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ORIGINAL ARTICLE

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Heart splitting at crosscutting of eucalypt logs

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Abstract The occurrence of heart splitting during the crosscutting of logs was discussed in relation to the released strain on *Eucalyptus* spp. logs. The strains released in the longitudinal and tangential directions were measured by the strain-gauge method and were correlated with the length of the heart split measured on the same logs. There were differences in the longitudinal strain; however, no significant correlation was found with the diameter that could be converted to a mean annual increment (i.e., a relation with the growth rate). The initial splits expand with the time after felling. The longer the initial split, the longer is the length 1 week after felling. The split length was significantly smaller at the butt end of the first log of every tree than at the other end, but there were no significant differences between the split length at the top of the first logs and at either end of the second logs, although there were differences among individual trees. The length of the heart split correlated with the released strain near the pith, which was estimated using Kubler's equation. The longitudinal released strain measured on the surface of logs is a good indicator of the heart splitting when crosscutting logs.

Key words Growth stress · Released strain · Heart split · *Eucalyptus grandis* · *Eucalyptus globulus*

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Introduction

Plantations have become important worldwide for maintaining the global environment and providing a sustainable supply of forest products. It is essential to increase the effectiveness of plantations by increasing the value of their products. Until now, various fast-growing hardwood species were planted to be used mainly as a source of pulp and paper. These trees are harvested as juveniles. However, many of these species produce wood of a density and texture that are suitable for manufacturing furniture and for use as interior building materials. To increase the value of forest plantations, it is essential to develop them as a source of timber.

When hardwood is sawn to produce lumber, the residual stress in the stem must be considered. Tree growth stress is a property of the cell wall of the outermost layer of the trunk that results from cell wall thickening; stress is distributed inside the trunk in response to the growth stress. This process continues as the trunk diameter increases. Consequently, the growth stresses and stress distribution are superimposed to generate a residual three-dimensional stress distribution inside a standing tree.[1,2]

When a standing tree is felled, the elastic energy of the residual stress is released with the formation of heart splits at the crosscut surface, and crooking and warping occur at sawing.[3–5] These phenomena reduce the yield of timber products at sawing; hence, residual stress is considered an obstacle to wood processing.

To solve the problems caused by growth stress it is necessary to improve genetic and silvicultural techniques by breeding trees with low growth stress and develop processing technology that relieves the residual stress in logs. This necessitates evaluating the defects in individual species. To assess the defects originating from growth stress, the surface released strain (growth strain) is usually measured on the xylem surface of individual trees because surface growth stress is an indicator of the residual stress inside a log.[6–9] However, few investigations have examined the relation between residual stress and the defects that occur during wood processing.

Some mechanical approaches to dealing with defects during processing have been made, such as model analysis of the redistribution of the residual stress during crosscutting and crooking during sawing.[4,5,10–13] However, no substantial studies have examined the heart splits that appear at crosscutting. This is due to the difficulty obtaining reliable data on heart splitting and the insufficient theoretical background. It seems to be common sense that the larger the growth stress the more severe is the heart split at crosscutting,[14] but there are no data on the relation between the measured released strain and heart splits at crosscutting. This paper discusses the relation between heart splitting and released strain on planted eucalypts.

