Forest Systems
24(3), e036, 9 pages (2015)
eISSN: 2171-9845
http://dx.doi.org/10.5424/fs/2015243-07712
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

RESEARCH ARTICLE

OPEN ACCESS

Influence of anatomy and basic density on specific cutting force for wood from *Corymbia citriodora* Hill & Johnson

Luiz-E. de L. Melo[1]*, José-R. M. da Silva[2], Alfredo Napoli[3], José-T. Lima[2] and Débora-F. R. Nascimento[2]

[1] *Universidade do Estado do Pará – Campus VIII, Departamento de Tecnologia e Recursos Naturais, Marabá, PA, Brazil.* [2] *Universidade Federal de Lavras, Departamento de Ciências Florestais, Lavras, MG, Brazil.* [3] *Centre de Coopération Internationale em Recherche Agronomique pour le Développement, Département de Performance des Systèmes de Production et de Transformation Tropicaux, Montpellier, France.*

Abstract

Aim of the study: The aim of this study was to evaluate the influence of xylem tissue cell structure, determined through biometry and basic density of the wood from *Corymbia citriodora* Hill & Johnson on consumption of specific 90º-0º longitudinal cutting force.

Area of study: The study area was in the region of the Vale do Rio Doce - Minas Gerais, Brazil.

Material and methods: A diametrical board with dimensions of 60 x 18 x 5 cm (length ***x*** width x thickness, respectively), with more than 1.3 m from the ground, was removed. In machining trials, a 400 mm diameter circular saw was used, with 24 "WZ" teeth, feed rate of 10 m.min^{-1}, cutting speed of 61 m.s^{-1}, and maximum instantaneous torque of 92.5 N.m. During cutting, test specimens were removed with alternated and parallel 1.5 cm edges in 6 radial positions, which were used for biometric determination of cell structure and basic density.

Main results: It was observed that wood basic density, vessel diameter, fiber wall thickness, fiber wall fraction and fiber wall portion were directly proportional to the specific cutting force. In contrast, vessel frequency and fiber lumen diameter proved to be inversely proportional to cutting force.

Research highlights: This work provides important values of quantification of influence of xylem tissue cell structure, determined through biometry and physical properties of the wood that may be used to prediction of consumption of specific cutting force.

Keywords: wood machining; wood properties; optimization of the process.

Citation: Melo, L.E. de L., da Silva, J.R.M., Napoli, A., Lima, J.T., Nascimento, D.F.R. (2015). Influence of anatomical and basic density on the specific cutting force of the wood from *Corymbia citriodora* Hill & Johnson. Forest Systems, Volume 24, Issue 3, e036, 9 pages. http://dx.doi.org/10.5424/fs/2015243-07712.

Received: 15 Mar 2015. **Accepted**: 20 Jul 2015

Funding: Vallourec Florestal Ltda, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) supported the experimental work.

Competing interests: The authors have declared that no competing interests exist.

Correspondence should be addressed to Luiz-E. de L. Melo: e-mail: luizeduardo.limamelo@gmail.com

Introduction

As a result of vertical integration of production, the need is perceived for better knowledge of wood behavior during processing since understanding the interaction between tools and raw material may have a positive effect on the productivity and economic health of the company.

The fact that wood is a biological material, structurally complex, heterogeneous, and anistropic, represents a significant challenge in predicting the influence of the grain, as well as the change in its properties in relation to the cutting axis/direction. The unpredictable variability of wood properties makes it difficult to predict the magnitude of variation of cutting forces during wood processing (Costes *et al*., 2004).

Monitoring the forces involved in the wood machining process is fundamental, but it is not an easy practice, due to the intrinsic characteristics of the material. The results obtained in the estimate of cutting forces are not always precise and satisfactory for industry. In this respect, Eyma *et al*. (2004a) highlighted that two species with the same density may require different cutting forces and that the forces may undergo oscillations throughout the cutting process and, for that reason, errors of around 50% may be contained in the calculations. Thus, mechanical processing of wood is still a bottleneck in diverse stages of woodworking because the wood characteristics that truly affect machining are not precisely understood.

Diverse studies have dealt with wood behavior during processing, especially in seeking explanations regarding the forces involved in the cutting process based on wood characteristics (Kivimaa, 1950; McKenzie, 1962; Koch, 1964; Fischer R, 1999; Aguilera & Martin, 2001; Eyma *et al.*, 2001, 2004a, 2004b, 2005; Porankiewicz *et al.*, 2011). However, most of these studies have focused on the density or moisture of the wood and few of them focus on the mechanical properties of the xylem tissue, describing its influence in the process. Satisfactory correlations among these wood properties and the cutting forces have been shown; but there are still gaps since such properties have not yet been able to completely explain the phenomenon or because the studies did not consider the particular nature of the anatomical structure of the species.

In a comparative study of wood cutting force, it is appropriate to use specific cutting force, which represents the amount of force necessary to remove a volume unit of material. It is directly connected with the forces that act on the cutting tool during processing (Koch, 1972).

Thus, the aim of this study was to evaluate the influence of xylem tissue cell structure, determined through biometry and basic density of the wood from *Corymbia citriodora* Hill & Johnson on consumption of specific 90º-0º longitudinal cutting force.

Materials and methods

Three individuals of *Corymbia citriodora* Hill & Johnson of 7 years of age, with 18.34 cm of average diameter at 1.3 m above ground were selected from an experimental plantation in the region of the Vale do Rio Doce/MG in Brazil (19°28′8″ S; 42°32′12″ W; 231 m altitude) from the Cenibra S.A. company. A diametrical board, with dimensions of 60 x 18 x 5 cm (length x width x thickness, respectively) was removed from each tree (Figure 1).

