Experimental Investigation on Rotary Peeling Parameters of High Density Coconut Wood

Henri Bailleres,[a,]* Louis Denaud,[b] Jean-Claude Butaud,[b] and Robert L. McGavin [a]

Substantial quantities of senile coconut palms are present in plantations within the Asia-Pacific region. Once coconut palms become over-mature, their production of traditional products, such as coconuts, significantly decreases, resulting in profitability challenges for farmers. Presently, few profitable markets exist for over-mature, senile coconut palms. Using the coconut palm stem in composite or engineered wood products could, however, provide an attractive alternative. Due to some of its unique characteristics, a processing system able to recover wood from the high-density zone near the stem periphery is desirable. A series of rotary veneer laboratory trials were undertaken to establish fundamental benchmark lathe settings and veneering characteristics for coconut palm stems. Different pressure bar configurations, billet pre-treatment temperatures, and veneer thicknesses were tested, and the resulting cutting forces and veneer quality were assessed. Optimal setting recommendations for peeling coconut wood are provided.

Keywords: Coconut wood; Veneer; Rotary peeling, Lathe; Machining; Processing; Cutting forces

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INTRODUCTION

A large portion of the Asia-Pacific region's coconut palms are over-mature and often do not produce enough coconuts or by-products to be profitable. In addition, the low financial returns from these over-mature palms is a barrier preventing effective harvesting and replanting. As aging palms produce fewer traditional raw materials, the livelihoods of millions of farmers are adversely affected. The Asia-Pacific's senile coconut plantations present a significant opportunity for sustainable wood production. There is an expanding regional and international market for wood veneers and composite wood products. Because access to the traditional resources for these products, particularly tropical rainforests, is constrained, the substantial volume of wood held in the estimated 120,000 hectares of senile coconut plantations within the Pacific Islands represents an attractive alternative resource (Arancon 2009). With the development of suitable technologies, processes, and expertise, a sustainable coconut wood veneering industry sector could be established to use the available resource. Such an industry would deal with the harvest and re-establishment of coconut plantations, conversion of recovered stems into veneer, assembly of composite products for local use, export, or trade, and production of useful agricultural products and fuel from stem and crown residues. The demand for coconut wood is a financial incentive for plantation owners to remove low-productivity senile stems and use their land in more productive ways, such as by planting a new crop of coconut trees or other agricultural alternatives.

Coconut wood differs significantly from hardwood, softwood, and even the wood of other palm stems in terms of tissue anatomy, fibre orientation, and density distribution. The complex tissue organization of palms such as coconut wood cannot be classified in a strict botanical sense as "wood" because it differs notably from that of dicotyledonous plants (*e.g.*, scattered vascular bundles). Coconut palm "wood" is therefore referred to as "cocowood" throughout this paper. Cocowood is a complex plant tissue with a structure somewhat like parallel cables embedded in foam. The simple botanical description of cocowood is a blend of two different tissues: fibrovascular bundles and the surrounding parenchyma (ground tissue). The fibrovascular bundle architecture follows an interlocked helix formation as it ascends the trunk. The specific architecture of cocowood has been described as a triple helix structure (Bailleres *et al.* 2010; Tomlinson *et al.* 2011; Gonzales *et al.* 2014).

Unlike the dicotyledonous trees traditionally used by the forest products industry, coconut palm (*Cocos nucifera* L.) is a monocotyledon. Due to the huge variation in cocowood's density, production of high-quality veneers from the external part of coconut palm logs appears to be the most attractive way to use this resource (Fig. 1). However, the unique structure of cocowood requires tight control of peeling parameters.

Fig. 1. Coconut disc with its specimen reference showing that the most valuable area for high density veneer production lies between the blue circles

Recent technical improvements in low-cost, spindle-less lathe equipment and the associated processing technologies provide great opportunities to add value to small-diameter, underutilized resources such as senile coconut palms. Indeed the processing of plantation hardwoods into veneer using relatively new small-scale spindleless veneer lathe technology has been demonstrated in research trials to deliver product recoveries that are much more favourable when compared to solid wood processing techniques (McGavin *et al.* 2014a, b and 2015). While the spindleless lathe technology approach is not necessarily new, recent advancements in design allow the technology to be well suited to smaller diameter plantation forest resources. The advancements have been quickly adopted through many Asian countries, including China and Vietnam, for successful veneer production from very small diameter hardwood billets. Arnold *et al.* (2013) report well over 5000 small-scale veneer mills operating in China. A parallel could be established between the emergence and proliferation of a eucalyptus veneer industry in China, as described by Arnold *et al*. (2013). Based on young, small-diameter logs, this industry has transformed a lower-value pulp resource into a higher-value feedstock for veneer production, supporting the manufacture of engineered wood products.

Diameter and density patterns are known to vary from the bottom to the top of the palm, as described by Gonzalez *et al.* (2014) and Bailleres *et al.* (2010). The density variation ranges from around 100 kg/m^3 in the centre of the trunk to more than 1000 kg/m^3 on the periphery. The bottom part of the palm is denser, with a steep density increase from the center to the periphery. The top part is less variable from the center to the periphery and has smaller bundle sizes in higher concentrations. It should be noted that at the same height, the average density of cocowood, and the center-to-periphery density variation, can differ significantly between trees and is influenced mainly by palm age (Bailleres *et al.* 2010; Hopewell *et al.* 2010). Tissue heterogeneity and density variation were expected to be major challenges in the production of quality cocowood veneer (Feng *et al.* 2011). A literature review on the peeling parameters of palms has revealed insignificant baseline data on the veneer processing of cocowood.

