Drying Influence on the Development of Cracks in *Eucalyptus* Logs

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The aim of this study was to evaluate the effect of the moisture loss, diameter, and wood density on the appearance of surface cracks and end splits in *Eucalyptus urophylla* logs. The drying and emergence of defects were evaluated in 108 logs with diameters ranging from 60 mm to 150 mm from the initial moisture content to the equilibrium moisture content. The defects were measured during this time. Smaller diameter logs dried faster than larger diameter logs and took less time to reach the fiber saturation point. Surface cracks tended to develop during the loss of bound water. End splits developed during free water loss and continued to appear during bound water loss. Smaller diameters presented higher percentages of surface cracks compared with larger diameters, while larger diameters had a tendency for higher percentages of end splits compared with smaller diameters. The density did not influence the total emergence of end splits, but it did influence the total emergence of surface cracks, indicating a possibility for the selection of genetic material with lower tendency for cracking. Overall, the results reinforce the need to control drying at its beginning in order to decrease the risk of defects.

Keywords: Bound water; Roundwood Diameter; Wood Defects; End splits; Free water; Surface cracks

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INTRODUCTION

Drying is a key step in the manufacturing of many products. It is a process in which moisture is removed from saturated porous materials (Kowalski 2003). Wood is a material that, in addition to being porous, is considered to be nonhomogeneous, hygroscopic, and anisotropic (Jankowsky and dos Santos 2005). Wood drying plays an important role in adding value and quality to wood-based products (Jankowsky and Luiz 2006). However, wood drying can potentially cause degradation (Kollmann and Côté Jr. 1968). During this process, defects can occur in wood, such as end splits, collapse, warp, surface cracks or checks, and internal cracks (honeycomb), among others (Forest Products Laboratory 1999; Tenorio *et al.* 2012), especially in *Eucalyptus* wood (Yang and Liu 2018).

Most of those defects are caused by deformation of the wood tissue (Forest Products Laboratory 2010). Drying stresses and shrinkage are the main causes of rupture because they can exceed the strength of this material (Kang and Lee 2004). Those phenomena are influenced by the moisture content in the wood, which can be observed in the two main forms of water, namely free water and bound water (Siau 1984; Engelund *et al.* 2013).

Free water is water that is present in the lumens or voids in the wood in liquid and vapor phases (Skaar 1972). The movement of free water in wood is affected by weak forces, such as capillary forces (Kollmann and Côté Jr. 1968). When a tree loses all free water, the fiber saturation point (FSP) is reached, which corresponds to a moisture content of 25% to 30% (Skaar 1972; Shmulsky and Jones 2011). Bound or adsorbed water is held in cell walls by intermolecular interactions and is in a vapor form. Its movement occurs by diffusion, and it interacts with the more or less hydrophilic wood polymers (Siau 1984; Engelund *et al.* 2013). Therefore, bound water loss, which is different from free water loss, can produce changes in the physical and mechanical properties of the wood, such as swelling and shrinking (Siau 1984; Lazarescu *et al.* 2009) and consequently it can cause cracking in wood. This water decreases to a sufficiently low moisture content to be at equilibrium with the ambient moisture content, which is called the equilibrium moisture content (EMC) (Skaar 1988). Knowing which of these two kinds of water loss influences the most on the development of cracks during drying could support the development of more effective drying schedules.

In addition to wood-water relationships, other factors, such as the density and log diameter, can influence wood drying behavior and consequently cause the appearance of cracks. Hornburg *et al.* (2012) found a statistical tendency for an increase in cracks with higher diameter logs. Da Cunha *et al.* (2015) tested the influence of the diameter on the emergence of end splits and reported that in *Eucalyptus grandis* logs, those defects increased with an increasing diameter and the opposite happened for the same wood defect in *E. benthamii*.