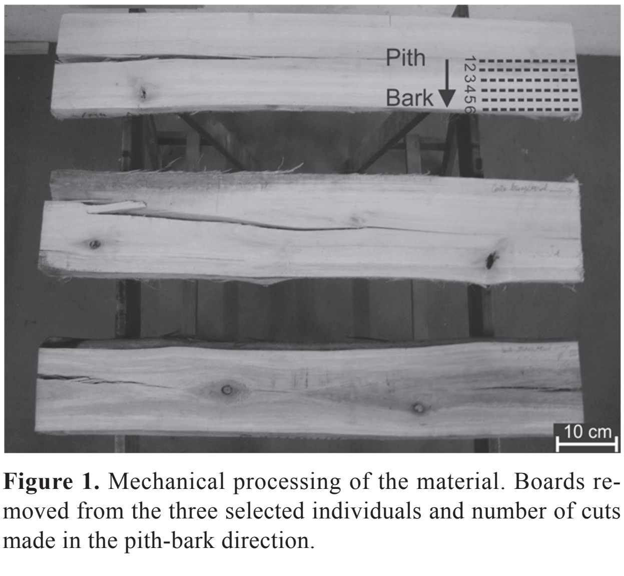

Figure 1. Mechanical processing of the material. Boards removed from the three selected individuals and number of cuts made in the pith-bark direction.

To obtain the consumption of specific longitudinal cutting force (90º-0º) in the pith to bark direction, the material was machined with a 7.5 HP table saw with sliding table, with a system for controlling feed and cutting speed. A circular saw was used with 400 mm diameter, 24 alternating teeth, WZ profile, 5 mm thickness, and without blade tooth wear (Figure 2). A table was adapted which allowed millimetric lateral feeds of the test specimens so that the cuts could be made at specific points of the xylem tissue in the pith to bark direction, which was established equal to the thickness of the circular saw teeth, for reduction of the effects of internal strains of the wood. This table also had pneumatic pistons for fastening the material, making for safe operation (Figure 3).

According with the pneumatic pistons dimension was analyzed only a ray (pith-bark direction) of each board. The wood analyzed presented centralized pith; however the small diameter of the boards only allowed six cuts, performed every 1.5 cm away from the pith and always at regions free of defects (Figure 1).

Collection and storage of the electrical parameters of processing the material was performed by a WEG frequency inverter, model CFW 08, equipped with serial communication interface (KSD CFW08) and Super Drive software (programming software of WEG drives), connected to a microcomputer (Figure 2).

During the cuts, the feed rate used was 10 m.min^{-1}, the cutting speed was 61 m.s^{-1}, corresponding to mean rotation of 2920 rpm, and maximum instantaneous torque was 92.5 N.m, with cutting duration of 5 s. Thus, the specific cutting force (J.cm^{-3}) was determined by the instantaneous measurements of torque (N.m) and by the rotation of the motor shaft (rpm). The frequency of data acquisition (rotation and torque) was 4 Hz.

Communication between the frequency inverter and the microcomputer was performed by the serial interface module RS-232 PC/Drive. For parameterization and monitoring of the data of the frequency inverter, the Super Drive software was used. For that purpose, the value proportional to the frequency (rpm), the output current of the motor (amperes), the output voltage of the motor (volts), and the motor torque (%) were acquired simultaneously. For calculation of specific cutting force (J.cm^{-3}), the instantaneous power curves were determined (Equation 1).

$$P_{instantaneous} = T_i \times n_i \qquad (1)$$

in which:

P_i = instantaneous power (W);

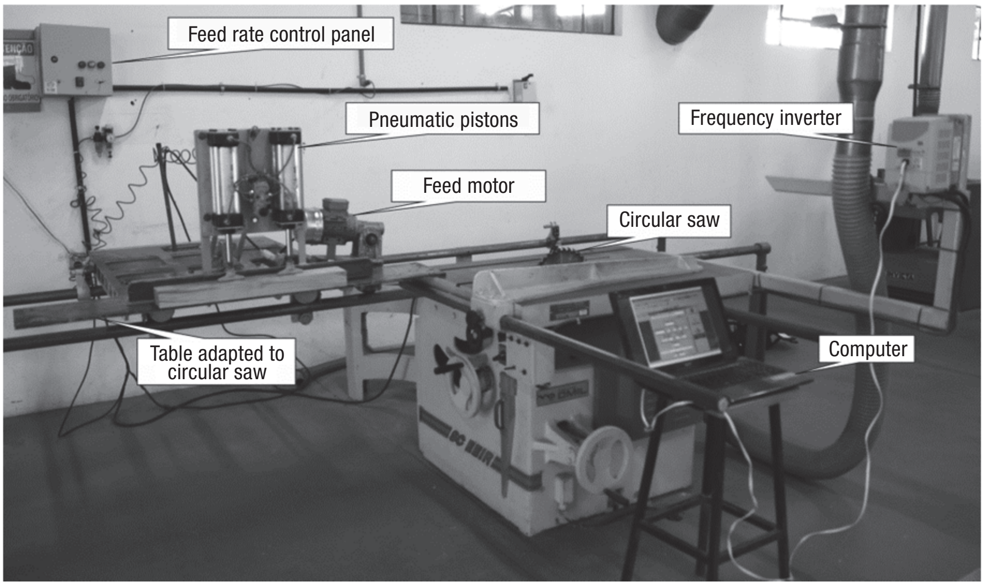

Figure 2. Setup used for data processing and acquisition.

T_i = instantaneous torque of the motor (N.m);
n_i = instantaneous speed of rotation (rpm).