The purpose of this study was to define the optimum range of rotary peeling parameters for the production of dense, homogeneous veneer. Given the limited information available regarding the potential for coconut palm trunks to be peeled, an exploratory campaign was designed to evaluate the influence of key process parameters on veneer quality. Since the number of samples was limited and there was no technical information available on the peeling process characteristics for cocowood when the investigation began, a sequential trial approach was chosen to investigate the key parameters. Although such an approach is not exhaustive, it minimized the number of experiments required and provided valuable, practical, and novel information.

EXPERIMENTAL

Cocowood Sampling

A total of 43 senile coconut palms (70 or more years old) were sampled from several Fijian plantations. Four discs, 25 mm thick, were taken from each palm trunk. These were cut from the trees at breast height (approximately 1.3 m from the ground) and then 25, 50, and 75% of the stem height which were labeled D1, D2, D3, and D4, respectively. Green sample discs were stored in air-tight film in a refrigerated chamber prior to further processing and trials. Disc allocation to trials ensured that they were grouped based on their diameter and density patterns.

Veneer Processing

Veneer processing was done using a specialized micro-lathe system developed by the Arts et Métiers ParisTech (AMPT, engineering school) in Cluny, France (Butaud *et al.* 1995). The micro-lathe system was equipped with appropriate control and instrumentation systems to facilitate the investigation of key rotary peeling processing parameters in a controlled manner. The micro-lathe system peels thin discs (25 mm thick) using brushless motor and cutting systems (Fig. 2) equipped with several displacement and force sensors. This allowed processing parameters, such as cutting forces, to be recorded precisely and quickly for a large number of specimens. Peeling discs instead of logs or billets enabled a range of parameters to be tested by using samples with similar properties (*i.e.*, a large number of discs can be removed from one short billet). The use of discs instead of billets also reduced the total volume of test material required. A narrow veneer ribbon is advantageous in facilitating thorough investigation of the veneer fragility (*e.g.*, propensity of splitting and brittleness). The edge effect exacerbates the breakability of such narrow veneer since deep checks tend to split the ribbon. This splitting should unlikely occur on commercial veneer width (1.2 m minimum) since the bundle interlacements prevent the local checks to propagate to the entire veneer width. The assessment of veneer fragility was important, given the known heterogeneous nature of cocowood (stiff fibro-vascular bundles embedded in friable parenchyma tissue) and the huge density variation from the center to the periphery of the trunk.

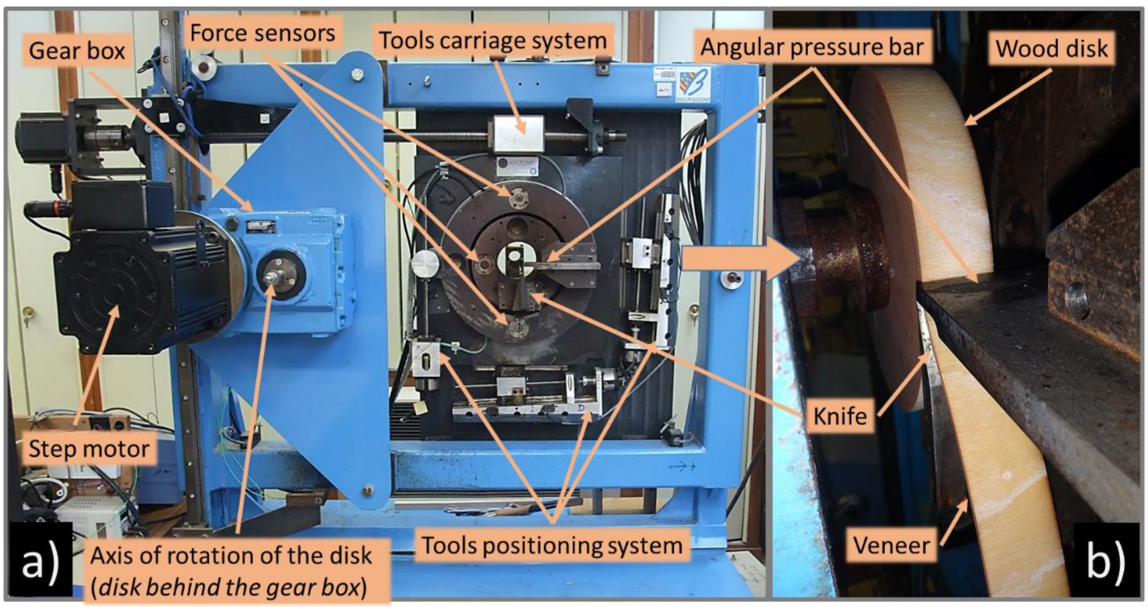

Fig. 2. Micro-lathe system (Butaud *et al.* 1995) a) overview; b) cutting system: knife and pressure bar

In the absence of any benchmark lathe settings for cocowood or published information regarding the effect of processing parameters on cocowood veneer quality, a series of relevant parameters were selected within the normal range for traditional wood veneer production. These parameters are well-established in wood veneer production and yield good structural and surface veneer qualities. These parameters also influence the cutting forces required and therefore the machining behavior (*i.e.*, machinery loading, power usage, and wear and tear) as described by Marchal *et al*. (2009). Several parameters were focused on in this work.

