SCIENTIA
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Study of the physical properties of *Corymbia citriodora* wood for the prediction of specific cutting force

Estudo das propriedades físicas da madeira de *Corymbia citriodora* para a predição da energia específica de corte

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Resumo

Objetivou-se verificar a influência da densidade e da umidade da madeira na energia específica de corte. Utilizou-se madeira de *Corymbia citriodora* Hill & Johnson, de plantios no Vale do Rio Doce, no Brasil. Retirou-se a tábua diametral de 60 x 18 x 5 cm (comprimento x largura x espessura, respectivamente), acima de 1,3 m do solo. Nos ensaios de usinagem, utilizou-se serra circular de 400 mm de diâmetro com 24 dentes “WZ”, velocidade de avanço de 10 $m.min^{-1}$, velocidade de corte 61 $m.s^{-1}$ e torque instantâneo máximo de 92,5 N.m. Durante os cortes foram retirados corpos de prova com aresta de 1,5 cm alternado e paralelo a cada corte, em 6 posições radiais, que foram usados para a determinação da umidade e densidade da madeira. Observou-se que a energia especifica de corte foi positivamente correlacionada com a densidade da básica e aparente da madeira, porém a umidade foi negativamente correlacionada com a energia de corte. A densidade básica foi a propriedade física que melhor explicou a variação da energia específica de corte. A umidade demonstrou ser uma propriedade importante para explicar a relação entre a energia específica de corte específica e a densidade aparente da madeira.

Palavras-chave: usinagem da madeira, umidade, densidade da madeira.

Abstract

The aim of this study was to verify the influence of wood density and moisture content on specific cutting force. We used wood from the species *Corymbia citriodora* Hill & Johnson, from tree plantations in the Vale do Rio Doce, Brazil. A diametrical board with dimensions of 60 x 18 x 5 cm (length x width x thickness, respectively), 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 alternate and parallel 1.5 cm edges in 6 radial positions, which were used for determination of moisture, and wood density. It was observed that the specific cutting force was positively correlated with apparent density and with the basic density of the wood; however the moisture content was negatively correlated. The basic density was the best property indicated for the prediction of specific cutting force. Moisture content proved to be an important property for explaining the correlation found between specific cutting force and the apparent density of the wood.

Keywords: wood machining, moisture, wood density.

INTRODUCTION

Wood machining deviates from conventional standards applied to other materials, mainly due to the variability in its properties, cellular heterogeneity and anisotropy characteristics of the raw material, and its cutting being a more complex phenomenon and deserving of further analysis.

Insufficient knowledge of the raw material to be processed may result in the inappropriate use of machinery and cutting tools in the wood processing. Therefore, knowledge of the wood properties

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is important; however the understanding of the magnitude of the influence of these properties on the processing of this material is still a big problem in the timber industry.

Néri et al. (1999) and Néri et al. (2000) studying the 90°-90° and 90°-0° orthogonal cutting force in *Corymbia citriodora*, *E. grandis* and *E. saligna* noted that the cutting force increases with increased wood density. The authors explain that this effect is dependent on the attack angle applied. Gonçalves (2005) said that cutting efforts in very dense woods can become five times higher as compared to softwoods.

For Eyma et al. (2004a) and Naylor and Hackney (2013) there are basically three factors that influence the shear cutting force results in wood: factors related to machining, the moisture parameter and specially the intrinsic properties of the species of machined wood. According to these authors, in this case, the wood density holds considerable importance.

Generally speaking, a decline in the cutting force is observed during machining with increased wood moisture content (LUCIC et al., 2004). Moradpour et al. (2013) observed that the forces in four different cutting directions (90°-90°, 0°-90°, 90°-0° and 90°-45°) were higher in wood with 12% moisture content compared to wood with 30% moisture content.

From the foregoing, the aim of this study was to determine the influence of some physical properties on the specific longitudinal force cutting (90°-0°) energy consumption of *Corymbia citriodora* Hill & Johnson wood.

MATERIALS AND METHODS

Three individuals of *Corymbia citriodora* Hill & Johnson, 7 years of age, were selected, originating from an experimental plantation of Cenibra S.A. company in the Vale do Rio Doce/MG region in Brazil (19°28′8″ S; 42°32′12″ W; 231 m altitude). A diametrical board, 60 x 18 x 5 cm (length x width x thickness, respectively), was removed from each collected tree at more than 1.3 m from the ground. The boards were kept in natural conditions for drying to carry out the machining tests with different moisture profiles.