After that, integration of the instantaneous power curves was carried out as a function of time to calculate the total cutting force (J), in accordance with Equation 2.

$$E_{Total} = \int_0^t P_{instantaneous} \times dt \tag{2}$$

in which:

E_{Total} = Total cutting force (J);
dt = time in seconds

Finally, consumption of specific cutting force (J.cm^{-3}) was determined from Equation 3.

$$Es = \frac{E_{total}}{c \times e \times k} \tag{3}$$

in which:
E_s = specific cutting force (J.cm^{-3});
c = length of test specimen (cm);
e = thickness of test specimen (cm);
K = thickness of the tool tooth (cm);

During the machining tests samples were removed at 1.5 cm of thickness located in an alternate and parallel manner to the cuts of the machining trials. The samples were subdivided into smaller specimens, duly oriented (radial, tangential and axial) with 1.5 cm edges, to determinate the average value of anatomical parameters and basic density in each of the six radial positions that the cuts were made (Figure 4).

Physical characterization was made for basic density (Db = Mo/Vsat, i.e. "anhydrous mass/saturated volume"), in accordance with NBR 7190 (ABNT, 1997). The moisture content average of the assessed boards was 16%.

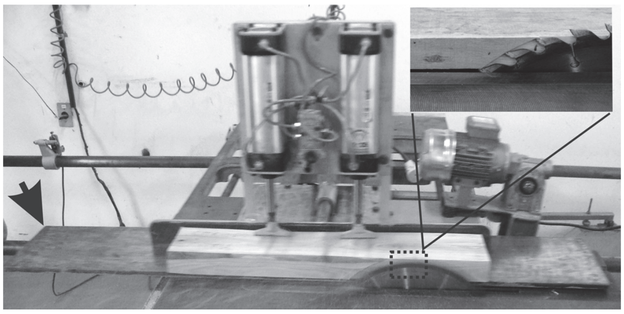

Figure 3. Table adapted to the circular saw with sliding table (arrow); cut made with 5 mm thickness (dashed square).

Figure 4. Obtaining of specimens for determining the average value of the biometrics cells (A) and basic density (F) on the radial position (p1).

Quantitative anatomy of the xylem tissue was carried out according to the International Association of Wood Anatomists (IAWA, 1989). For preparation of the macerated material, the method of Franklin (1945) was used and 30 measurements at each obtained specimen were made for the biometry of the elements of vessels (number per mm^2 and diameter), of rays (height and width), and of fibers (length, total width, lumen diameter). After that, fiber wall thickness and fiber wall fraction were calculated (Equations 4 and 5, respectively).

$$Wall\ thickness = \frac{\text{Fiber width} - \text{Lumen diameter}}{2} \qquad (4)$$

$$Wall\ fraction = \frac{2 \times \text{Wall thickness}}{\text{Fiber width}} \times 100 \qquad (5)$$

To estimate the fiber wall portion available per mm², Equation 6 was developed, based on the values of mean vessel frequency and diameter and fiber wall fraction, disregarding the portion of parenchymal cells in the xylem tissue.

$$FWP = \left[1 - \left(Fv \times \frac{\pi Dv^2}{4}\right)\right] \times FWF \qquad (6)$$

In which:
FWP = Fiber wall portion, in %;
Fv = number of vessels per mm²;
Dv = mean diameter of vessel elements, in mm;
FWF = fiber wall fraction, in %.

A test for homogeneity of variances was conducted (Bartlett's test, at 5% probability) preliminary to analysis of variance. For all the parameters evaluated, deviations from these analysis' assumptions were not observed. The data were subjected to Analysis of variance (ANOVA) and F-test at $p<0.05$ to verify differences between the radial positions. The experimental design was established with six points, the anatomical parameters and the basic density were considered as independent factors and the specific power cut as the dependent variable. From the mean values obtained in the six radial positions sampled in the three boards, Pearson correlation analysis was performed between the evaluated properties and applied linear regression analysis to assess the functional relationships between the biometrics of the cells and the basic density with specific strength of longitudinal section (90º-0º). All statistical analysis was performed using the R software, version 3.0.1 (R Development Core Team, 2013) through the packages ExpDes (Ferreira *et al.,* 2013) and Stats (R Development Core Team, 2013).

Results

The radial variation and descriptive statistics of the measured properties are listed in Table 1. Table 2 shows the summary of the analysis of variance for wood properties and specific cutting force at pith to the bark direction. It is observed that except for the height and width of the rays and also the width of the fiber, all other anatomical parameters measured, as the basic density and specific cutting force presented significant statistical difference to the source of variation in radial position pith to bark. In general there was an increase in the radial direction of the pith to the bark for the specific cutting force, basic density, vessel diameter, fiber length, fiber wall thickness, fiber wall fraction and fiber wall portion. Opposite behaviour was observed for the frequency of vessels and diameter of the fibers lumen, in which there was a reduction of the average values of the pith toward the bark. It can be observed from the descriptive statistics presented in Table 1, mainly from the low values obtained for the overall coefficient of variation of the data, the average of the properties among the individuals was very close. The radial variation profile of the properties did not differ between the evaluated individuals.

The correlation between the properties is shown in Table 3. The main results show that some anatomical parameters are correlated with each other and with density, significant correlations were observed between biometrics of the cells and specific gravity with specific cutting force. The anatomical parameter with the highest number of significant correlations was the frequency of vessels per mm², because with the exception of the height and width of the rays, all other anatomical parameters evaluated and also the basic density were strongly correlated with this anatomical parameter. Mostly negative correlations were observed; only the lumen diameter of the fibers was positively associated with the frequency of vessels. In general also the anatomical parameters related to the size of the fibers showed strong correlations with each other, the width and the lumen diameter of the fibers were the only negatively correlated with the basic density.

For the correlations of biometrics cells and basic density with the specific cutting force was observed that the specific cutting force was positively correlated with the basic density of the wood (r = 0.94). A better fit was also observed for the simple linear model for basic density ($R^2 = \mathbf{0}.89$) (Figure 5). An increase was seen in consumption of specific cutting force in accordance with an increase in wood density.