Lathe settings

According to Feihl (1986), the knife grinding angle commonly applied during rotary peeling ranges from 19 to 21° for hardwoods, and 21 to 25° for softwoods. Fondronnier and Guillerm (1979) showed that the minimum log spinning force was achieved with a 21° angle. The 21° knife angle was used in this study because the density of cocowood is similar to that of common, high-density hardwood species. A standard industry knife, made of a Ni-Cr alloy and heat-treated with hardness superior to 55 HRC, was selected. The knife was regularly sharpened during the trials to ensure consistent sharpness.

The knife clearance angle (or pitch angle) was reported by Marchal and Negri (1997) to have the most influence on the machining quality of thin veneers, particularly of dense woods. The high density of the outer part of the cocowood trunks influenced the decision to limit the knife clearance angle range investigated between 0 and 2°. The knife clearance angles of 0, 1, and 2° were explored in a preliminary investigation. Only clearance angles of 1 and 2° produced acceptable-quality veneers. There was no noticeable difference between these two settings. This finding is consistent with observations in the literature regarding peeling trials on other, very dense wood species and large-diameter peeler billets (Fondronnier and Guillerm 1979; Thibault 1988). Consequently 1° knife clearance angle was used in this study.

The cutting speed for all trials was set at 45 m/min because preliminary observations showed that cutting speeds above 45 m/min can cause premature tool damage. It should be noted that increasing the cutting speed to 60 m/min or even to 90 m/min could improve the surface quality of the veneer, as reported by Sales (1990) and Porankiewicz *et al.* (2005). However, increasing the cutting speed could be detrimental to the knife service life, as explained by Darmawan *et al.* (2012), particularly in high-density cocowood, which is reported to contain high minerals content (Bailleres *et al.* 2010; Hopewell *et al.* 2010).

Parameters studied

Cutting forces

The 25 mm thick discs were first debarked and rounded to remove the natural trunk edge. Peeling followed at a linear cutting speed of 45 m/min. Instead of using traditional chuck systems, as commonly used on lathes, the discs were held in place with a specific drive system using large-diameter (110 mm) clamping plates. This system was used to prevent problems gripping the low-density cocowood disc centre. The modified drive system was designed to ensure a homogeneous, suitable distribution of torque across a larger surface area of the disc than with a traditional chuck system.

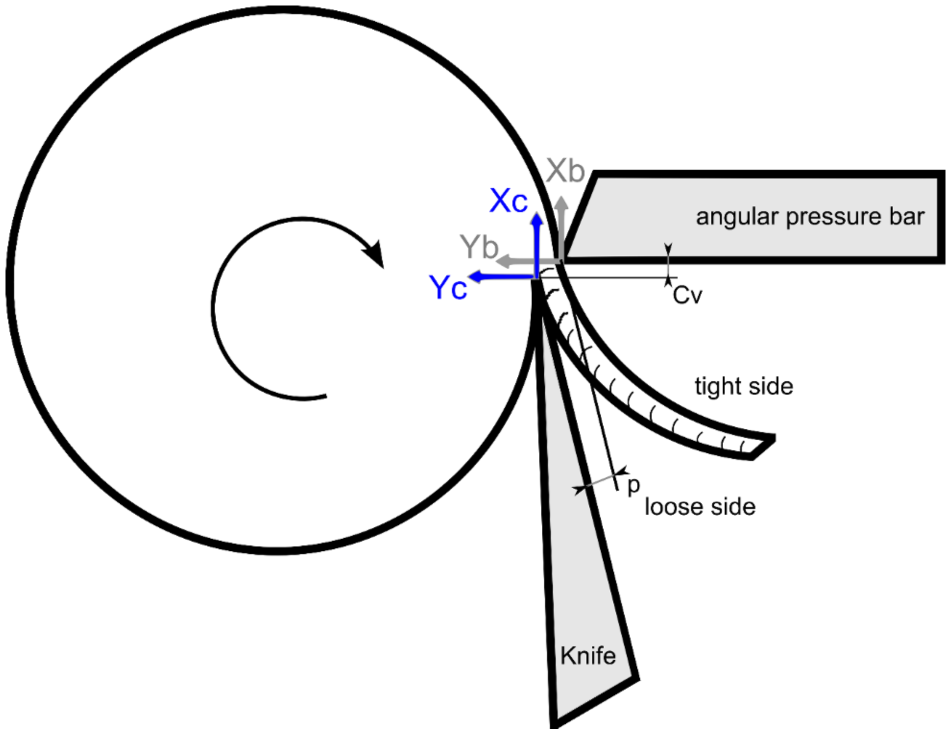

Fig. 3. Cutting force reference system for **angular pressure bar**. *P* is the knife gap and C_v is the vertical gap