To obtain the consumption of specific longitudinal cutting force (90°-0°) in the pith to bark direction, the material was machined with a 7.5 HP table saw with sliding table, with a feed cutting speed control system. A circular saw was used with 400 mm diameter, 24 alternating teeth, WZ profile, 5 mm thickness, and without blade tooth wear (new). A table was adapted (Figure 1) 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 (5 mm), for reduction of the wood internal strain effects. This table also had pneumatic pistons for fastening the material, making for a safe operation.

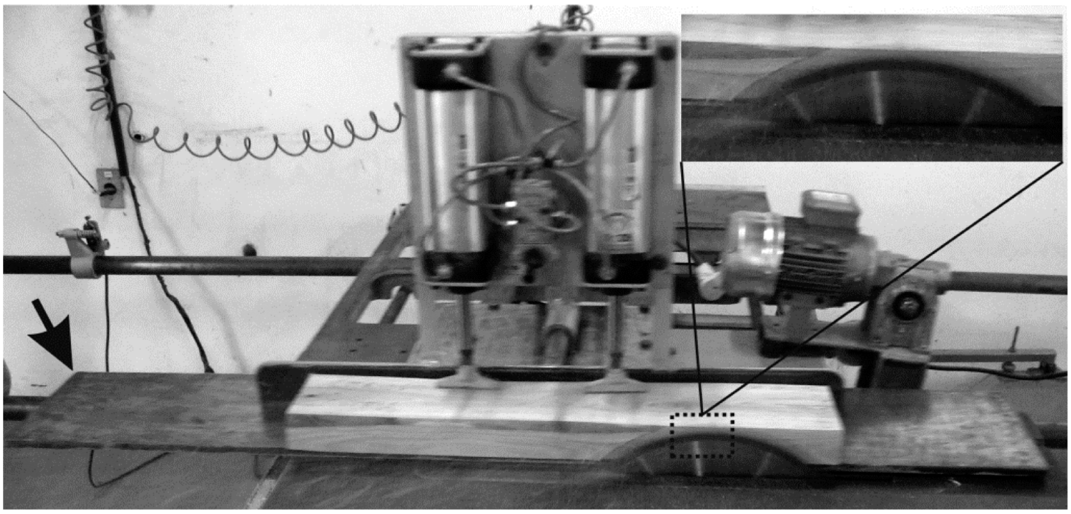

Figure 1. Mechanical processing the specimen, table adapted to the circular saw with sliding table (arrow); cut made with 5 mm thickness (dashed square).

Figura 1. Processamento mecânico do corpo de prova, mesa adaptada a serra circular de carrinho (seta); corte realizado com espessura de 5 mm (quadrado tracejado).