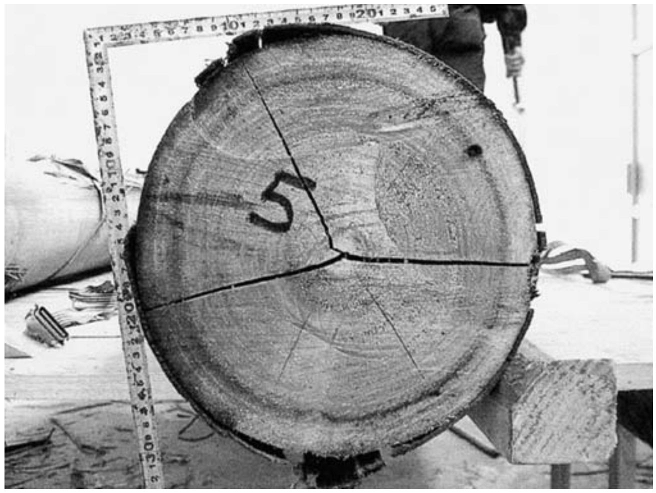

Fig. 1. Heart splits at 1 week after crosscutting of *Eucalyptus grandis*

Materials and methods

Selecting test trees

The trees used were *Eucalyptus grandis* planted in a forest in Tacuarembo, Uruguay and *Eucalyptus globulus* planted in Coonack downs, Australia. Both trees were 11 years old.

The planted density of *E. grandis* was 1666 trees per hectare. No thinning had been done, because the trees were planted for pulp and fuel production. The annual growth rate of this forest is 25–30 m^3 per hectare. The study site was flat, and the trees were straight. Twenty straight trees, 25.5–33.0 m high and 16.2–34.9 cm dbh were selected and felled for the measurements.

Eucalyptus globulus had been planted 1200–1500 trees per hectare in a flat field. The growing conditions are almost the same as for *E. grandis*. Twenty-nine straight trees, 25–30 m in height and 11–47 cm dbh were selected.

Preparing test logs

Eucalyptus grandis trees were felled at 15 cm above the ground, and two 4-m-long logs were prepared from adjacent portions of each tree. The lower log was called the first log, and the upper log was the second log.

Eucalyptus globulus trees were felled at 10–20 cm above the ground after measuring the released strains at the breast height position. The length of the heart split was then measured at the nearest position of the strain measurement.

Measuring heart splits

In most logs, a heart split is formed with a pop at the time of crosscutting, and the length of the split increases with time. In case of *E. grandis*, the total length of the heart splits on each 4-m log was measured 5 days after felling and recorded as the mean length at both the butt and top end surfaces of each log. To examine the time-dependent expansion of the heart split, the length of each heart split at a given end was measured twice. After measuring the surface released strains at the middle of the 4-m log, the log was cut into two 2-m logs. The total lengths of the heart splits were measured at the larger end of the 2-m log, twice after cutting, and again 1 week later (Fig. 1). In the case of *E. globulus*, the total length of the heart split was measured on the end surface of the upper log after crosscutting at the position where the released strains were measured.

Measuring released strain

The strain-gauge method was used to evaluate the released strain of growth stresses in the longitudinal and tangential directions.[15] In case of *E. grandis*, the 4-m-long logs were put on a flat rack. Four measuring positions were established equally spaced around the middle of the 4-m log, where the log was carefully debarked with a hand chisel so as not to scratch the xylem surface. Two pairs of 8-mm strain gauges (Minebea E-8-12-T11) and a foil terminal (Minebea TF-10) were attached to the surface in the longitudinal and tangential directions, respectively, using an instant adhesive (Kyowa CC-33). The gauges were connected to a multiscanning strain meter (Kyowa USB-11A, UCAM-1A) using the three-wire connection method. After taking an initial reading of the strains and waiting for output stability, the two-dimensional stress was released by cutting grooves about 10 mm deep approximately 5 mm from the gauges.

Eight strains at the four measuring positions were measured per log. The mean values of the four longitudinal and tangential strains were taken as the released strain of each log. During strain measurement, fiber strain is induced by the weight of the log and adds to the released strain, but this contributed less than 0.003% of the released strain. In the case of *E. globulus*, the released strain was measured prior to the felling in the same manner as for *E. grandis*.