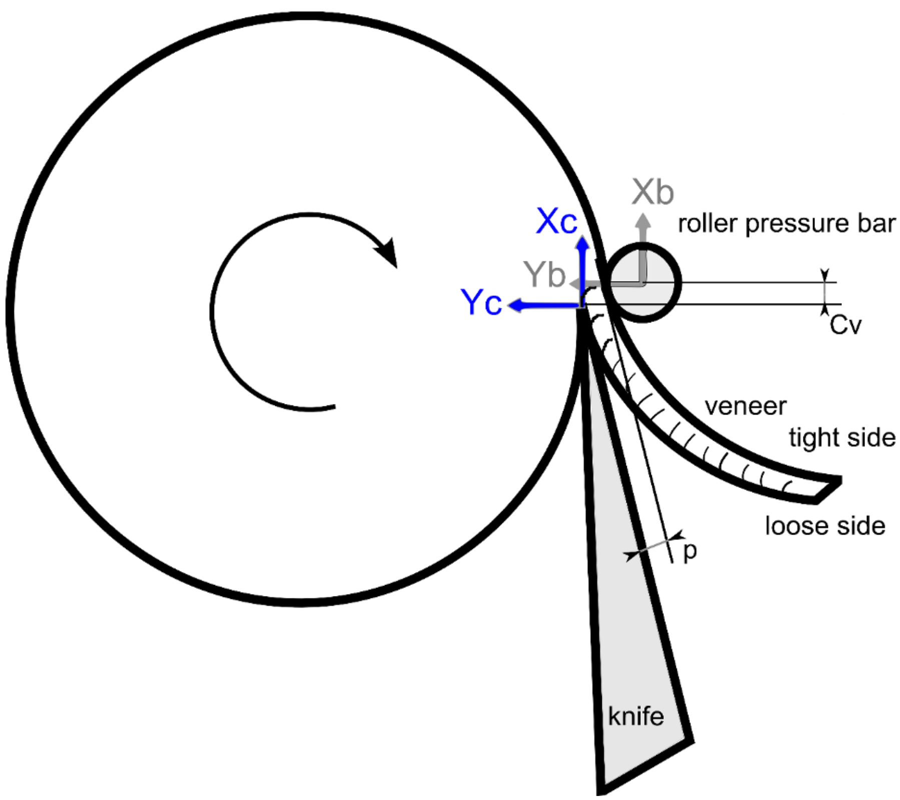

Fig. 4. Cutting force reference system for **roller pressure bar**. *P* is the knife gap and C_v is the vertical gap

For each lathe setup, the forces were measured according to the cutting plane in orthogonal directions, where *X* is the tangential axis and *Y* the radial axis for both tools (see Figs. 3 and 4). The measurements were recorded according to the methodology described by Butaud *et al.* (1995) and Marchal *et al.* (2009) in which *Xc* and *Yc* were measured on the knife, and *Xb* and *Yb* were measured on the pressure bar (Figs. 3 and 4). The forces exerted in the cutting plane, both on the pressure bar and the knife, were measured using piezoelectric load cells with the signal smoothed by a low-pass filter (50 Hz) prior to being sampled at 1000 Hz sampling frequency. The revolution angle was simultaneously recorded to obtain data as a function of the peeling revolution. To eliminate the impact of slight thickness variations between discs, the forces were expressed relative to the disc thickness (daN/cm). An example of the measurement and data extraction of the cutting forces is displayed in Fig. 5.