The density gives an idea of the amount of cell material in the wood, which influences the drying rates, shrinkage, strength, and many other characteristics (Kollmann and Côté Jr. 1968; Zanuncio *et al.* 2015). Furthermore, studies have provided technical information on the drying of *Eucalyptus* logs, such as the effects of the drying stack with and without the presence of bark (Vital *et al.* 1985), log diameter (Vital *et al.* 1985; Rezende *et al.* 2010), moisture gradient along the pole during drying (Zanuncio *et al.* 2015), correlation between the drying and anatomical characteristics of the logs (Monteiro *et al.* 2017), and velocity of free and bound water flow in logs (Monteiro *et al.* 2018). Also, the viscoelasticity of wood makes the behavior of the material time dependent, causing creep crack growth (He et al. 2017).

The drying behavior of *Eucalyptus* logs is complex, and its wood is important in world forest production. Its textural features and mechanical strength are remarkable, which makes it popular and used in a variety of applications (Kong *et al.* 2018). However, *Eucalyptus* is known to present a high number of end splits soon after its felling because of the presence of growth stresses in the species. Those defects result in financial loss for the wood industry, specifically for the sawn wood industry, which causes noticeable yield reductions (Yang and Waugh 2001; Scanavaca Jr. and Garcia 2003; de Matos *et al.* 2003; Murphy *et al.* 2005).

Therefore, avoiding the development of cracks is a challenge to be overcome by the wood industry, and more information is necessary in order to achieve that. With this in mind, the aim of this study was to evaluate when cracks occur in wood logs with different diameters during drying.

EXPERIMENTAL

Materials

Eighteen *E. urophylla* hybrid trees were selected from a clonal reforestation plot that belongs to a company located in Montes Claros, Brazil. Inside the plantation, spacing among the trees was 2 m × 3 m. The trees were 4 years old, and the mean values of tree heights and diameter at breast height were 15.35 m and 115 mm respectively. Trees with the pith well located in the geometric center of the logs and in a flat area were selected, aiming to avoid the presence of reaction wood as recommended by Ferreira *et al*. (2008). Also, to avoid the edge effect, trees were selected from within the plot.

After the trees were felled, three logs were taken from the base of each tree and three logs from the top (0.5-m length) to monitor the drying and defects. This totaled 108 logs with diameters that ranged from 60 mm to 150 mm. To compare the drying behaviors, the logs were divided into two diameter classes. The first was comprised of logs from the top of the tree with diameters from 60 mm to 100 mm, and the second was composed of logs from the base of the tree with diameters from 100 mm to 150 mm. Additionally, 5-cm thick discs were taken from between the logs to study the basic density of the wood. After cutting, the samples (logs and discs) were identified with information about the tree and longitudinal position of origin. Then, the logs and discs were taken to the Forest Products Laboratory in the Federal University of Minas Gerais for drying in a covered shed. The basic density of the wood logs was calculated using the green volume obtained by immersion in water and the oven-dry mass of the discs, according to ASTM D2395-14 (2001).

Drying occurred in a shed at room temperature in a covered place without sidewalls, so that air circulation could happen naturally, as was suggested in the methodologies adopted by Zanuncio *et al.* (2015) and Monteiro *et al.* (2018). The logs took six months to reach the EMC. During that time, the logs were weighed using a 10-kg capacity electronic scale three times a week. The logs were organized and separated on the floor with standard spaces between each log to facilitate air movement and to ensure that the drying process happened as naturally and homogeneously as possible.

After stabilization of the log weights, the dry weights of the logs were obtained by drying them in a kiln at 103 °C ± 2 °C. The dry weights were used to calculate the moisture content of each log after each weighing. The first weight measured during drying was used as the initial moisture content. The FSP was considered to be 30%, which was an average value reported by Skaar (1972). The weight considered to be the EMC was the final constant weight at the end of drying (approximately 12%). That information allowed the researchers to know when each log achieved the FSP and EMC, and when to make the drying curves.

Methods

Measurement of the defects

Measurement of the drying defects was conducted during the six months of drying, until the logs achieved EMC, twice a week on the same days that the samples were weighed, with the aim of collecting information on the crack intensity at the FSP and EMC. For measuring the length of each crack, this study used a digital caliper with a 0.001-mm precision.

