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Influence of basic wood density on the specific cutting energy

Influência da densidade básica da madeira na energia específica de corte

Influencia de la densidad básica de la madera en la energía específica de corte

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Abstract
The density of the wood influences directly on the quality of the surface, on the resistance to cutting as well as on the energy required for processing. The aim of this study was to obtain the association between specific cutting energies and basic wood densities in peripheral milling with the use of a computer numerical control. For this purpose, wood from nine species with a wide range of basic densities were used. The specimens were milled in a router with a CNC. Both the feeding and routing speeds were constant, and there was no source of variation among treatments. The values of specific energy were calculated taking into account the active power, the cutting time and the volume of wood removed. Results showed that there was a moderate correlation (r=0.61) between specific cutting energy and basic wood density data. However, by observing the particularities of each species, it was noticeable that the specific cutting energy varied as a result of factors such as the anatomical structure and the type of wood grain. It was concluded that the basic wood density has a positive correlation on the specific cutting energy required, yet it does not explain this relationship alone.
Keywords: Energy analyzer; Optimization of mechanical processing; Peripheral milling.

Resumo
A densidade da madeira influencia diretamente na qualidade da superfície, na resistência ao corte e na energia requerida para o processamento. O objetivo deste estudo foi obter a associação entre as energias específicas de corte e as densidades básicas das madeiras na fresagem periférica com comando numérico computacional (CNC). Para isso, foram utilizadas madeiras de nove espécies com ampla variação das densidades básicas. As madeiras foram secas em estufa e aclimatizadas. Os corpos de prova foram fresados em tupia, com CNC. A velocidade de avanço e a rotação foram mantidas constantes, e não foram fonte de variação nos tratamentos. Os valores de energia específica foram calculados considerando a potência ativa, o tempo de corte e o volume de madeira removida. Os resultados mostraram que houve moderada relação (r = 0,61) entre os dados de energia específica de corte e densidade básica da madeira. Contudo, observando as particularidades de cada espécie notou-se que a energia específica de corte apresentou variação em função de fatores como a estrutura anatômica e o tipo de grã da madeira. Concluiu-se que a densidade básica da madeira exerceu relação positiva na energia específica de corte requerida, porém não explica sozinha e completamente esta relação.
Palavras-chave: Analisador de energia; Otimização do processamento mecânico; Fresagem periférica.

Resumen
La densidad de la madera influye directamente en la calidad de la superficie, en la resistencia al corte así como en la energía necesaria para su elaboración. El objetivo de este estudio fue obtener la asociación entre las energías específicas de corte y las densidades básicas de la madera en el fresado periférico con el uso de un control numérico computarizado. Para ello se utilizaron maderas de nueve especies con un amplio rango de densidades básicas. Las probetas se fresaron en una fresadora con un CNC. Tanto la velocidad de alimentación como la de enrutamiento fueron constantes y no hubo fuentes de variación entre los tratamientos. Los valores de energía específica se calcularon teniendo en cuenta la potencia activa, el tiempo de corte y el volumen de madera removido. Los resultados mostraron que había una correlación moderada (r=0,61) entre la energía específica de corte y los datos básicos de densidad de la madera. Sin embargo, al observar las particularidades de cada especie, se notó que la energía específica de corte variaba en función de factores como la estructura anatómica y el tipo de veta de la madera. Se concluyó que la densidad básica de la madera tiene una correlación positiva sobre la energía de corte específica requerida, pero no explica por sí sola esta relación.
Palabras clave: Analizador de energía; Optimización del procesamiento mecánico; Fresado periférico.

1. Introduction

Knowledge on the technological properties of wood is paramount to make products with adequate characteristics and also to predict its behavior during its processing, thus ensuring greater control of the whole process (Melo et al., 2016; Taques & Arruda, 2016; Guedes et al., 2020).