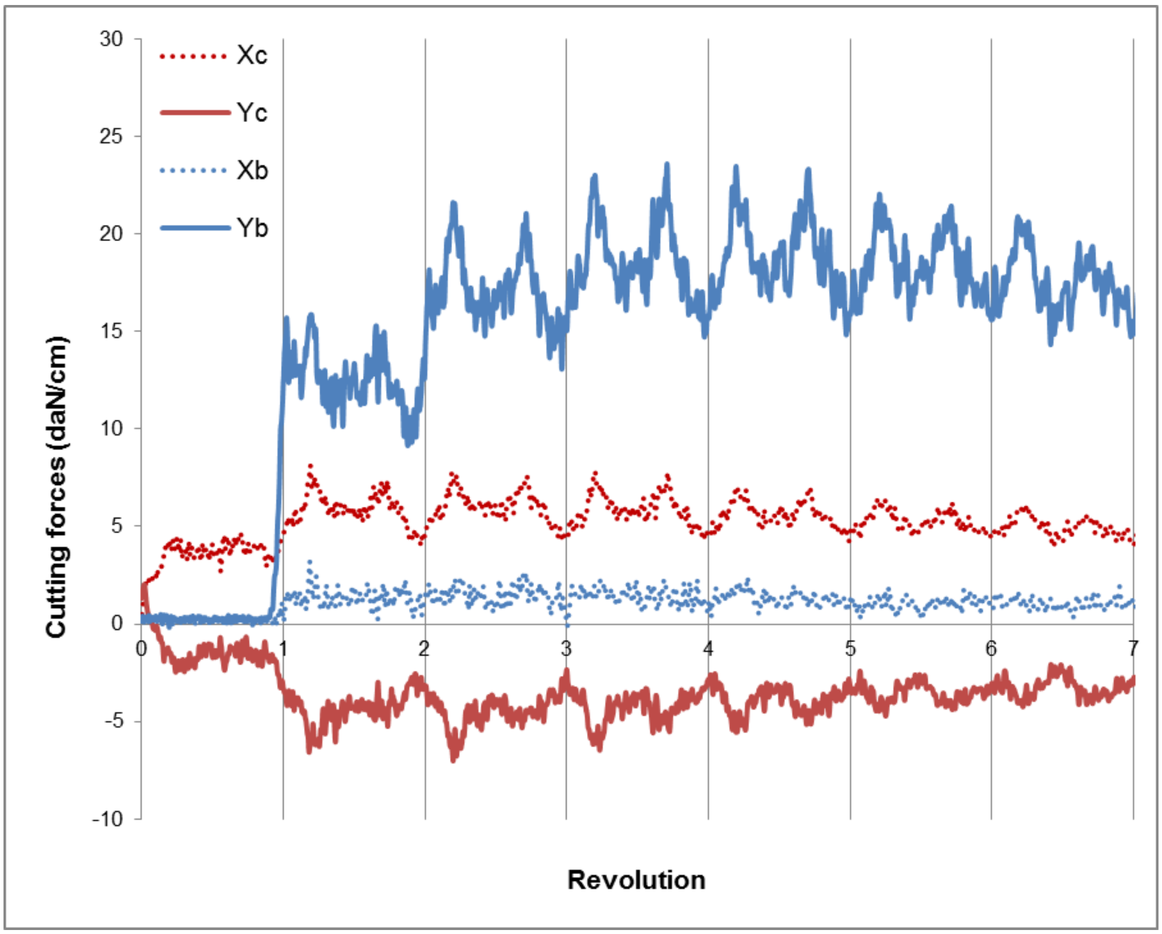

Fig. 5. Example cutting force data profile

Veneer Quality Assessment

Preliminary veneer quality assessments were conducted using a visual assessment method, and the quality was categorized into four groups ranging from a very fragmented, rough, and fuzzy veneer (1) to a continuous, smooth, and polished veneer (4). The rupture of the ribbon due to edge effects was not taken into account in the visual score. More detailed assessments of veneer thickness profiles and check characteristics were done using a specifically designed apparatus (SMOF) and assessment methodology as described by Palubicki *et al.* (2010).

The SMOF apparatus allows checks to be accurately measured using digital image analysis. Veneer checks produced during peeling are opened by bending the veneer on a 6 cm diameter roller. Special lighting is used to highlight the checks (Fig. 6). A video camera on the SMOF records the veneer profile and simultaneously analyzes it with dedicated software. The software algorithm identifies each check, calculates its depth, and determines the distance between consecutive checks. Only veneers with a visual score of 2 or above were assessed with the SMOF.

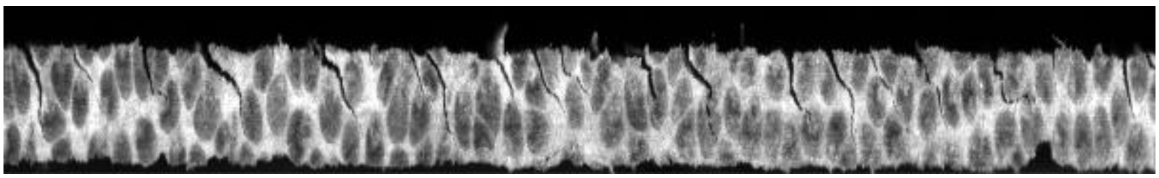

Fig. 6. Coconut wood veneer (2.5-mm-thick) lathe checks recorded by the SMOF. The veneer visual score is 2.

Compression rate

The first parameter of interest was the type of pressure bar used. An angular pressure bar, commonly used for homogeneous wood species, and a roller pressure bar, more suitable for heterogeneous wood species, were tested. To understand the effect of bar pressure on veneer quality (*e.g.*, checks and thickness variation), a standard compression rate range (from 0 to 20%) was investigated. This was set by adjusting the horizontal gap following the procedures described by Lutz (1974) and Feihl (1986). The compression rate, τ, was expressed as a percentage of the veneer thickness (e) relative to the knife gap (Eq. 1) (p, in Figs. 3 and 4).

$$\tau = \left(\frac{e-p}{e}\right) \times 100 \qquad (1)$$

A total of 35 trials were done to determine the effects of three compression rates (5, 10, and 20%) and five vertical gap (C_v) settings (0.1, 0.4, 0.7, 1.0, and 1.26 mm) on veneer quality.

Heating temperature

The heating temperature was also studied. Baldwin (1995) reported that most high-density species benefit from hydrothermal treatment. This treatment improves deformability (Yamauchi *et al.* 2005) and reduces the cutting forces required, limiting damage to the veneers (Lutz 1960; Marchal *et al.* 2009; Dupleix *et al.* 2012). In the traditional wood veneering industry, billet heating temperatures usually range from 50 to 80 °C.

Given that the overall chemical composition of cocowood is close to that of wood (Khalil *et al.* 2006), sample discs were heated for 1 hour in a water bath to 50, 60, 70, or 80 °C. Ambient temperature discs were also included. A preliminary trial demonstrated that 1 h of heating was sufficient to achieve the target temperature.

Veneer thickness

A range of thicknesses between 1 and 4 mm were tested (1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 mm). This range includes most of the common veneer thicknesses produced within the traditional wood rotary veneer industry.

Basic density

The basic density was measured on the ribbons. Each ribbon section was oven-dried at 103 °C for 4 to 6 h until constant oven-dry mass was attained. Basic wood density was calculated as the oven-dry mass divided by the green volume.