Defects in the *Eucalyptus* logs were classified as surface cracks (Fig. 1a) and end splits (Fig. 1b). Surface cracks occur in the rolling surface of the logs, while end splits are found in the cross-section of the logs.

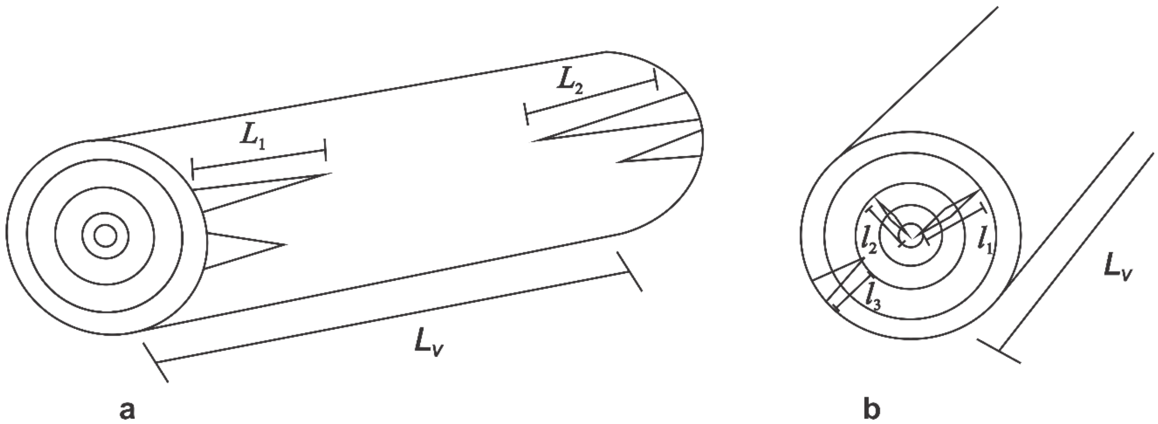

Fig. 1. (a) Measurement of the surface cracks and (b) end splits in the *Eucalyptus* logs; l_1, l_2, and l_3 are the individual lengths of the cracks (mm); L_1 and L_2 are the longer cracks at the extremities (mm); and L_V is the total length of the piece (mm)

To quantify the percentage of the defects, the adapted methodology from IBDF (1983) and the classification suggested by Mendes and Severo (1984) were used. End splits and surface cracks in the *Eucalyptus* logs were calculated using Eqs. 1 and 2, respectively.

$$RES\ (\%) = \frac{l1 + l2 + \dots lx}{LV}\ x\ 100\% \tag{1}$$

$$RSC\ (\%) = \frac{L1 + L2}{LV}\ x\ 100\% \tag{2}$$

where *RES* is the representative index of the end splits in the *Eucalyptus* logs (%); l_1, l_2, and l_x are the individual lengths of the cracks (mm); L_V is the total length of the piece (mm); *RSC* is the representative index of the surface cracks in the *Eucalyptus* logs (%); and L_1 and L_2 are the longest cracks at each extremity (mm).

Statistical analysis

For the percentages of end splits and superficial cracks in the *Eucalyptus* logs, multiple linear regression was used as a function of the moisture content, along with the drying and log diameters (from 70 mm to 150 mm) in order to identify when it was possible to notice a higher development of cracks. For that, 12 multiple regression models were tested (Table 1). Model 1 tested the independent effect of the diameter and moisture content on the percentage of cracks and model 12 tested all of the interactions possible. These models aim to verify the existence of linear quadratic effects between the explanatory variables as well as their interactions, allowing the selection of the best model to describe the phenomena. The quality of the adjustment was evaluated by the determination coefficient (R^2), Akaike's information criterion (AIC), and Bayesian information criterion (BIC). To adjust the regression models, this study used the lm function in the R software (R Core Team, Vienna, Austria). To make the response surface plots, the software SigmaPlot (v.11, Systat Software, Inc., San Jose California, United States of America) was used. To test the influence of the density on the final percentage of cracks, the Pearson's correlation test was used ($p < 0.05$).

