio de Janeiro, Brazil.

ABNT NBR 7190 (1997). "Design of timber structures," Brazilian Association of Technical Standards Association, Rio de Janeiro, Brazil.

Bao, X., Ying, J., Cheng, F., Zhang, J., Luo, B., Li, L., and Liu, H. (2018). "Research on neural network model of surface roughness in belt sanding process for *Pinus koraiensis*," *Measurement* 115, 11-18. DOI: 10.1016/j.measurement.2017.10.013

Cool, J., and Hernández, R. E. (2011). "Improving the sanding process of black spruce wood for surface quality and water-based coating adhesion," *Forest Prod. J.* 61(5), 372-380. DOI: 10.13073/0015-7473-61.5.372

de Moura, L. F., Cool, J., and Hernández, R. E. (2010). "Anatomical evaluation of wood surfaces produced by oblique cutting and face milling," *IAWA J.* 31(1), 77-88. DOI: 10.1163/22941932-90000007

de Moura, L. F., and Hernández, R. E. (2006). "Effects of abrasive mineral, grit size and feed speed on the quality of sanded surfaces of sugar maple wood," *Wood Sci. Technol.* 40(6), 517-530. DOI: 10.1007/s00226-006-0070-0

Denes, L., Lang, E. M., and Kovacs, Z. (2006). "Product development from veneer-mill residues: An application of the Taguchi's method," *Wood Fiber Sci.* 38(1), 36-48.

Gottlöber, C. (2014). *Zerspanung von Holz und Holzwerkstoffen: Grundlagen – Systematik – Modellierung – Prozessgestaltung* [*Cutting Wood and Wood-based Materials: Basics – Systematics – Modeling – Process Design*], Fachbuchverlag Leipzig im Carl Hanser Verlag, Munich, Germany.

Gu, F., Hall, P., Miles, N. J., Ding, Q., and Wu, T. (2014). "Improvement of mechanical properties of recycled plastic blends *via* optimizing processing parameters using the Taguchi method and principal component analysis," *Mater. Design* 62, 189-198. DOI: 10.1016/j.matdes.2014.05.013

Hamzaçebi, C. (2016). "Optimization of process parameters in oriented strand board manufacturing by Taguchi method," *BioResources,* 11(3), 5987-5993. DOI:10.15376/biores.11.3.5987-5993

Juan, J. (1992). *Comment Bien Usiner le Bois*, CTBA, Paris, France.

Ke, Q., Lin, L., Chen, S., Zhang, F., and Zhang, Y. (2016). "Optimization of L-shaped corner dowel joint in pine using finite element analysis with Taguchi method," *Wood Res.–Slovakia* 61(2), 243-254.

Kilic, M., Hiziroglu, S., and Burdurlu, E. (2006). "Effect of machining on surface roughness of wood," *Building and Environment* 41(8), 1074-1078. DOI:10.1016/j.buildenv.2005.05.008

Merry, F., Soares-Filho, B., Nepstad, D., Amacher, G., and Rodrigues, H. (2009). "Balancing conservation and economic sustainability: the future of the Amazon timber industry," *Environmental Management* 44(3), 395-407. DOI: 10.1007/s00267-009-9337-1

Mertol, A. (1995). "Application of the Taguchi method on the robust design of molded 225 plastic ball grid array packages," *IEEE T. Compon. Pack. B* 18(4), 734-743. DOI: 10.1109/96.475283

Pertuzzatti, A., Missio, A. L., de Cademartori, P. H. G., Santini, E. J., Haselein, C. R., Berger, C., Gatto, D. A., and Tondi, G. (2018). "Effect of process parameters in the thermomechanical densification of *Pinus elliottii* and *Eucalyptus grandis* fast-growing wood," *BioResources* 13(1), 1576-1590. DOI: 10.15376/biores.13.1.1576-1590

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingleye, D., *et al.* (2017). "The wood from the trees: The use of timber in construction," *Renew. Sust. Energ. Rev.* 68(Part 1), 333-359. DOI: 10.1016/j.rser.2016.09.107

Saloni, D. E., Lemaster, R. L., and Jackson, S. D. (2005). "Abrasive machining process characterization on material removal rate, final surface texture, and power consumption for wood," *Forest Prod. J.* 55(12), 35-52.

Tiryaki, S., Malkoçoğlu, A., and Özşahin, S. (2014). "Using artificial neural networks for modeling surface roughness of wood in machining process," *Constr. Build. Mater.* 66, 329-335. DOI: 10.1016/j.conbuildmat.2014.05.098

Ugulino, B., and Hernández, R. E. (2018). "Analysis of sanding parameters on surface properties and coating performance of red oak wood," *Wood Mater. Sci. Eng.* 13(2), 64-72. DOI: 10.1080/17480272.2016.1266511

Varasquim, F. M. F. d. A., Alves, M. C. d. S., Gonçalves, M. T. T., Santiago, L. F. F. S., and de Souza, A. J. D. (2012). "Influence of belt speed, grit sizes and pressure on the sanding of *Eucalyptus grandis* wood," *CERNE* 18(2), 231-237. DOI: 10.1590/S0104-77602012000200007

Xavior, M. A., Manohar, M., Patil, M. M., and Jeyapandiarajan, P. (2017). "Investigation of surface integrity during turning Inconel 718," *T. Can. Soc. Mech. Eng.* 41(3), 387-394. DOI: 10.1139/tcsme-2017-1027

Zhang, L., Sun, L., Han, J.-g., and Guo, Y.-h. (2015). "Wettability optimization analysis of lead-free solders with Taguchi method," *J. Mater. Sci.–Mater. El.* 26(4), 2605-2608. DOI: 10.1007/s10854-015-2730-z

Article submitted: November 19, 2018; Peer review completed: January 26, 2019; Revised version received: and accepted; February 9, 2019; Published: February 15, 2019.
DOI: 10.15376/biores.14.2.2773-2783