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

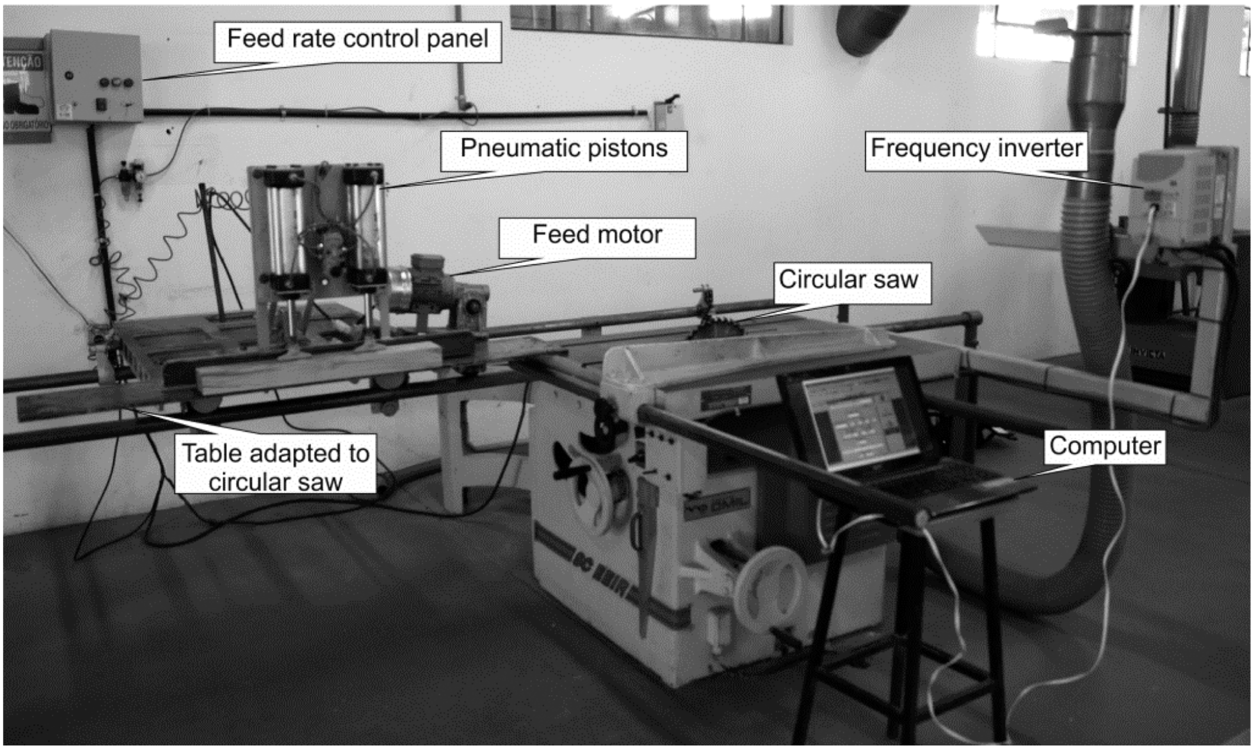

Figure 2. Setup used for data acquisition and processing.
Figura 2. Organização utilizado para processamento e aquisição de dados.

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 5s. 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 data acquisition frequency (rotation and torque) was 4 Hz.

Communication between the frequency inverter and the microcomputer was conducted through the serial interface module RS-232 PC/Drive. For parametrization and monitoring of the frequency inverter data the software Super Drive 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}), instantaneous power curves were determined (Equation 1).

$$P_{\mathbf{instantaneous}} = T_i \times \mathbf{n}_i \qquad (1)$$

where:
P_i = instantaneous power (W);
T_i = instantaneous motor torque (N.m);
n_i = instantaneous rotation speed (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 and Figure 3.

$$E_{Total} = \int_0^t P_{\mathbf{instantaneous}} \times dt \qquad (2)$$

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

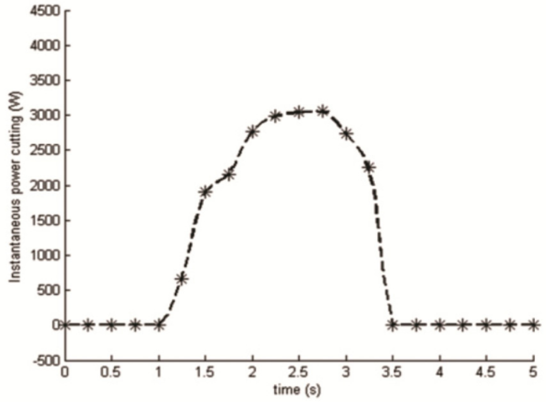

Figure 3. Measurement of instantaneous cutting power and integral calculus of cutting force.
Figura 3. Medição da potência instantânea de corte e cálculo integral da energia de corte.

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

$$Es = \frac{E_{total}}{c * e * k} \qquad (3)$$

where:
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);

Physical characterization was made for moisture content, apparent and basic density, in accordance with NBR 11941 (ABNT, 2003).

During the machining five test samples 1.5 cm thick, were removed located in an alternate and parallel manner to the cuts of the machining trials. Five specimens per each sample radial position were removed. The samples were subdivided into smaller specimens, duly oriented (radial, tangential and axial) with 1.5 cm edges to determine the average moisture content and apparent and basic density values in each of the six radial positions of the cuts.

From the mean values obtained in the six radial positions sampled in the three boards, Pearson correlation analysis was performed among the evaluated properties and linear regression analysis applied to assess the functional relationships between moisture content, apparent density, and basic density with specific strength of longitudinal section (90°-0°).

RESULTS AND DISCUSSION

In general, specific cutting force (J.cm^{-3}) and basic and apparent density (g.cm^{-3}) showed an increasing profile of variation from pith to bark (Table 1). However, the basic density magnitude variation was greater than that of apparent density. This fact may be seen by the difference between the coefficients of variation (Table 1 and 2). For moisture (%), a small reduction of the mean values is observed from pith to bark, exhibiting values near local equilibrium moisture content (±15%). Nevertheless, at 4.5 cm from the pith (4th cut) a sharp reduction in moisture was observed, which was reflected in a higher coefficient of variation (Table 1 and 2).