Table 1. Multiple Linear Regression Models Tested to Describe the Percentage of Cracks as a Function of Diameter and Moisture Content in *Eucalyptus* Logs

Model	Function
1	$Z_i = a + bx_i + cy_i + e_i$
2	$Z_i = a + bx_i + cx_i^2 + dy_i + e_i$
3	$Z_i = a + bx_i + cy_i + dy_i^2 + e_i$
4	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + e_i$
5	$Z_i = a + bx_i + cy_i + dx_iy_i + e_i$
6	$Z_i = a + bx_i + cx_i^2 + dy_i + fx_iy_i + e_i$
7	$Z_i = a + bx_i + cy_i + dy_i^2 + fx_iy_i + e_i$
8	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + gx_iy_i + e_i$
9	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + gx_iy_i + hx_i^2y_i + e_i$
10	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + gx_iy_i + hx_iy_i^2 + e_i$
11	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + gx_iy_i + hx_i^2y_i + jx_iy_i^2 + e_i$
12	$Z_i = a + bx_i + cx_i^2 + dy_i + fy_i^2 + gx_iy_i + hx_i^2y_i + jx_iy_i^2 + kx_i^2y_i^2 + e_i$

Z_i – percentage of cracks; x_i – diameter; and y_i – moisture content

RESULTS AND DISCUSSION

All 108 logs took an average of five months (146 d) to reach the EMC (Fig. 2). The smaller diameter logs started drying with the highest moisture content value (104.5%), followed by those with a larger diameter (98.9%). It should be noted that for the genetic material studied, the logs with a smaller diameter took fewer days to reach the FSP and EMC than the logs that had larger diameters (Fig. 2). That result was understandable because wood from the higher part of the stem (smaller diameter) contains more sapwood and it is known that water flow is a lot faster in sapwood than in heartwood (Kollmann and Côté Jr. 1968; Mendes and Severo 1984).

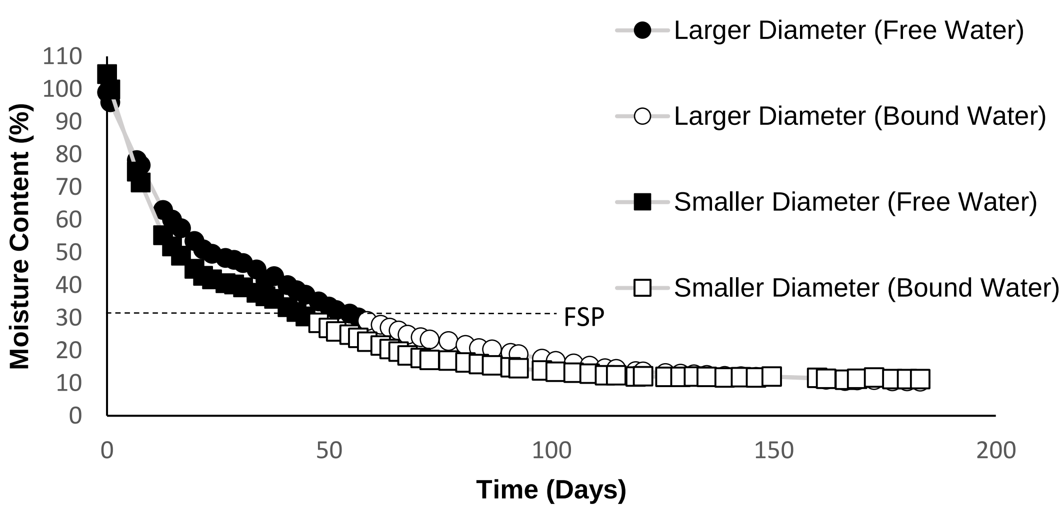

Fig. 2. Drying curves for the two diameter classes studied

Another way to understand the reason for these results is by analyzing wood growth, structure, and how water exits wood. In a tree, the stem grows in diameter with the addition of cell wall layers every year. Therefore, during drying, water moves from the interior to the surface of the wood (Denig *et al.* 2000; Forest Products Laboratory 2010). Accordingly, in large diameter logs, water needs to cross a greater number of layers than in small diameter logs. Pertuzzatti *et al.* (2013) studied 8-year-old *E. globulus* logs with a 2.20-m length from four different diameter classes and found similar results, where the larger diameter logs took more time to reach the FSP (230 d) than the smaller diameter logs (190 d), when starting at a 125% moisture content.