Physical characteristics such as wood density may play a role in its processing, for example, on the quality of the surface, the cutting resistance and the energy required to cut (Koch, 1964; Axelsson et al., 1993; Porankiewicz et al., 2008; Goli et al., 2009; Cristóvão et al., 2012; Chuchala et al., 2013; Delatorre et al., 2020). However, there is little research measuring to what extent wood density interferes with the energy required for the processing. Moreover, the few existing studies presented superficial results, not showing the full spectrum of variation between the characteristics of the wood and the parameters obtained at the end of the process (Guedes, 2016).

For timber industries, the knowledge of the behavior of the wood during its cutting is a necessity when it comes to its processing, mainly due to economic and productive reasons. Machinery and tools made for wood processing, as well as operators, need reliable information concerning the main factors that influence mechanical processing (Eyma et al., 2004; Carvalho et al., 2010; Souza et al., 2011; Andrade et al., 2019; Csanády et al., 2019; Paul et al., 2019).

The major problems faced by the timber industry are: i) how to reduce costs with energy used in processing; ii) avoid stopping the production as a result of exceeding the limit of the nominal power of motors; and iii) seeking better quality of the processed wood by efficiently using the power of the motors.

The specific cutting energy is an important variable to be evaluated so as to make sure that machines are efficient in mechanical processing, with no energy wastage. It can also avoid overloads that might, in turn, stop the production, also denominated technical maintenance stops, for exceeding the load limits of motors (Andrade et al., 2018; Guedes et al., 2020).

The influence of the wood density on its cutting processes is not well described in literature yet, since studies in this area mostly report the use of the low density amplitude, lacking knowledge on this property in the specific cutting energy.

Thus, the aim of this study was to obtain the association between specific cutting energies and basic wood densities in peripheral milling with a computer numerical control (CNC).

2. Methodology

2.1 Biological material

Wood from nine species was used to guarantee a wide range of density classes so as to relate them to the specific cutting energy. The wood species were: B*owdichia nitida*, *Cryptomeria japonica*, *Eucalyptus grandis*, *Eucalyptus saligna*, *Hymenaea* spp., *Qualea dinizii*, *Tabebuia serratifolia*, *Tectona grandis* and *Toona ciliata.* All of the wood species belong to the group of the eudicotyledonous angiosperms, with the exception of *Cryptomeria japonica*, which is a gymnosperm. These wood species were chosen based on relevant literature, which indicated a range in their basic density from 0.200 g.cm^{-3} to 1.000 g.cm^{-3}.

2.2 Preparation of specimens

Ten specimens per species with different dimensions were used for the specific cutting energy tests. The specimens came from dry boards and had all their faces straightened and thickened and their tops were cut off.

Subsequently, all specimens were stacked with 2.0-cm-thick partitions in the Laboratório de Usinagem da Madeira (Wood Machining Laboratory), Forest Sciences Department, at the Federal University of Lavras.

The control of the moisture stabilization of the specimens was carried out by weighing three of the specimens per class of density every 3 days. The stabilization of moisture was confirmed by calculating mass loss and using the description of the NBR 7190 standard (Brazilian Association of Technical Standards 2010).

2.3 Peripheral milling

Peripheral milling was performed with a pantograph router, Tecnopampa, Model Router, coupled and controlled by CNC. The router was equipped with a straight, double-edged cutter with a maximum cutting depth of 15.6 mm and 6 mm diameter (Figure 1).

Figure 1. Bosch milling cutter used to make cuts in wood of different densities.

Source: Authors.

To prevent the wear of the cutter from interfering with the cutting energy data, some precautions were taken before performing the cut. First, the sequential numbering of all specimens was made. Next, they were drawn by lot so as to distribute the effect of the wear of the tool among species, specimens and densities. Also, a brand-new cutter was used.

The parameters used during the processing were fixed to ensure the same cutting conditions for all densities and specimens. Thus, the rotation of the tool axis was 17000 min^{-1}, according to Guedes (2016) and the cutter feed speed was 2000 m.min^{-1}, to allow the cutting of the wood with the highest class of density.