Table 1. Mean values of specific cutting force, basic density and biometric determination of the cells by radial position, in which Scf = specific cutting force; Bd = basic density; Vf = vessel frequency; Vd = vessel diameter; Rh = ray height; Rw = ray width; Fl = fiber length; Fwi = fiber width; Fd = fiber lumen diameter; Fw = fiber wall thickness; FWF = fiber wall fraction, and FWP = fiber wall portion.

Radial position sampled	Scf (J.cm^{-3})	Bd (g.cm^{-3})	Vf (per mm^2)	Vd (µm)	Rh (µm)	Rw (µm)	Fl (µm)	Fwi (µm)	Fd (µm)	Fw (µm)	FWF (%)	FWP (%)
Near the pith – 1st cut	29.0 (28.2)(1)	0.52 (6.5)	11.5 (4.6)	99.0 (7.5)	181.3 (1.9)	15.3 (11.5)	659.2 (14.3)	14.1 (6.6)	6.5 (4.3)	3.8 (8.7)	53.9 (1.0)	49.1 (0.04)
At 1.5 cm from the pith – 2nd cut	31.2 (51.7)	0.62 (25.9)	8.2 (11.4)	101.1 (13.4)	173.5 (1.6)	16.6 (11.3)	811.7 (8.9)	14.1 (1.5)	5.7 (13.8)	4.2 (14.2)	59.7 (12.2)	55.8 (11.2)
At 3 cm from the pith – 3rd cut	33.7 (20.9)	0.65 (17.7)	9.8 (7.4)	94.2 (3.4)	192.7 (14.3)	12.7 (32.2)	836.5 (0.3)	13.4 (4.9)	4.8 (29.4)	4.3 (13.8)	64.2 (17.9)	59.9 (17.9)
At 4.5 cm from the pith – 4th cut	36.5 (18.9)	0.71 (19.8)	5.8 (26.7)	107.3 (2.9)	205.5 (11.2)	16.4 (9.6)	898.8 (1.7)	13.8 (5.3)	4.8 (24.3)	4.5 (7.3)	65.7 (12.0)	62.2 (13.3)
At 6 cm from the pith – 5th cut	35.7 (15.7)	0.65 (12.5)	6.9 (5.3)	114.6 (11.9)	196.9 (15.1)	15.1 (11.4)	950.6 (4.8)	14.2 (7.7)	4.1 (47.0)	5.0 (19.5)	71.1 (25.7)	66.0 (23.9)
Near the bark – 6th cut	37.7 (36.4)	0.72 (13.2)	6.1 (5.6)	109.3 (4.3)	164.2 (5.9)	12.9 (15.0)	1057.8 (5.8)	13.5 (15.2)	3.7 (55.6)	4.9 (11.8)	73.2 (25.7)	69.0 (26.6)
Minimun	14.5	0.43	5.8	83.5	157.4	12.7	538.1	12.8	3.7	3.3	49.2	46.4
Maximun	37.7	0.72	12.3	116.1	205.5	20.2	1058.8	16.7	8.4	5.0	73.2	68.9
Average	28.4	0.58	8.4	101.1	178.9	16.1	837.4	14.2	6.1	4.1	58.0	54.2
Overall coefficient of variation	25.2	16.0	25.3	9.6	8.3	14.2	17.1	7.6	25.2	13.4	14.8	14.9

(1) Coefficient of variation of the radial position in parenthesis.

Table 2. Summary of the analysis of variance to specific cutting force, basic density and biometric determination of the cells between radial positions, in which Scf = specific cutting force; Bd = basic density; Vf = vessel frequency; Vd = vessel diameter; Rh = ray height; Rw = ray width; Fl = fiber length; Fwi = fiber width; Fd = fiber lumen diameter; Fw = fiber wall thickness; FWF = fiber wall fraction, and FWP = fiber wall portion.

SV	DF	Mean Square											
		Scf (J.cm^{-3})	Bd (g.cm^{-3})	Vf (per mm^2)	Vd (µm)	Rh (µm)	Rw (µm)	Fl (µm)	Fwi (µm)	Fd (µm)	Fw (µm)	FWF (%)	FWP (%)
Rp	5	1018*	0.42*	13.1*	237.6*	137.1^{ns}	5.3^{ns}	65462*	2.5^{ns}	45.5*	20.7*	4145*	3623*
Error	12	18.9	0.002	0.63	44.9	214.1	5.1	1954	0.94	1.1	0.07	29	25.1
F-value	–	60.4	172	20.7	5.3	0.64	1.1	33.5	2.7	43	274.2	143.2	144.2
p-value	–	< 0.05	< 0.05	< 0.05	< 0.05	0.67	0.43	< 0.05	0.07	< 0.05	< 0.05	< 0.05	< 0.05
CV exp (%)	–	37.3	14.4	9.4	6.7	8.28	13.6	5.3	6.7	43.7	17.4	23.4	23.89

SV: source of variation; DF: degrees of freedom; Rp: radial position; CV_{exp} (%): experimental coefficient of variation; ^{ns}: non significant by the F test, at 5% probability; *: significant by the F test, at 5% probability.

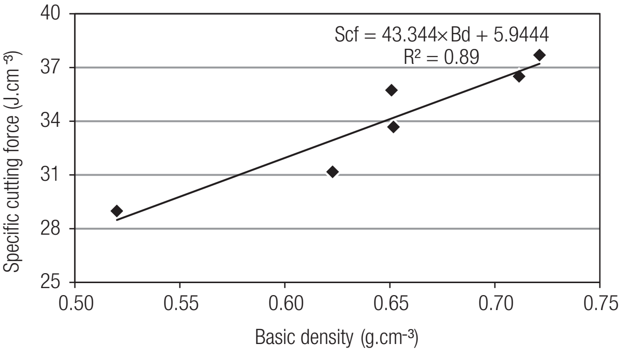

Figure 5. Correlation between specific cutting force and basic density of *C. citriodora* wood (F-statistic: 32.91, p-value: 0.00, residual standard error: 1.23).