However, the logs that were dried in this study did not show the same behavior below and above the FSP (Fig. 2), which agrees with what has been reported in several studies (Simpson 1983; Davis *et al.* 2002; Engelund *et al.* 2013). From the maximum moisture content to the FSP (free water), drying of the logs occurred quickly, while drying happened more slowly from the FSP to the EMC (bound water). That result was possibly because, below the FSP, the water present inside the lumen of each cell had already left the wood *via* capillaries in an easy and fast manner, given that it was held by relatively weak forces. What remained were water molecules in the cell walls that were more difficult to remove because they were attracted to the wood by stronger forces (Skaar 1988).

The difference in the drying behavior of the logs between these two stages can be seen when analyzing the angular coefficient of the equations (Table 2), wherein the free water had a noticeably steeper curve than the bound water for both diameter classes. In the same equations, it was also observed from the β_0 coefficient value (value that represents the regression constant or intercept) that the logs with a larger diameter started with a higher moisture content.

Table 2. Drying Curve Adjustments as a Function of the Time and Moisture Content from the Smaller and Larger Diameters in the Free and Bound Water Flows

Diameter Class	Water Flow	Estimated Model	R^2
Smaller Diameter	Free	$MC = 84.42^{**}e^{-0.025^{**}T}$	90.91
	Bound	$MC = 29.01^{**}e^{-0.006^{**}T}$	81.3
Larger Diameter	Free	$MC = 85.26^{**}e^{-0.019^{**}T}$	96.29
	Bound	$MC = 41.28^{**}e^{-0.008^{**}T}$	93.99

R^2 = determination coefficient; MC = moisture content (%); and T = time (d). ** indicates the significance of the parameters of the models is at the 1% and 5% significance levels for the t-test

In Table 2 it is also possible to see that drying time statistically influenced the moisture content. This study used exponential models because they better represent the inclination of the drying curves, especially for free water. The R^2 values showed better adjustments for free water, given that it has a sharper curve than bound water (Fig. 2), and consequently there was a better relationship with the exponential behavior. Zanuncio *et al.* (2015) also used exponential regression models to study the wood moisture content and variables, such as the diameter and density, for different drying times for *Eucalyptus* and *Corymbia* logs.

Cracks Evaluation

The adjustment quality assessors for the models in Table 1 are shown in Table 3 for the percentages of end splits and surface cracks. This study used model 8 and model 12 to describe the percentages of end splits and surfaces cracks, respectively, as a function of the diameter and moisture content. We chose the models that presented the lowest AIC and BIC values. Surface cracks showed low R^2 values, which indicated that there was a weak association between the response and explanatory variables. This reduced the reliability of the generalization of its results.

Table 3. Adjustment Quality Assessors for 12 Multiple Regression Models Tested to Describe the Percentage of Cracks as a Function of the Diameter and Moisture Content in the *Eucalyptus* Wood Logs

Model	End Splits (%)			Surface Cracks (%)		
	R^2	AIC	BIC	R^2	AIC	BIC
Model 1	55.13	18297.29	18320.20	10.61	21539.00	21561.91
Model 2	55.27	18292.21	18320.85	12.91	21481.90	21510.53
Model 3	55.85	18262.73	18291.37	17.02	21372.30	21400.94
Model 4	56.00	18256.69	18291.05	19.13	21315.87	21350.23
Model 5	55.73	18268.63	18297.27	10.81	21535.93	21564.57
Model 6	55.94	18259.85	18294.21	13.28	21474.20	21508.56
Model 7	56.53	18229.56	18263.92	17.11	21371.73	21406.09
Model 8	56.76	18219.19	18259.27	19.34	21311.80	21351.88
Model 9	56.77	18220.81	18266.63	20.83	21271.57	21317.39
Model 10	56.77	18220.63	18266.44	19.55	21308.10	21353.91
Model 11	56.78	18222.24	18273.78	21.04	21267.52	21319.06
Model 12	56.83	18221.78	18279.04	21.70	21250.53	21307.79

The adjusted models are shown in Table 4. It should be noted that for both the end splits and surface cracks, the influences of the moisture content and diameter were statistically significant, as well as the interaction between these variables. However, the surface cracks showed linear and exponential influences for all of the interactions. This was different from the end splits, which are diameter independent, where only its exponential influence was significant.