RESULTS AND DISCUSSION

The cutting forces often display periodicities due to tangential density variation or over-thickness patterns. The latter type of periodicity is common when peeling very dense wood, according to Marchal *et al.* (1997). It was also noted that, similarly to wood, a convergence of forces towards a nominal value was observed when cutting cocowood veneers after a few revolutions. However, this stabilization did not last more than a few revolutions since the density tends to rapidly decrease towards the center of the disc. The region of interest in this study was restricted to 5 cm in depth from the periphery, since this region contains the highest density wood and offers potentially superior quality veneers (Fig. 1). In this region the cocowood density exceeded 600 kg/m^3. The analyses were based on the forces extracted from rotations 4, 5, and 6 counted from the first contact of the nose bar.

Pressure Bar

An initial trial was conducted using an angular pressure bar with a nominal green veneer thickness of 2.5 mm, a vertical gap of 0.8 mm, a disc temperature of 80 °C, and compression rates of 5, 10, 15, and 20%. Only veneers machined from discs taken from the top of the palm (50 and 75% of the stem height) produced acceptable, semi-continuous veneer ribbons with adequate roughness and checks (visual scores of 3 or 4) (Fig. 7b). The discs from the bottom of the palm produced short, fragmented veneer ribbons of poor quality (visual scores of 1 or 2). It was hypothesized that the production of relatively poor quality veneers was because the angular pressure bar acted as a rasp against the alternating bundles of hard and soft ground tissue on the cocowood surface. This phenomenon is supported by Fig. 7a in which the tight face (bottom side) of the veneer displayed evidence of large-diameter bundles being torn from the veneer surface. The upper, external part of the palm trunk is made of smaller diameter bundles in higher concentration than in the bottom part of the trunk. This explains the lower impact of the angular pressure bar on the veneer quality of the discs sourced from higher parts of the palm trunk.

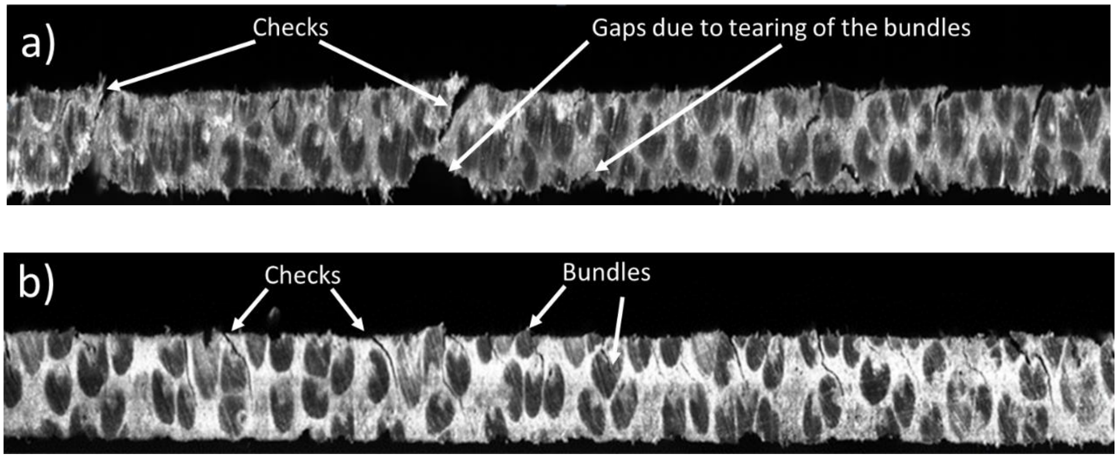

Fig. 7. Sections of cocowood veneers peeled with an (a) angular pressure bar with a visual score of 1 or (b) roller pressure bar with a visual score of 4.

The opening and growth mechanism of peeling checks was comprehensively described by Thibaut (1988). In summary, checks develop due to the action of the knife resulting in tensile stress normal to the plane of the crack and perpendicular to the bundle axis. After initiation, the cracking propagates ahead of the knife edge and then curves towards the tight face under the flexion movement imposed by the knife to the veneer (Figs. 3 and 4). This mechanism was observed during the cocowood peeling process with the development of peeling checks on the loose face. The size and, to a lesser extent, the frequency of the bundles significantly influence check propagation. This is because the tensile strength in the transverse direction is higher in bundles than in ground tissue (Fathi and Fruhwald 2014). Checks that developed in the soft ground tissue had minimal impact on the overall veneer quality.

A pressure bar imposes an extensive tangential movement of the surface of the disc, resulting in shear stresses. At the tissue scale, the bundles can be considered non-deformable cylinders, and the induced shear stresses cause incipient fractures or avulsions visible on the tight face of the veneer (Fig. 7a). Along with peeling checks, this dual splitting mechanism (on both sides) explains the extreme fragility of the veneer manufactured with the angular pressure bar.

A roller pressure bar can convey the veneer through the cutting zone without friction, therefore limiting the shear stress imposed on the ground tissue. Consequently, the continuity of the ribbon, the check depth and frequency, and the surface quality were less impacted in roller bar veneers. The use of a roller pressure bar yielded significantly better-quality veneers on all discs and confirmed the checking mechanism described above, as illustrated in Fig. 7b. Subsequent trials were performed only with a roller pressure bar.