It was observed that the anatomical parameters showed significant correlation with the specific cutting force in the pith to bark direction, with the exception of height (r = 0.17) and ray width (r = 0.3) and fiber width (r = -0.42), which did not show significant correlation.

For the vessel elements, it was observed that the frequency per mm^2 showed the best correlation, a negative correlation with specific cutting force (r = –0.88). In contrast, a positive correlation (r = 0.66) was observed for diameter. The vessel frequency per mm^2 was responsible for approximately 77% of radial variation (Figure 6a). As for the correlations obtained between specific cutting force and vessel diameter (Figure 6b), a

Table 3. Correlation between wood properties, in which Scf = specific cutting force; Bd = basic density; Vf = vessel frequency; Vd = vessel diameter; Rh = ray height; Rw = ray width; Fl = fiber length; Fwi = fiber width; Fd = fiber lumen diameter; Fw = fiber wall thickness; FWF = fiber wall fraction, and FWP = fiber wall portion.

	Vf (per mm^2)	**Vd (µm)**	**Rh (µm)**	**Rw (µm)**	**Fl (µm)**	**Fwi (µm)**	**Fd (µm)**	**Fw (µm)**	**FWF (%)**	**FWP (%)**	**Bd (g.cm^{-3})**	**Scf (J.cm^{-3})**
Vf (per mm^2)	1.00											
Vd (µm)	-0.77	1.00										
Rh (µm)	-0.12	0.10	1.00									
Rw (µm)	-0.10	0.18	0.28	1.00								
Fl (µm)	-0.87	0.69	-0.11	-0.37	1.00							
Fwi (µm)	0.13	0.32	0.12	0.77	-0.40	1.00						
Fd (µm)	0.78	-0.64	-0.03	0.50	-0.97	0.45	1.00					
Fw (µm)	-0.82	0.82	0.07	-0.28	0.94	-0.16	-0.95	1.00				
FWF (%)	-0.81	0.71	0.02	-0.43	0.98	-0.37	-1.00	0.98	1.00			
FWP (%)	-0.84	0.69	0.03	-0.41	0.99	-0.40	-0.99	0.97	1.00	1.00		
Bd (g.cm^{-3})	-0.89	0.48	0.11	-0.25	0.90	-0.55	-0.86	0.77	0.85	0.89	1.00	
Scf (J.cm^{-3})	-0.88	0.66	0.17	-0.33	0.94	-0.42	-0.95	0.89	0.95	0.96	0.94	1.00

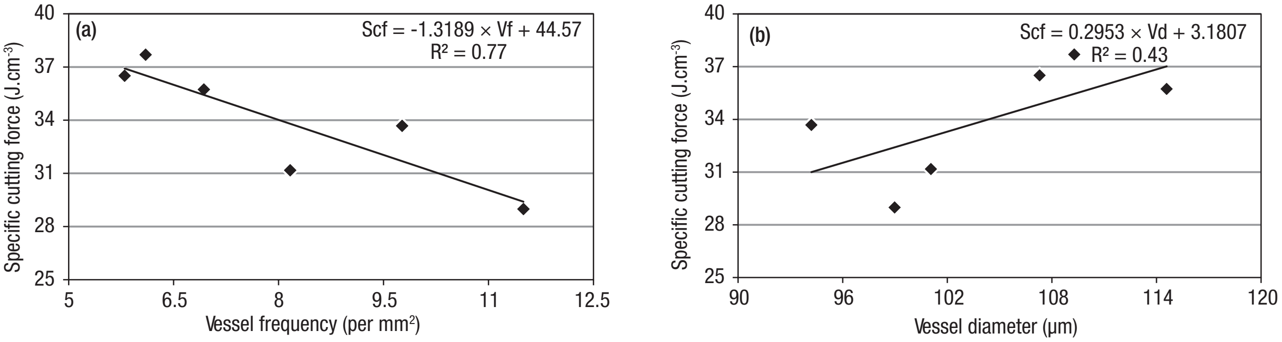

Figure 6. Correlation between specific cutting force and the vessels elements of *C. citriodora* wood. (a) correlation with vessel frequency per mm^2 (F-statistic: 13.70, p-value: 0.02, residual standard error: 1.77); (b) correlation with vessel diameter (F-statistic: 3.08, p-value: 0.15, residual standard error: 2.81).

moderate positive relation was observed ($R^2 = 0.43$). It was observed that the behavior of increasing vessel diameter in the pith to bark direction occurred along with reduction in vessel frequency and increase in fiber wall thickness and basic density of the wood, this result is confirmed from the strong negative correlation between the frequency of vessels with the vessel diameter, wall thickness and basic density, r = -0.95, -0.81 and -0.81 respectively (Table 2 and Figures 7 and 8).

It was observed that fiber lumen diameter was negatively correlated with the specific cutting force (r = –0.95), with the increase in this anatomical parameter, there was a decreasing tendency of specific cutting force, responsible for 90% of the radial variation of this magnitude (Figure 9).