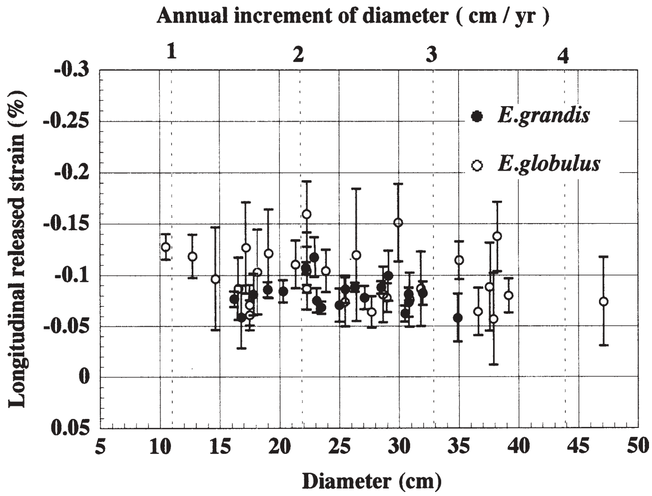

Fig. 2. Relation between longitudinal released strain and log diameter. Plot shows the mean of released strains in four cardinal directions for each log. The range shows the standard deviation

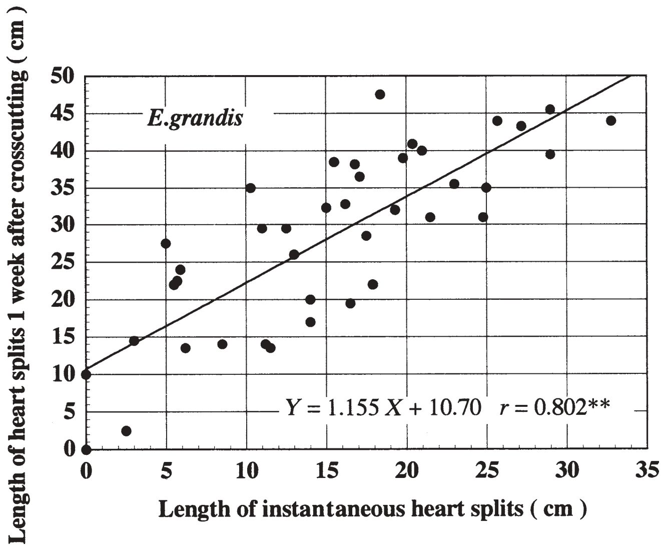

Fig. 3. Correlation between the length of heart splits at crosscutting and one week after crosscutting

Results and discussion

Released strain in the longitudinal direction

Figure 2 shows the mean value and standard deviation of the longitudinal released strain of the first logs of *E. grandis*. For *E. globulus* the strain at breast height of standing trees is plotted against the log diameter. There was variation in the longitudinal strain, but there was no significant correlation with diameter. The diameter is converted to the average annual increment of diameter because all the trees were the same age. Hence the data predict that growth stress is not affected by the growth rate. This finding concurs with previous data showing that growth stress is not affected by growth rate in fast-growing species younger than 15 years.[8,9,14] Because planted eucalypts with large diameters are reported to have lower released strain,[16] Fig. 2 could be interpreted as showing that trees larger than 30 cm in diameter had lower strain, although the difference is statistically insignificant.

Heart split expansion after cutting

Figure 3 shows that there was a good correlation between the total lengths of the heart splits in the middle of the 4-m logs immediately after crosscutting and 1 week later. On average, the split length increased from 15.2 cm to 28.3 cm. Only one log did not incur any heart splits. The longer the initial split, the greater is the increase after 1 week.

Some splits exceeded 30 cm and reached the surface of the xylem; such splits are called heart shakes. To evaluate the extent of a heart split, its width should also be considered because both lengthening and widening of the split release the elastic energy of residual stress. If the released energy could be evaluated properly, the energy might show good correlation with the released strain.