The predictions of consumption of specific cutting force, related to apparent and basic densities, are shown in Figure 4a, b, respectively. It was observed that the specific cutting force was positively correlated with apparent density (r = 0.73) and with the basic density of the wood (r = 0.94). A better fit was also observed for the simple linear model for apparent density (R^2 = 0.56) and basic density (R^2 = 0.89).

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Table 1. Minimum, mean, and maximum values, overall mean, and coefficient of variation of moisture, apparent and basic densities, and specific cutting force in the radial positions.
Tabela 1. Valores mínimos, médios, máximos, média geral e coeficiente de variação da umidade, das densidades aparente e básica e da energia específica de corte, nas posições radiais.

Radial position	Moisture content (%)	Density (g.cm^{-3}) Apparent	Density (g.cm^{-3}) Basic	Specific cutting force (J.cm^{-3})
Near the pith – 1st cut	16.64	0.893	0.520	28.99
1.5 cm from the pith – 2nd cut	17.28	0.843	0.623	31.17
3 cm from the pith – 3rd cut	15.00	0.850	0.652	33.68
4.5 cm from the pith – 4th cut	10.71	0.940	0.712	36.50
6 cm from the pith – 5th cut	16.33	0.926	0.651	35.73
Near the bark – 6th cut	15.01	0.980	0.721	37.69
Minimum	10.71	0.843	0.520	28.99
Maximum	17.28	0.980	0.721	37.69
Overall mean	15.16	0.905	0.646	33.96
Coefficient of variation	15.57	5.91	11.25	9.86

Table 2. Summary of the analysis of variance for specific cutting force, basic density and moisture content between radial positions.
Tabela 2. Sumário da análise de variância para a energia específica de corte, densidade básica e umidade entre as posições radiais.

SV	DF	Mean Square: Moisture content (%)	Specific cutting force (J.cm^{-3})	Density (g.cm^{-3}) Apparent	Density (g.cm^{-3}) Basic
Rp	5	143*	1018*	0.36*	0.42*
Error	12	15.6	18.9	0.06	0.002
F-value	-	9.2	60.4	6.1	172
p-value	-	< 0.05	< 0.05	< 0.05	< 0.05
CV exp (%)	-	27.85	37.3	34.16	14.4

SV: source of variation; DF: degrees of freedom; Rp: radial position; CVexp (%):experimental coefficient of variation; *:significant by the F test, at 5% probability.

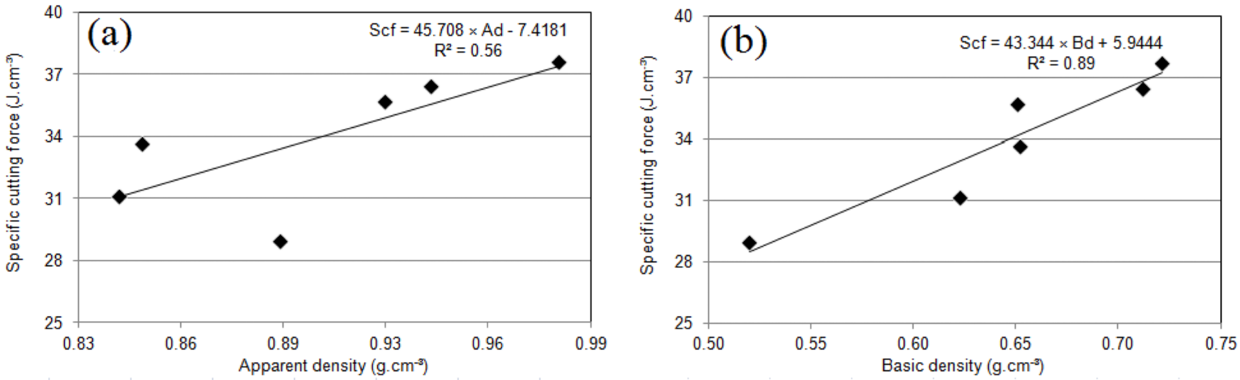

Figure 4. Correlation between specific cutting force and wood density of *C. citriodora*; (a) correlation with apparent density (F-statistic: 5.06, p-value: 0.08, residual standard error: 2.48); (b) correlation with basic density (F-statistic: 32.91, p-value: 0.00, residual standard error: 1.23).
Figura 4. Correlação entre a energia específica de corte e a densidade da madeira de *C. citriodora*. (a) correlação com a densidade aparente (F-calculado: 5,06, p-valor: 0,08, erro padrão residual: 2,48); (b) correlação com a densidade básica (F-calculado: 32,91, p valor: 0,00, erro padrão residual: 1,23).