The length (r = 0.94), the wall thickness (r = 0.90), the wall fraction (r = 0.95), and the fiber wall portion (r = 0.96) were positively correlated with specific cutting force, according to Figure 10a, b, c, d, respectively. The fiber wall portion alone was capable of explaining around 93% of the radial variation of the specific cutting force, analyzing the angular coefficients of the regression obtained it was also observed that every 1% of the fiber wall portion increase (pith-bark direction) there is an increase of approximately 0.45 J.cm^{-3} of the specific cutting force (Figure 10d). This anatomical parameter allowed closer determination of the true behavior of the wood during machining. In comparison to the results obtained from basic density, there was a 4% improvement in explanation of the percentage of variation of specific cutting force.

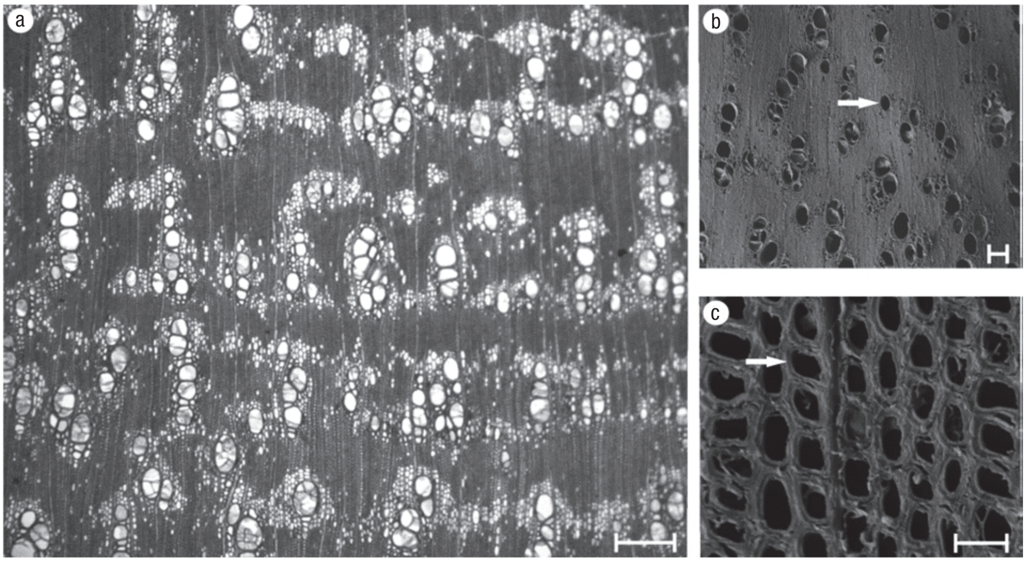

Figure 7. Anatomical structure of *C. citriodora* wood in the position near the pith. (a) greater vessel frequency (scale bar 300 µm); (b) smaller vessel diameter (scale bar 100 µm); (c) lower fiber wall thickness (scale bar 10 µm).

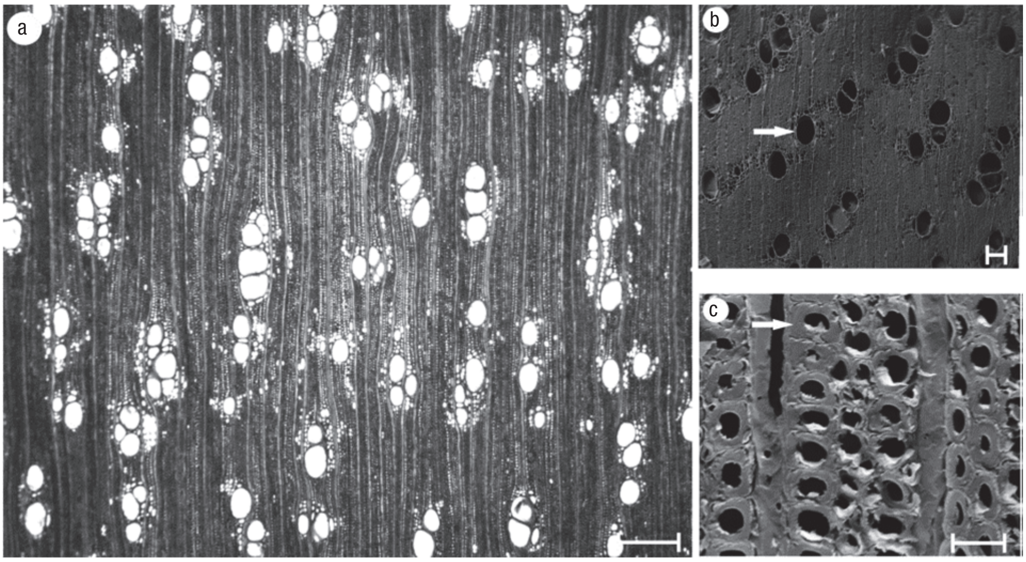

Figure 8. Anatomical structure of *C. citriodora* wood in the position near the bark. (a) lower vessel frequency (scale bar 300 µm); (b) greater vessel diameter (scale bar 100 µm); (c) greater fiber wall thickness (scale bar 10 µm).

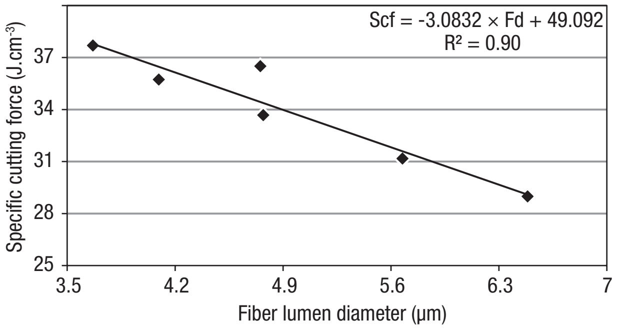

Figure 9. Correlation between the specific cutting force and fiber lumen diameter of *C. citriodora* wood (F-statistic: 36.86, p-value: 0.00, residual standard error: 1.17).