Ten cuts were made in each specimen. The shape of the cut was in a straight line, arranged transversely on the specimen (Figure 2) with a dimension of 60 x 6 x 3 mm (length x width x depth). The ten cuts were performed in the central region, 20 mm apart, due to the total length of the specimens.

Figure 2. Scheme of straight cuts in the pantographic router and their location in the specimens.

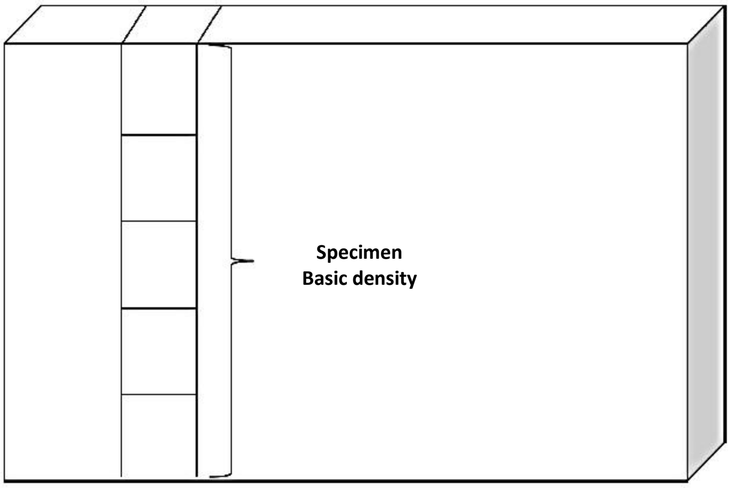
Source: Authors.

To carry out the peripheral milling, it was used a drawing software AutoCAD™ (CAD - Computer Aided Design), a software SheetCam (2.1/2D CAM) for converting the CAD (DXF) to machine language, and a machine language interpretation and table movement control software Mach 3 CNC Controller (Tecnocut Plasma CNC 2000/2500 Series) in the pantograph router.

2.4 Physical test

The sampling to perform the physical test of basic density was perpendicular to the axis and 5 cm away from the top, as shown in Figure 3. The methodology used for this test is described in the NBR 11941 standard (Brazilian Association of Technical Standards 2003).

Figure 3. Position of specimen removal for the basic density test.



Source: Authors.

2.5 Measurement of the cutting energy

Data for measuring the cutting energy was collected through a system capable of reading the parameters, such as power, in real time during the peripheral milling. For this, two probes were used. The first was used to capture the voltage, in Volts (V). The second one was used to capture the electric current, in Amperes (A). Both probes were connected to the energy analyzer, Fluke, Model 435.

The cutting energy for each specimen was determined by having the electric parameters measured by the energy analyzer (Fluke, Model 435) connected to the pantograph router motor. Data of the active power was recorded in a *datalogger* by the analyzer during the mechanical processing of the wood.

The data gathered by the Fluke energy analyzer were exported from the software *Powerlog Classic* 4.4 to *Excel*. Subsequently, data was adjusted and graphs were crafted.

Data was collected with no interruptions over time and two readings were taken per second (Time = 0.5s). Thus, it was necessary to filter data, selecting only data of active power in which there were cuts, that is, data was only selected when the cutting tool was in operation and cutting the wood.

The electrical energy was calculated by Equation 1 with data from the energy analyzer. The specific cutting energy was taken by means of Equation 2, which considers the volume of wood removed.

$$E_{el} = \sum_{k=0}^{n} p(k)T \qquad (1)$$

Where:
Eel = cutting electric energy (J);
p(k) = cutting electric power for sampling k (W);
T = time interval between two samples (s);
n = number of samples of each cut;

$$Es = \frac{E_{el}}{Vol} \qquad (2)$$

Where:
Es = specific energy ($J.cm^{-3}$);
Eel = cutting electric energy (J);
Vol = volume of material removed (cm^3)

2.6 Data analysis

In evaluating the experiment, a completely randomized block design with 10 replications was used. Analysis of variance (ANOVA) at 5% significance was performed for the specific cutting energy values. If there was a significant difference, the Scott-Knot grouping test, at 5% significance, was used for multiple comparisons. The simple correlation between the specific cutting energy and the basic density was also determined.