An increase was seen in consumption of specific cutting force in accordance with an increase in wood density (Figure 4a, b), corroborating studies of Kivimaa (1950), Koch (1964, 1972), Orlowski et al. (2013) and Chuchala et al. (2014). These authors affirmed that woods of greater density commonly exhibit fewer lumens and more cell walls, as well as being more resistant. During processing, denser woods tend to exhibit heavier chips, which require greater force for their removal. These factors require greater power for moving the cutting tool, a fact that effectively occurs in wood processing.

Basic density was better able to explain the radial consumption of specific cutting force of the wood, and is responsible for 89% of its variation. However, apparent density showed a moderate coefficient of determination (R^2 = 0.56). Some authors affirm the existence of correlation between wood density and the forces involved in the cutting process. However, the density factor is not always enough to precisely explain the influence of the wood on the cutting process, for there are exceptions, especially related to the specificities of the species being worked (CHARDIN, 1958; KOCH, 1964; EYMA et al., 2001, 2004a, 2004b, 2005). Naylor et al. (2012) showed that the wood density has less influence on the cutting force along the grain. Cooz and Mayer (2006) found that the specific cutting force in the 90°–90° cutting direction is less for maple tension wood compared to the corresponding normal wood.

As the determination of apparent density considers the current moisture in the wood during sampling, this fact may have affected the low correlation of specific cutting force with the apparent density of the wood. This hypothesis may be confirmed by the low correlation shown between moisture and the specific cutting force (r= - 0.58); although there was a tendency toward reduction in cutting force with larger units; the coefficient of determination obtained (R^2 = 0.57) was moderate (Figure 5). Undoubtedly, the moisture content of wood is one of the main features that greatly affects the wood cutting operation; several authors have investigated the correlations between wood moisture and the forces involved in the cutting process, reporting that there is a tendency toward reduction in cutting force with an increase in wood moisture (KOCH, 1964, 1972; WOODSON; KOCH, 1970; FRANZ'S, 1958; LUCIC et al., 2004; MORADPOUR et al., 2013).

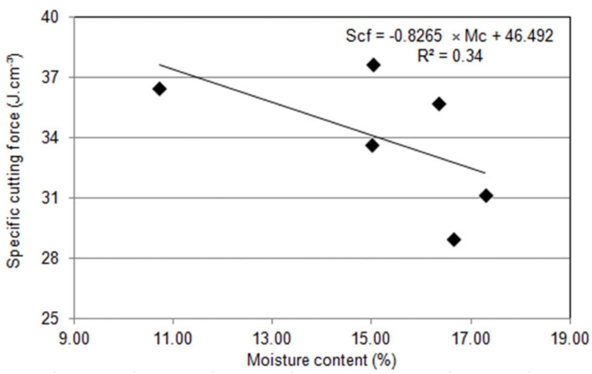

Figure 5. Correlation between specific cutting force and the moisture content of *C. citriodora* wood (F-statistic: 2.04, p-value: 0.22, residual standard error: 3.04).

Figura 5. Correlação entre a energia específica de corte e a umidade da madeira de *C. citriodora* (F-calculado: 2,04, p-valor: 0,22, erro padrão residual: 3,04).

In a general analysis of the mean values obtained for wood moisture content, considering the highest (17.28%) and lowest (10.71%) values found, it was observed that the specific cutting force showed an increase of 17% (31.17 to 36.5 $J.cm^{-3}$).

When the wood is dried below the fiber saturation point (± 28% moisture), there is reduction in the submicroscopic spaces and consequent approximation between the microfibrils of the cell wall, a fact which leads to the increase of rigidity and resistance of the wood in an exponential manner (KOCH, 1964).

It should be emphasized however that wood moisture may show positive correlation, negative correlation, or not even show significant correlation with the cutting forces (KIVIMAA, 1950; FRANZ'S,1958; KOCH, 1964; WOODSON; KOCH, 1970). The influence of moisture on the forces involved in the cutting process have not been fully clarified, since the point at which the presence of moisture in the wood may affect its resistance properties and thus, in fact, have an effect on the machining process, has not been defined. There are complex interactions among moisture and other properties, which depend on the characteristics of the species and on the particular nature of the machining process adopted.

CONCLUSIONS

The physical properties represented an increase in understanding the behavior and the influence of the wood on machining.

The basic density was the best property indicated for the prediction of specific cutting force.

Moisture proved to be an important property for explaining the correlation found between specific cutting force and the apparent density of the wood.

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