Discussion

The increase in basic density in the pith to the bark direction promoted consumption of specific cutting force in the external position of the boards closest to the bark. The basic density was able to explain the radial consumption of specific cutting force of the wood, and is responsible for 89% of its variation. This may be due to the presence of weak and lighter wood at the first radial centimetres near the pith and more dense and resistant wood near the bark which demanded most motor torque to cut the wood which has led to

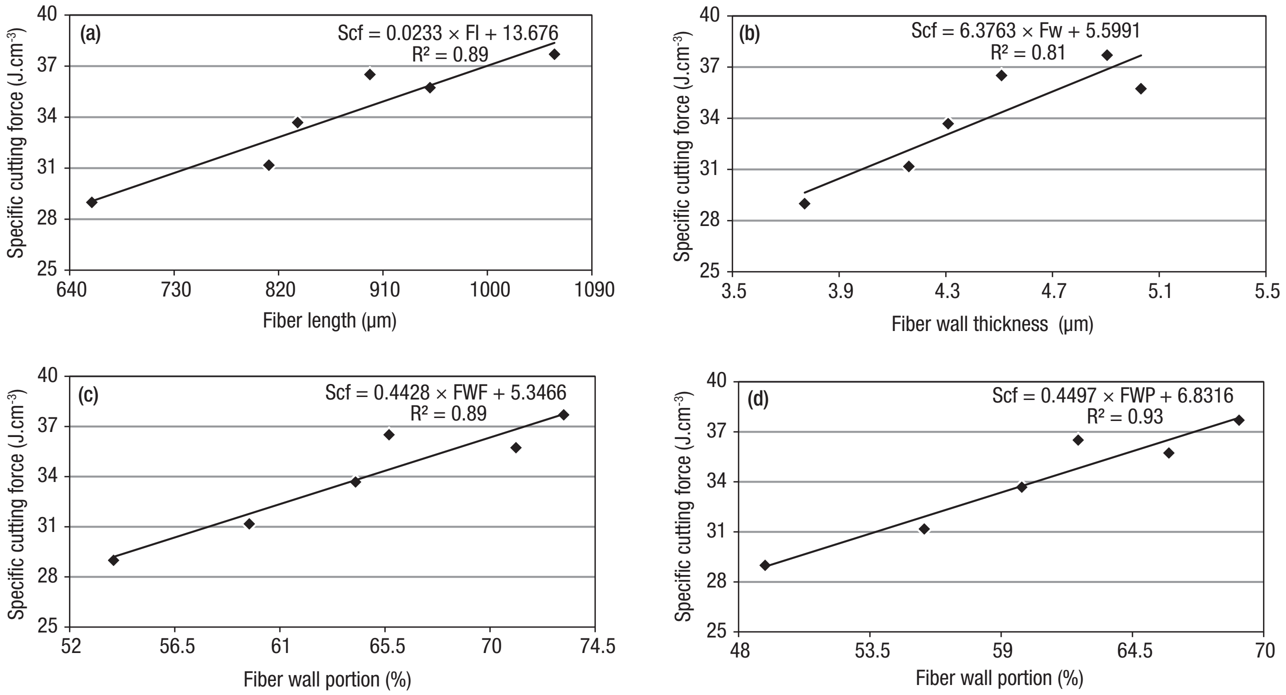

Figure 10. Correlation between specific cutting force and the fibers dimensions of the *C. citriodora* wood. (a) correlation with fiber length (F-statistic: 32.03, p-value: 0.00, residual standard error: 1.24); (b) correlation with fiber wall thickness(F-statistic: 17.02, p-value: 0.01, residual standard error: 1.63); (c) correlation with fiber wall fraction (F-statistic: 33.78, p-value: 0.00, residual standard error: 1.21); (d) correlation with fiber wall portion (F-statistic: 51.25, p-value: 0.00, residual standard error: 1.00).

increased the consumption of specific strength cut. Similar results were obtained by many authors (Kivimaa 1950; Koch 1964, 1972; Eyma *et al.*, 2001, 2004a, 2004b, 2005), which agreed that during processing, denser woods, or even denser regions of the same sample tend to introduce heavier chips that require more strength to their removal, and consequently more energy to move the cutting tool. The fact that the basic density showed high degree of correlation with the specific cutting force, as it is observed in results, can be an evidence of this.

For correlations established between the cells biometrics and the specific cutting force the initial hypothesis was that greater values of vessel frequency per mm^2 and vessel diameter would result in a negative effect on consumption of specific cutting force because the greater presence of empty spaces leads to wood with lower density and mechanical resistance (Zobel & Van Buijtenen, 1989), requiring less force for cutting. However, this prediction was confirmed only for vessel frequency per mm^2 in this study. From the physiological point of view, the increase in vessel diameter is related to the plant investing in water efficiency because vessel elements of greater diameter are more effective in conveying water per unit area. In contrast, with the prominent reduction in vessel frequency, xylem tissue is more highly occupied by thick wall fibers responsible for mechanical support of the main stem, and which consequently leads to production of denser wood (Chave *et al.*, 2009).

It was observed that the behavior of increasing vessel diameter in the pith to bark direction occurred along with reduction in vessel frequency and increase in fiber wall thickness. Thus, it is probable that the effect expected for the increase in vessel diameter in terms of consumption of specific cutting force was annulled by the reduction in vessel frequency and increase in fiber wall thickness in the radial direction in which the cut was made.

With the exception of lumen diameter of the fibers were found high positive correlation between the dimensions of the fibers and the consumption of specific cutting force. This behavior is due to the fact that fibers of greater dimensions normally are characteristics of woods that have high mechanical resistance, and, as such, more resistant to cutting and the lumen represents the space that is not occupied by the fiber cell wall.