3. Results and Discussion

In the general analysis of the data for specific cutting energy, it was observed that the specimen belonging to the species *Hymenaea* spp had the highest value, with 1401 $J.cm^{-3}$. It was also found that *Toona ciliata* was the species with the lowest value of specific cutting energy, requiring 388 J for each cubic centimeter of material removed.

The analysis of variance showed that there was a statistical significance between the means of the species, at 5% significance, allowing us to infer that the choice of the genetic material to be mechanically processed (milling) does influence the value of energy required during the removal of a given wood volume.

The variation in the values for the specific cutting energy is not related with the classes of basic densities of the machined material. As presented in Table 1, it was observed that the species with the greatest range in data for specific cutting energy was *Toona ciliata*, which has a low basic density (ρ = 0.273 $g.cm^{-3}$) and a coefficient of variation of 17.2%, followed by the species *Eucalyptus saligna* (ρ = 0.598 $g.cm^{-3}$ and CV = 16.2%) and *Bowdichia nitida* (ρ = 0.801 $g.cm^{-3}$ and CV = 15.7%) with medium and high densities, respectively. The most homogenous species in terms of variation of specific cutting energy were *Qualea dinizii* (ρ = 0.562 $g.cm^{-3}$) and *Eucalyptus grandis* (ρ = 0.495 $g.cm^{-3}$) with coefficients of variation of 9.8% and 9.9%, respectively, both species being classified as having medium basic density.

Table 1. Mean values of specific cutting energy and basic density by species during CNC router milling.

Specie	Basic density ($g.cm^{-3}$)	Specific cutting energy ($J.cm^{-3}$)	Coefficient of variation (%)
Toona ciliata	0.273	666.3	17.2
Cryptomerica japonica	0.417	626.8	14.9
Tectona grandis	0.442	709.4	12.8
Eucalyptus grandis	0.495	845.5	9.9
Qualea dinizii	0.562	750.6	9.8
Eucalyptus saligna	0.598	855.8	16.2
Bowdichia nitida	0.801	907.0	15.7
Hymenaea	0.837	930.3	12.8
Tabebuia serratifolia	0.880	832.6	10.5

Source: Authors.