Table 4. Multiple Regression Models Adjusted to Describe the Percentage of Cracks as a Function of the Diameter and Moisture Content in the *Eucalyptus* Wood Logs

Variable	Equation
Sc%	$Z = -4.29e^{+02} + 1.03e^{+02}{**}X - 5.29e^{+00}{**}X^2 + 1.27e^{+01}{**}Y - 8.73e^{-02}{**}Y^2 - 3.108e^{+00}{**}XY + 1.62e^{-01}{**}X^2Y + 2.15e^{-02}{**}XY^2 - 1.13e^{-03}{**}X^2Y^2$
Es%	$Z = 5.67 + 2.82X + 0.27{**}X^2 - 0.34{**}Y + 0.01{**}Y^2 - 0.04{**}XY$

** indicates the significance of the parameters of the models is at the 1% significance level for the t-test; Es = end splits; and Sc = surface cracks

The predicted values generated from the adjusted models (Table 4) made it possible to generate graphs that showed the tendencies for the development of end splits and surface cracks as a function of the diameter and moisture content. The influence of the diameter and moisture content on the surface cracks is shown in Fig. 3.

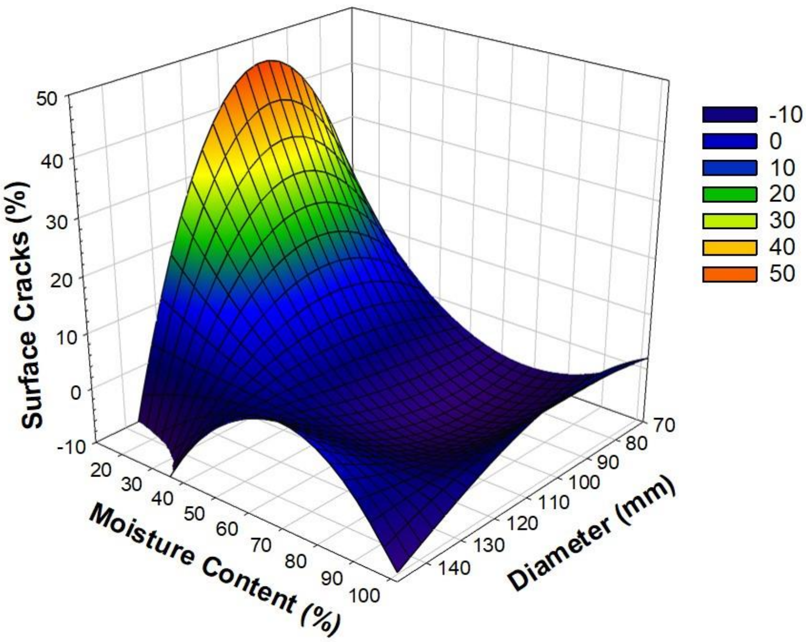

Fig. 3. Surface response graph for the representation of the surface cracks as a function of the moisture content and diameter of the *Eucalyptus* wood logs during drying

The independent effect of the moisture content on the surface cracks was analyzed at the beginning of drying or at high moisture contents, and the graph shows values below zero. Those negative values showed that surface cracks did not develop or tend to appear during this drying period. The positive values represented the presence of surface cracks. The graph remained that way until a moisture content of approximately 30%, which corresponded to the FSP. From that point on, there was a remarkable increase in the percentage of surface cracks as the moisture content decreased. That being said, it was assumed that drying during bound water loss affected the emergence of surface cracks more remarkably. This tendency was possibly because of drying stresses caused by moisture concentration gradients. The region that was closer to the surface of the wood log tended to dry below the FSP as it started losing bound water because the cell walls began to dry and caused shrinkage (Evans *et al.* 2008; Lazarescu *et al.* 2009). However, the core region of the logs was still above the FSP, which caused the fibers in the surface to be under tensile stress. When those stresses exceeded the final wood strength, surface cracks occurred (McMillen 1955; Tarmian *et al.* 2009).