The thickness of the fiber cell wall and the fraction of its volume may have a positive influence on wood density, which is commonly associated with mechanical strength of woody species (Salmén & Burget, 2009; Uetimane & Ali, 2011). According to Poorter *et al.* (2010), in most leafy species, fibers make up the biggest part of the xylem tissue (from 26 to 74% of the area of the cross section). The influence of this anatomical parameter on the wood machining process is thus understandable, notably related to the forces involved in the cutting process. Thus correlations obtained shows that consumption of specific cutting force is dependent on the percentage of cell wall effectively available for cutting and that, in general, when there is an increase in this percentage, there is also an increase in the consumption of this specific cutting force.

Conclusions

The increase in basic density in the pith to the bark direction had a positive effect on the cutting force, the highest values of density found near the bark led to higher consumption of specifies power cut at this region.

The frequency of vessels per mm² showed a strong negative correlation with the specific cutting force, accounting for 77% of the radial variation.

The variations in the parameters related to the dimensions of the fibers, especially in regard to wall proportions, allowed substantial improvement in understanding specific power consumption during machining of the wood under analysis. The wall portion of the fibers explains 93% of the radial variation of the specific cutting force, a 4% increase compared to the basic density.

References

Aguilera A, Martin P, 2001. Machining qualification of solid wood of *Fagus silvatica* L. and *Picea excelsa* L.: Cutting forces, power requirements and surface roughness. Holz Roh Werkst 59(6): 483-488. http://dx.doi.org/10.1007/s001070100243

Associação Brasileira De Normas Técnicas – ABNT, 1997. NBR 7190: projetos de estrutura de madeiras. 107 pp.

Chave J, Coomes D, Jansen S, Lewis SL, Swenson NG, Zanne AE, 2009. Towards a worldwide wood economics spectrum. Ecol Lett 12(4): 351-366. http://dx.doi.org/10.1111/j.1461-0248.2009.01285.x

Costes JP, Ko PL, Ji T, Deces-Petit C, Altintas Y, 2004. Orthogonal cutting mechanics of maple: modeling a solid wood-cutting process. J Wood Sci 50(1): 28-34. http://dx.doi.org/10.1007/s10086-003-0527-9

Eyma F, Meausoone PJ, Martin P, 2001. Influence of the transitional zone of wood species on cutting forces in the router cutting process (90-0). Holz Roh Werkst 59(6): 489-490. http://dx.doi.org/10.1007/s00107-001-0250-4

Eyma F, Meausoone PJ, Martin P, 2004a. Strains and cutting forces involved in the solid wood rotating cutting process. J Mater Process Tech 148(2): 220-225. http://dx.doi.org/10.1016/S0924-0136(03)00880-X

Eyma F, Meausoone, PJ, Martin P, 2004b. Study of the properties of thirteen tropical wood species to improve the prediction of cutting forces in mode B. Ann For Sci 61(1): 55-64. http://dx.doi.org/10.1051/forest:2003084

Eyma F, Meausoone PJ, Larricq P, Marchal R, 2005. Utilization of a dynamometric pendulum to estimate cutting forces involved during routing. Comparison with actual calculated values. Ann For Sci 62(5): 441-447. http://dx.doi.org/10.1051/forest:2005040

Ferreira EB, Cavalcanti PP, Nogueira DA, 2013. ExpDes:experimental designs pacakge. Version 1.1.22013. Available in http://cran.r-project.org/web/packages/ExpDes/index.html. [14 July 2013].

Fischer R, 1999. Wood cutting simulation – A program to experiment without a machine. In: Proceedings of the 14th International Wood Machining Seminar, Paris (France) September 12-19. pp: 553–562.

Franklin GL, 1945. Preparation of thin sections of synthetic resins and wood-resin composites, and a new macerating method for wood. Nature 155(3924): 51-51. http://dx.doi.org/10.1038/155051a0

IAWA, 1989. List of microscopic features for hardwood identification. Iawa Bull 10(3): 219-332.

Kivimaa E, 1950. Cutting force in wood working. The State Isnt. For Tech Res, Helsinki. 101 pp.

Koch P, 1964. Wood machining process. Ronald press company, New York. 530 pp.

Koch P, 1972. Utilization of The Southern Pines. Vol. II: Processing. U.S. Dept. of Agriculture Forest Service. 420 pp.

Mckenzie W, 1962. The relationship between the cutting properties of wood and its physical and mechanical properties. Forest Products Journal 12(6): 287-294.

Poorter L, Mcdonald I, Alarcón A, Fichtler E, Licona JC, Peña-Claros M, Sterck F, Villegas Z, Sass-klaassen U, 2010. The importance of wood traits and hydraulic conductance for the performance and life history strategies of 42 rainforest tree species. New Phytol 185(2): 481-492. http://dx.doi.org/10.1111/j.1469-8137.2009.03092.x

Porankiewicz B, Axelsson B, Gronlund A, Marklund B, 2011. Main and normal cutting forces by machining wood of pinus sylvestris. Bioresources 6(4): 3687-3713.

R Development Core Team. R, 2013. A language and environment for statistical omputing. Vienna: R Foundation for Statistical Computing. Available http://www.R-project.org/ [14 July 2013].

Salmén L, Burgert I, 2009. Cell wall features with regard to mechanical performance. A review COST Action E35 2004-2008: Wood machining - micromechanics and fracture. Holzforschung 63(2): 121-129. http://dx.doi.org/10.1515/HF.2009.011

Uetimane E, Ali AC, 2011. Relationship between mechanical properties and selected anatomical features of ntholo (Pseudolachnostylis maprounaefolia). J Trop Forest Sci 23(2): 166-176.

Zobel BJ, Buijtenen JP, 1989. Wood variation. Its cause and control. Springer-Verlag, Berlin. 363 pp. http://dx.doi.org/10.1007/978-3-642-74069-5