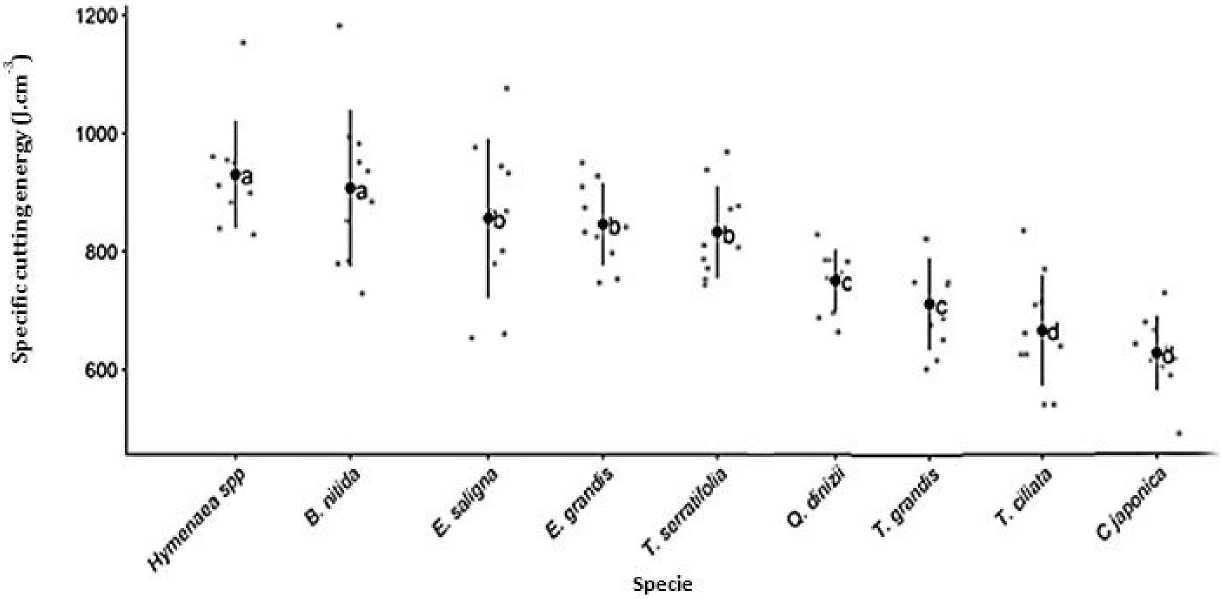
It is noticed that the class of wood with basic density between 0.201 $g.cm^{-3}$ and 0.400 $g.cm^{-3}$ was represented only by *Toona ciliata*. The average consumption of specific cutting energy of this wood was 666.3 $J.cm^{-3}$. For the class of wood that has a basic density between 0.401 $g.cm^{-3}$ e 0.600 $g.cm^{-3}$, the widest representativeness of species was found. In this class are grouped *Cryptomeria japonica* (ρ = 0.417 $g.cm^{-3}$), *Tectona grandis* (ρ = 0.442 $g.cm^{-3}$), *Eucalyptus grandis* (ρ = 0.495 $g.cm^{-3}$), *Qualea dinizii* (ρ = 0.562 $g.cm^{-3}$) and *Eucalyptus saligna* (ρ = 0.598 $g.cm^{-3}$) (Table 1). There was an increase of 43% in the value of basic density for this class. However, when analyzing the variation of specific cutting energy required for peripheral milling of these woods, an increasing trend similar to that found for the class of basic density was not seen. It was observed that in the initial interval of increase in the basic density, there was also an increase in the specific cutting energy and as the density increased, the specific cutting energy decreased. Yet, when observing only the variation of specific cutting energy in this class of density, it is noticed a variation of 37% between species that required the lowest and the highest specific cutting energy.

For the class of wood with basic density, between 0.801 $g.cm^{-3}$ and 1.000 $g.cm^{-3}$, represented by *Bowdichia nítida* (ρ = 0.801 $g.cm^{-3}$), *Hymenaea* spp. (ρ = 0.837 $g.cm^{-3}$) and *Tabebuia serratifolia* (ρ = 0.880 $g.cm^{-3}$), there was an increase of 10% in the values of basic density (Table 1). Similar to the class of basic density of 0.401 to 0.600 $g.cm^{-3}$, the variation in specific cutting energy required for milling wood with higher basic densities initially increased with the increase in basic density and followed by a decrease in the specific cutting energy in the final portion of the increase in basic density.

In the general analysis of all the woods used, on average, it was not observed that a lower specific cutting energy was required for the peripheral milling of wood with a lower average density. It is noticed (Table 1), that *Cryptomeria japonica* (ρ = 0.417 $g.cm^{-3}$) was the species that required the lowest cutting energy (626.8 $J.cm^{-3}$), and not *Toona ciliata* (ρ = 0.273 $g.cm^{-3}$), contradicting Guedes (2016) and Brown et al. (1949). However, *Cryptomeria japonica* is the only one among the nine species evaluated that is classified as a gymnosperm. This shows that not only the density of the wood may affect the value of specific cutting energy required. In this case, it can be inferred that the anatomical composition of the wood is relevant for defining the energy required, since gymnosperms would require less energy to cut, as they have greater homogeneity in the composition of their wood, in terms of both cell types and arrangement.

Through the multiple comparison of means by the Scott-Knott test (Figure 4), at 5% significance, it was observed that the species were separated into four four distinct groups according to the specific cutting energy.