Temperature

During the preliminary tests on discs processed at room temperature, the cutting forces were so high that it was not possible to produce a continuous veneer ribbon because, in most cases, a catastrophic disc rupture occurred after a few revolutions. In addition, excessive damage (*i.e.*, dents, chips, and blunting) to the knife cutting edge was apparent after only a few meters of peeled veneer were produced (Fig. 8). Deep dents were observed and were likely due to the impact of bundles with the knife edge. The dents on the cutting edge of the knife were consistent with the size of the bundles when cut tangentially, as illustrated in Fig. 8. These types of damage are experienced infrequently when peeling other palms, such as oil palm, in which the average bundle density is significantly lower than that of senile coconut palms (Loh *et al.* 2011).

The forces measured on the pressure bar were substantially reduced when the disc temperature increased (Fig. 9). An increase from 50 to 80 °C reduced machining forces by nearly 50%. The impact of temperature on the knife cutting force was less significant. The forces perpendicular to the knife cutting plane (Y_c) evolved from nearly zero at 50 °C to negative values at temperatures above 70 °C, reflecting slight knife dive, reported by Marchal *et al.* (1997) as a favorable cutting behavior.

The forces acting on the tools were particularly high compared to those when peeling traditional wood species under similar conditions. For example, Dupleix (2013) reported trials processing Douglas fir (thickness, 3 mm; τ = 5%; V_c = 1 m/s; T = 80 °C) in which the observed maximum of any of the four forces per revolution was 4.5 daN/cm. With this heterogeneous species (with a large density variation between early and late wood), Dupleix *et al*. (2012) demonstrated the beneficial effect of temperature on check occurrence and magnitude. Subsequent trials were performed with a nominal disc temperature of 80 °C.

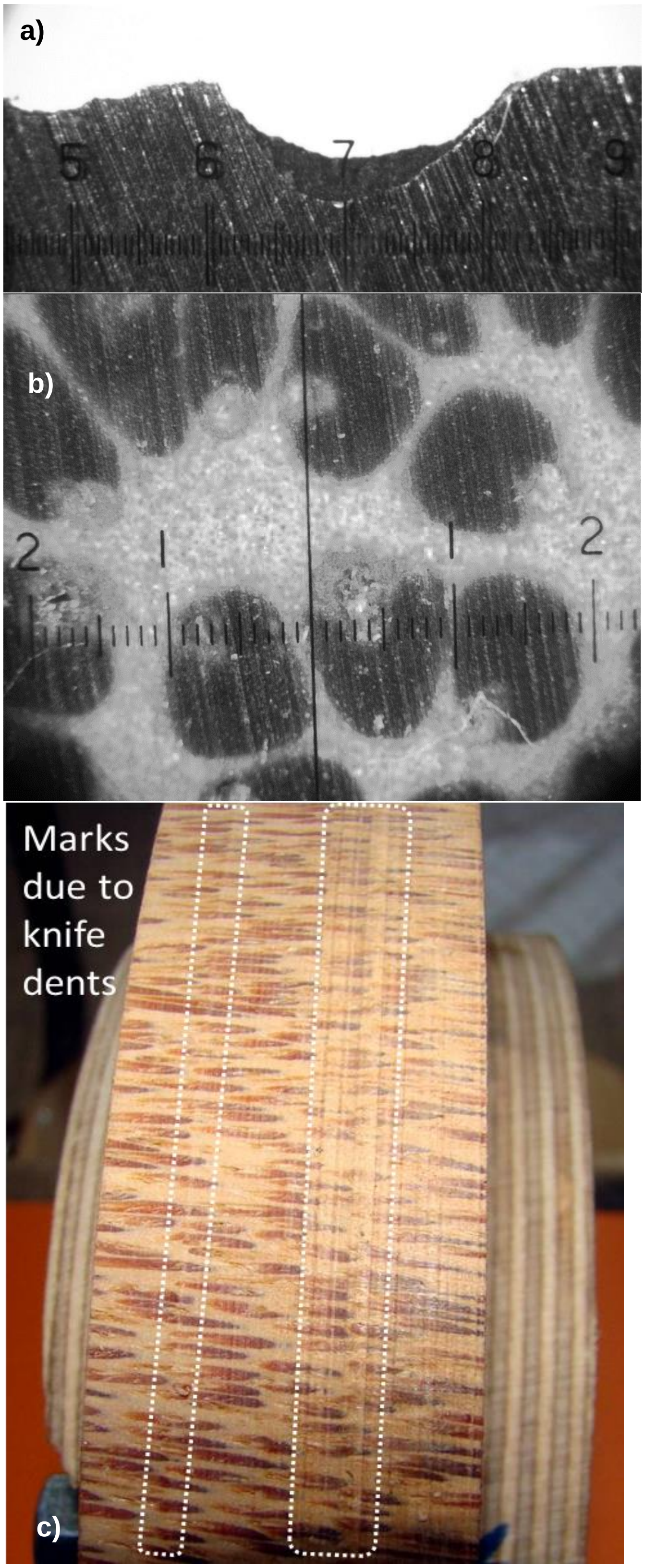

Fig. 8. (a) Knife cutting edge showing a 2-mm-wide dent; (b) transverse view of bundles (black dots) in high-density coconut wood, with diameter around 1-mm; and (c) knife marks materialize as light color lines parallel to the edge of the peeled disc (25 mm thick) inside the white dotted boxes; the darker zones are the bundles cut tangentially.