Because the interactions between the diameter, surface cracks, and moisture content were significant, the behavior of those cracks for different diameters was different. The intermediate diameters (approximately 100 mm) studied showed a higher tendency for surface cracks, but when the largest (140 mm) and smallest (70 mm) diameters were compared by analyzing the predicted values, the smallest diameters tended to have a higher presence of surface cracks than the largest diameters. That was possibly because of the fact that the smallest diameters dry faster, which causes a higher difference between the surface moisture content when it dries below the FSP and core moisture content. This consequently results in more drying stresses.

End splits (Fig. 4) showed a tendency to appear soon after the felling of logs with high moisture contents, and they increased gradually as the moisture content decreased for all of the diameters studied. Also, compared with surface cracks, end splits showed a tendency to achieve higher values than surface cracks. While the end splits tended to achieve percentage values of 100% and a mean value of 32.67 mm per crack, the surface cracks tended to only reach 50% of the maximum values and a mean value of 16.76 mm per crack, showing that end splits have a higher potential for degrading wood logs than surface cracks.

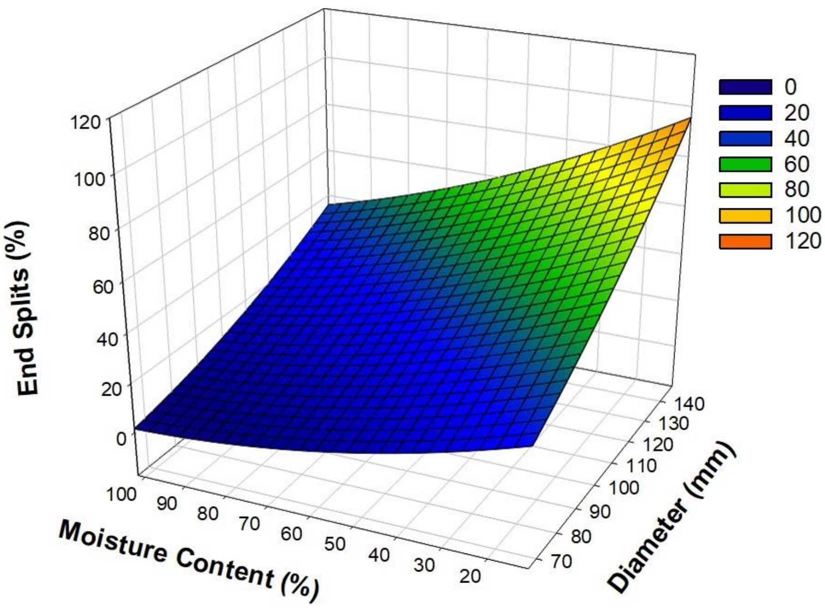

Fig. 4. Surface response graph for the representation of the end splits as a function of the moisture content and diameter of the *Eucalyptus* wood logs during drying

The tendency for the appearance of end splits at the beginning of the drying process was possibly because of the release of growth stresses. The wood industry has long known the problems created by growth stresses (Jacobs 1945; Kubler 1987; Fang *et al.* 2008), especially in young trees (Walker 2006). Beltrame *et al.* (2015) found a high correlation between growth stresses and end split rates, which made it clear that growth stresses relieved during felling or sawing can cause cracks and subsequent devaluation of a wood piece. Thus, it was possible to associate the presence of end splits with the young age of the trees and the species studied.