Figure 4. Multiple comparisons of means for the specific cutting energy parameter. Means followed by at least one letter do not differ from each other at 5% of significance by the Scott-Knott test.



Source: Authors.

The classes proposed by the Scott-Knott Test did not separate the specific cutting energy in relation to the density of the species. These data do not corroborate results found by Guedes (2016), in which the author reports that the cutting energy is closely related to the density. This author used only three classes of densities represented by only one species each, though. Yet, when observing data of density with a larger spectrum of values, which is not only low, medium or high density, as in the case of the present study, it is noted that the density alone is not the decisive factor for the specific cutting energy.

Despite having a variation of 222% (ρ = 0.273 g.cm^{-3} to ρ = 0.880 g.cm^{-3}) in the values of basic wood density, the variation in the specific cutting energy was 48%. Although, this percentage did not cover all of the variation of the basic density, since the highest value (930.3 J.cm^{-3}) was shown by the wood of *Hymenaea* spp. and the lowest (626.8 J.cm^{-3}) was shown by the wood of *Cryptomeria japonica*, representing the variation of 201% in the basic density of the wood.

By analyzing several models adjusted for the nine classes of density, it was noted that the linear model had the best data behavior and it was significant. It is found that according to the coefficient of determination (R^2), only 38% of the total variation of the specific cutting energy can be explained by the variation in the basic density of the woods. The significant (r) correlation coming from basic wood density and specific cutting energy data was 0.61 and it is considered to be moderate (Figure 5).

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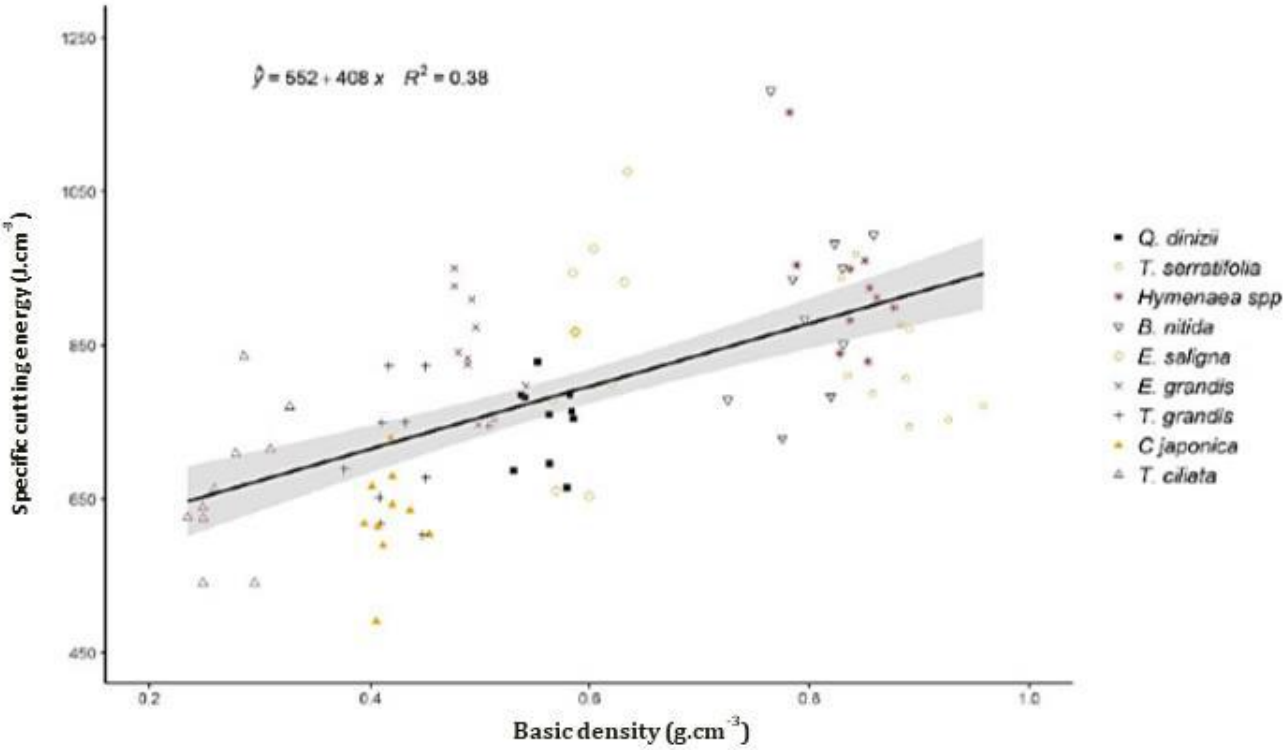
Figure 5. Relationship between basic density and specific cutting energy data for CNC router milling for the nine species.