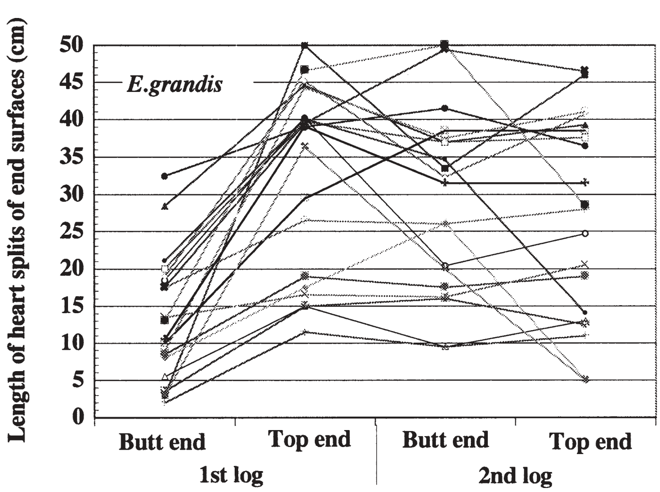

Fig. 4. Length of heart splits on the end surfaces of 4-m logs

Heart splits at end surfaces

Figure 4 compares the total lengths of heart splits on the end surfaces of 4-m *E. grandis* logs 1 week after crosscutting. The plots were connected by lines to distinguish individual logs.

Five trees showed marked differences in the lengths of the heart splits at each end, whereas the change in the other 15 trees was regular. Because a heart split is a fracture phenomenon, a large fluctuation in heart splits is to be expected. However, a nonsignificant difference in the split length was observed between the top end of the first log and both ends of the second log, although there were differences among individual trees. By contrast, the split length at the butt end of the first log from all trees was significantly smaller than at the other ends.

Generally, longitudinal released strain is uniform throughout the height of a tree, except around reaction

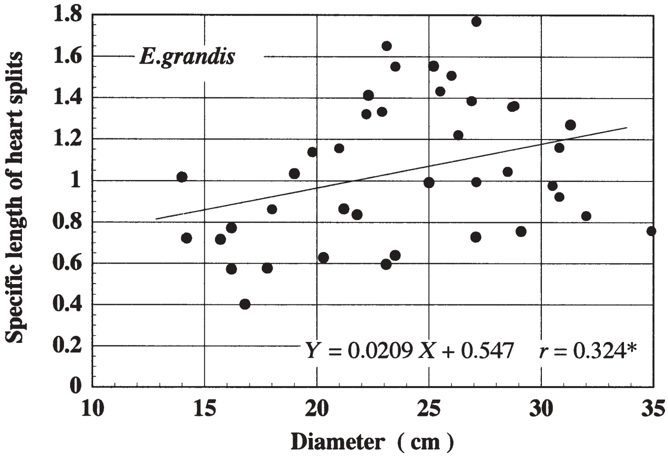

Fig. 5. Relations between the specific length of heart splits and the diameter of the log

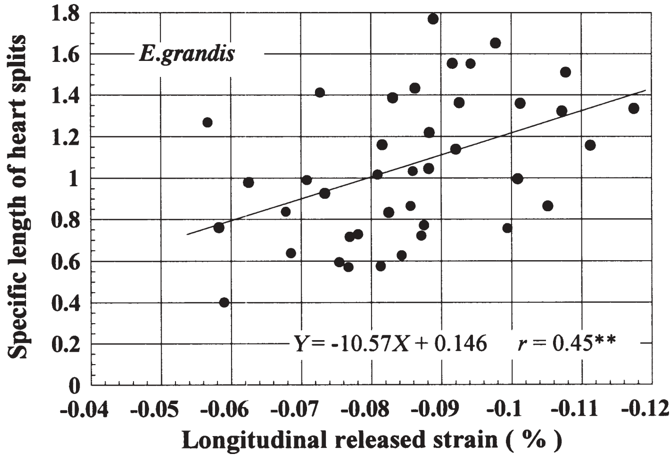

Fig. 6. Relations between the specific length of heart splits and the longitudinal released strain

wood,[17] and there are no reliable data that the growth stress is extremely small at the stem near the root. However, it has been reported that the roots of some species have much lower growth stress than the stem.[18] It has also been pointed out that the increased cross-graining found in the trunk near the ground would prevent the development of heart splits.[19] The lower incidence of heart splits in the basal part of the trunk is likely due to the effect of root characteristics in the transition part of the stem.