The tendency for end splits to continue their development as the moisture content decreased showed that growth stresses possibly continued acting until they were relieved (Fig. 4). From that moment on, the drying stresses may have interacted with the growth stresses and influenced the presence of this defect. That may have also been the reason why there were more end splits than surface cracks, because two kinds of stresses acting simultaneously may have had a larger effect than only one.

When analyzing the behavior of the diameters independently (Fig. 4), there tended to be more end splits in the large diameter logs than in the small diameter logs for all of the moisture contents. This result was similar to that of da Cunha *et al.* (2015), who studied the development of end splits in *E. benthamii* and found a higher presence of those defects in larger diameter logs. However, for *E. grandis* logs, the same study found the opposite tendency. Hornburg *et al.* (2012) studied the quality of logs from six different species of *Eucalyptus* and also found a tendency for a higher number of cracks with an increasing diameter. The higher presence of end splits in the larger diameter logs was possibly because of the presence of juvenile and mature wood in those logs and the presence of brittle heartwood next to the pith (Calonego and Severo 2005).

Density

The wood basic density values ranged from 0.411 g/cm^3 to 0.627 g/cm^3, which correlated with the values in the literature for *E. urophylla* wood (Rezende *et al.* 2010; Couto *et al.* 2013; Zanuncio *et al.* 2015; Monteiro *et al.* 2017; Monteiro *et al.* 2018). Logs with a larger diameter presented the lowest density values. The results for the Pearson's correlation test between the density and emergence of cracks are shown in Table 5.

Table 5. Correlation between the Density and Defects in the *Eucalyptus* Wood Logs

Defect	*t*	*p*-value	*r*
End Splits	-0.582	0.561	-0.056
Surface Cracks	4.253	4.56E-05	0.382*

r = Pearson's correlation value; *t* = student t-value; and *significant at a 5% significance level

The value for the end splits was not statistically significant ($p < 0.05$), while the value for the surface cracks was significant. This meant that the density was not related to the end splits, but it was related to the surface cracks, although weakly. That was possibly because of the fact that surface cracks showed a tendency to occur below the FSP, when there was shrinkage caused by bound water loss, especially in the tangential direction. Batista *et al.* (2010) studied the density and shrinkage of three *Eucalyptus* species and found a high correlation between those two variables. Barbosa *et al.* (2005) studied the susceptibility of *Eucalyptus* wood to drying defects and found that the density itself is not capable of explaining variations in the drying speed or the occurrence of defects during the drying process. Monteiro *et al.* (2017) found no significant correlation between the basal density and free water flow in *Eucalyptus* and *Corymbia* logs. However, those authors reported that there was a negative correlation between the density and total drying of the logs (free water and bound water).

CONCLUSIONS

1. Smaller diameter logs dried faster and took less time to reach the fiber saturation point (FSP) than larger diameter logs. This information reinforces the need for sorting logs in the drying field, especially considering the principle that for wood pieces to be dried together, they must have the same drying speed to optimize drying and avoid a lack of uniformity and subsequent weight imbalance.
2. Surface cracks showed a tendency to occur more during bound water loss. Therefore, to avoid this kind of crack it is necessary to control drying at its beginning so that logs can take longer to achieve FSP and the effect of drying stresses can be reduced.
3. The smaller diameter logs tended to present higher percentages of surface cracks compared with the larger diameter logs. Accordingly, smaller diameter logs need to be

stored in places with lower temperatures, as far as possible from sunlight so it can dry in a slower way and decrease the risk of defects.

4. End splits showed a tendency to develop during free water loss and continued increasing as the moisture content decreased, even during bound water loss. This fact indicates that more studies need to be carried out in order to answer how long growth stresses influence on cracking and its interactions with drying stresses. Also, the use of the fracture mechanics concept and the use of numerical tools that help to model crack propagation in wood is necessary to complete the results proposed in this paper generating more information about how, when and why cracks occur in wood.
5. The density was not related to the final percentage of end splits. However, it showed a weak but significant correlation with the final percentage of surface cracks. This finding encourages the development of coming works that evaluate how density and its connection to shrinkage can affect on the emergence of defects. More studies in this area could allow the genetic selection of wood materials that have a lower tendency to crack.

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