Source: Authors.

It is noticed that wood from *Tectona grandis* and *Cryptomeria japonica* are overlapping on the axis of basic density, with an average density of 0.430 g.cm^{-3}. Although, in relation to the energy required for cutting the same volume, the wood from *Tectona grandis* required 709.4 J.cm^{-3} whereas the wood from *Cryptomeria japonica* required 626.8 J.cm^{-3}, which correspond to a 13% increase in the specific energy to carry out the peripheral milling in a router controlled by the CNC. As previously mentioned, the wood from *Cryptomeria japonica* is the only one among the nine species used here belonging to the gymnosperm class, which has a more homogenous (less complex) anatomical structure than the other species belonging to the eudicotyledonous angiosperms.

In the milling of *Tectona grandis,* the cutter must overcome the mechanical resistance imposed by the tissue that was formed by different anatomical elements (fibers, vessels and parenchyma cells), i.e., the spatial arrangement of the elements in the formation of the wood is heterogeneous, which may lead to a deviation in grains, for instance. In order to mill *Cryptomeria japonica,* the cutting tool must only overcome the resistance of the tracheids, which normally have a predominantly homogenous orientation.

The data also showed that with the density alone it was not possible to explain the difference in the specific cutting energy required to make the same cutting between different genetic materials. This fact may be better understood when observing the values of specific cutting energy for the species *Eucalyptus saligna* (0.598 g.cm^{-3}) and *Qualea dinizii* (0.562 g.cm^{-3}). It is noteworthy that these two woods are angiosperms and, therefore, have similar anatomical structures in composition and also have similar density values. It is possible to notice that the wood of *Eucalyptus saligna* required specific cutting energy, on average, 14% higher than the wood of *Qualea dinizii*. In this case, the type of wood grain may have influenced. Because in the peripheral milling conducted in this study, the cutting direction is presented in a concordant and discordant way, simultaneously on both faces of the cutting, the presence of the intercrossed grain, commonly present in

Eucalyptus spp. makes it difficult for the cutting tool (mill) to overcome the resistance of the material, which is expressed as an increase in the energy required.

4. Conclusion

Given the wide range in the spectrum of data, it was not observed a direct and complete association of the increase in the specific cutting energy as a result of the basic density of the woods. But, overall, there was an increasing relationship between the basic density of the wood with the energy required for cutting, with 38% of this variation being explained. The wood from *Cryptomeria japonica*, which is a gymnosperm, required less specific cutting energy when compared to wood from eudicotyledonous angiosperms. The increase of 201% in the basic density of the wood (0.417 $g.cm^{-3}$ to 0.837 $g.cm^{-3}$) promoted a 48% increase in the specific cutting energy (626.8 $J.cm^{-3}$ to 930.3 $J.cm^{-3}$).

It is recommended to carry out research relating the type of wood grain to the force necessary for the cutting tool to overcome the resistance of the material during cutting, with the hypothesis being that woods with intercrossed grain require greater cutting energy than wood with straight grain. In addition, it is also recommended to research the anatomical structure and mechanical properties of wood to better understand the interferences in the specific cutting energy.

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