Length of heart splits and log diameter

Figure 5 shows the relation between the specific length of the heart splits (i.e., the length of the heart split divided by the diameter) at both ends of the 4-m *E. grandis* logs 1 week after felling and the diameter at the middle of the log. There was correlation at the 5% level. This shows that the larger the diameter, the longer is the heart split. That is, the larger the growth rate, the more severe is the heart split.

According to the superposition theory of growth stresses, even when uniform growth stresses are generated in the outermost layer of the trunk during every growing period the longitudinal compressive stress around the pith increases with the diameter.[1,2] Consequently, a larger expansive strain is generated around the pith during crosscutting of a trunk with a larger diameter. This large expansive strain induces large tensile stress in the tangential direction by Poisson's effect[11,14] and causes the heart split.

Length of heart split and longitudinal released strain at the xylem surface

Figure 6 shows the relation between the specific length of the heart split and the longitudinal released strain. Both are correlated at the 1% significance level, which is better than the correlation in Fig. 5. This means that the released strain of the growth stress has a greater effect than diameter in generating a heart split.

Combined effect of released strain and diameter on heart-split generation

As shown in Fig. 1, a heart split usually grows in a star-like manner from the pith toward the bark. The origin of a heart split is a tensile fracture in a tangential direction (T-direction) around the pith region. When the tensile stress or expansive strain exceeds the tensile strength or maximum strain in the T-direction around the pith, a heart split occurs. To confirm this mechanism, we need to know the tensile stress or expansive strain induced near the pith at crosscutting. However, we cannot measure these parameters before crosscutting. Nevertheless, it is possible to estimate them theoretically from the longitudinal released strain measured at the xylem surface.

Kubler[20] represented the residual stress distribution as a function of the radius and the growth stress, σ_L, generated in the outermost layer. When a uniform growth stress is generated annually, the residual stress distribution in the L-direction across the radius, $\sigma_{L(r)}$ is represented as

$$\sigma_{L(r)} = \sigma_L(2\ln r/R + 1) \quad (1)$$

where r is an arbitrary position on radius R. A similar pattern of residual stress distribution has been confirmed using different elastic models.[1,2]

Assuming homogeneity of the log, the stresses can be approximated as released strains using

$$\varepsilon_{L(r)} = \varepsilon_L(2\ln r/R + 1) \quad (2)$$

where ε_L is the measured longitudinal surface released strain, and $\varepsilon_{L(r)}$ is the estimated released strain at position r inside the log. The strain at a small r gives the estimated longitudinal released strain around the pith.

The horizontal axis in Fig. 7 is the estimated longitudinal released strains at r = 1 cm. It is clear that large, expansive strains are induced around the pith.

The regression lines are $Y = 3.107\varepsilon_{L(r)} + 0.00189$, $r = 0.62^{**}$ for *E. grandis* and $Y = 1.22\varepsilon_{L(r)} - 0.0292$, $r = 0.53^{**}$

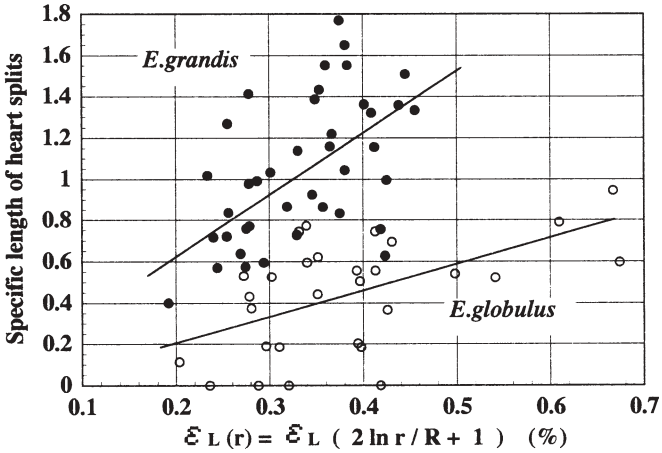

Fig. 7. Relation between the specific length of heart splits and the longitudinal released strain near the pith, at 1 cm from the pith, estimated by Eq. (2)

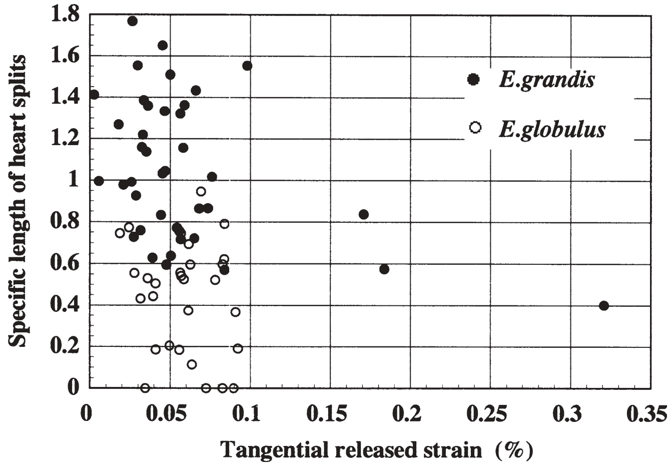

Fig. 8. Relation between the specific length of heart splits and the tangential released strain

for *E. globulus*. The relations give a good correlation between the heart split and longitudinal released strain near the pith. The greater the expansive strain, the longer is the heart split.

Contractive strains are induced in the tangential and radial directions according to Poisson's effect owing to the large, expansive strain induced by the instantaneous release of a large longitudinal compressive stress around the pith. The large longitudinal released strain around the pith then generates a heart split.

Based on these results, it can be said that the occurrence of heart split depends on both growth stress and the diameter. The total length of heart splits increases in proportion to the longitudinal released strain, and it increases logarithmically with the diameter. The growth strain in the longitudinal direction is a good indicator of the heart split.

The relation also depends on the species. The incidence of heart split in *E. globulus* is much lower than in *E. grandis*. It depends on the difference in the fracture characteristics of the species, and we can estimate the degree of heart split of individual species by measuring the longitudinal released strain and the diameter.

Length of heart splits and tangential released strain on the xylem surface

Figure 8 shows the relation between the specific length of the heart splits and the tangential released strain in 4-m logs at crosscutting. All the expansive strains predict the existence of compressive stresses at the xylem surface in the T-direction. These tangential strains involve the strain due to Poisson's effect on longitudinal released strains. Large tangential strains occurred where large longitudinal released strains were measured. Obviously, the larger the tangential released strain, the shorter is the length of the heart split. Excluding the outliers, the correlation was significant at the 1% level. Based on these results we can state that the released strain in the outer part of a log induces a compressive stress in the T-direction, which prevents elongation of the heart split.

Conclusions

The relation between the released strain, the growth strain measured on the xylem surface, and heart splits was discussed using data for 11-year-old *E. grandis* and *E. globulus* logs. The generation of growth stress does not depend on the growth rate in trees up to 11 years old. One week after crosscutting the heart splits were 1.5–3.0 times longer than they were initially, and the increase was proportional to the total lengths of the splits. Approximately half of the splits grew into heart shakes at 1 week. Heart splits were significantly smaller at the butt surface of the first log, whereas they were fairly similar on the other surfaces, although individual differences did exist. The lengths of the heart splits were well correlated with the longitudinal released strain near the pith estimated from the measured surface released strain using Kubler's equation. Hence it follows that the occurrence of heart split depends on both the growth stress and the diameter. The longitudinal released strain is a good indicator of heart splitting. The tangential released strain was negatively correlated with the length of the heart splits.

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