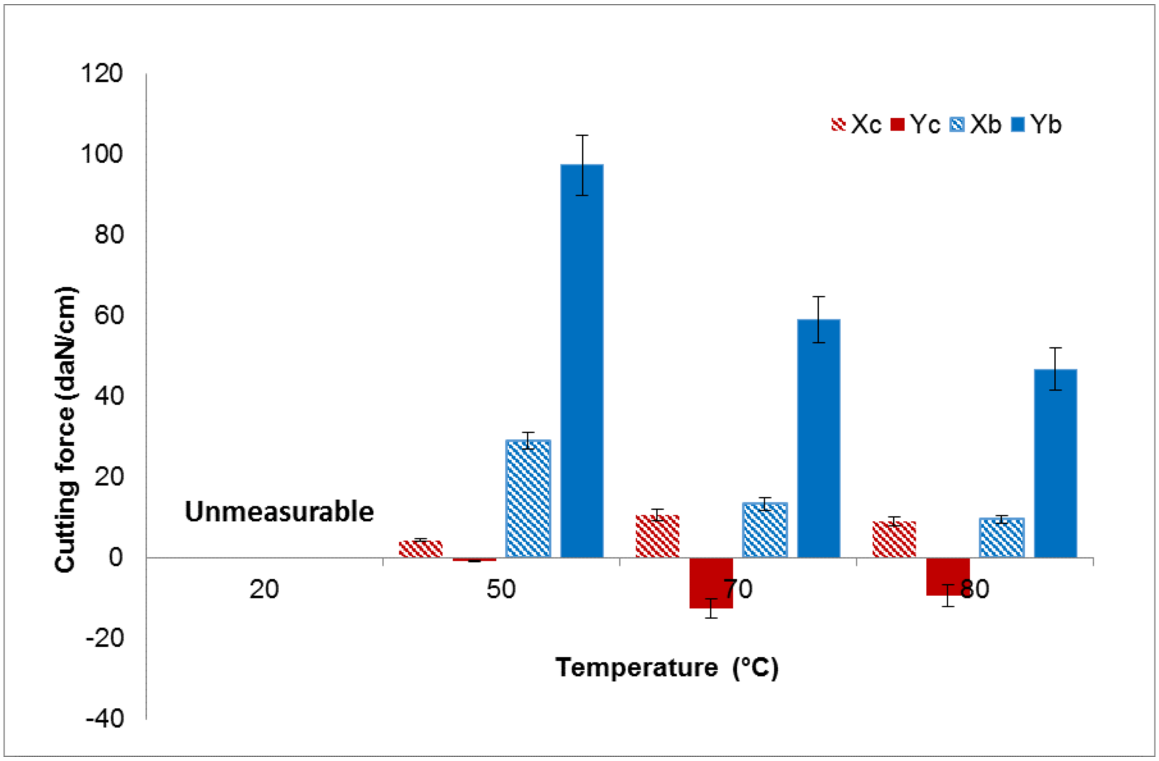

Fig. 9. Effect of temperature on cutting forces. Data acquired from 3 discs (D1 and D2) per temperature and 3 revolutions per disc. The cutting conditions were a roller pressure bar, 10% pressure, 2.5-mm veneer thickness, and 45 m/min speed.

Cutting Forces *versus* Veneer Quality

The cutting force was demonstrated to be a relevant predictor of veneer quality, as shown in Fig. 10. As the visual quality of the veneer improved, the average cutting forces and their variability decreased. This observation is in accordance with the findings of Marchal *et al.* (2009). The radial force on the pressure bar decreased significantly with increasing veneer quality, indicating that cutting with a lower compression rate improved veneer quality. Even when cutting conditions were favorable and the quality of the veneer was good (visual rank 4), the cutting forces for cocowood remained significantly high compared to those of traditional woods (*e.g.*, less than 4.5 daN/cm for all forces) (Dupleix *et al*. 2013). As shown in Table 1, for low compression rates (5 and 10%), the cutting forces are lower and more stable than when applying a 20% compression rate.

Table 1. Mean Cutting Forces and Mean Veneer Quality Scores for the Different Compression Rates Trialed

Compression rate (%)	Mean Xc (daN/m)	Mean Yc (daN/m)	Mean Xb (daN/m)	Mean Yb (daN/m)	Mean veneer quality score
5 *N=14*	9.05 *(1.48)*	8.60 *(2.66)*	2.26 *(0.61)*	-16.65 *(3.93)*	2.64 *(1.39)*
10 *N=12*	10.17 *(1.71)*	10.30 *(2.00)*	2.65 *(0.70)*	-23.68 *(3.05)*	2.42 *(1.16)*
20 *N=9*	15.10 *(2.20)*	14.61 *(3.19)*	5.77 *(1.32)*	-53.65 *(6.90)*	1.67 *(1.32)*

The cutting conditions were a roller pressure bar, 2.5-mm veneer thickness, 45 m/min speed, and 80 °C. N is the number of discs peeled. The standard deviations are shown in parenthesis.

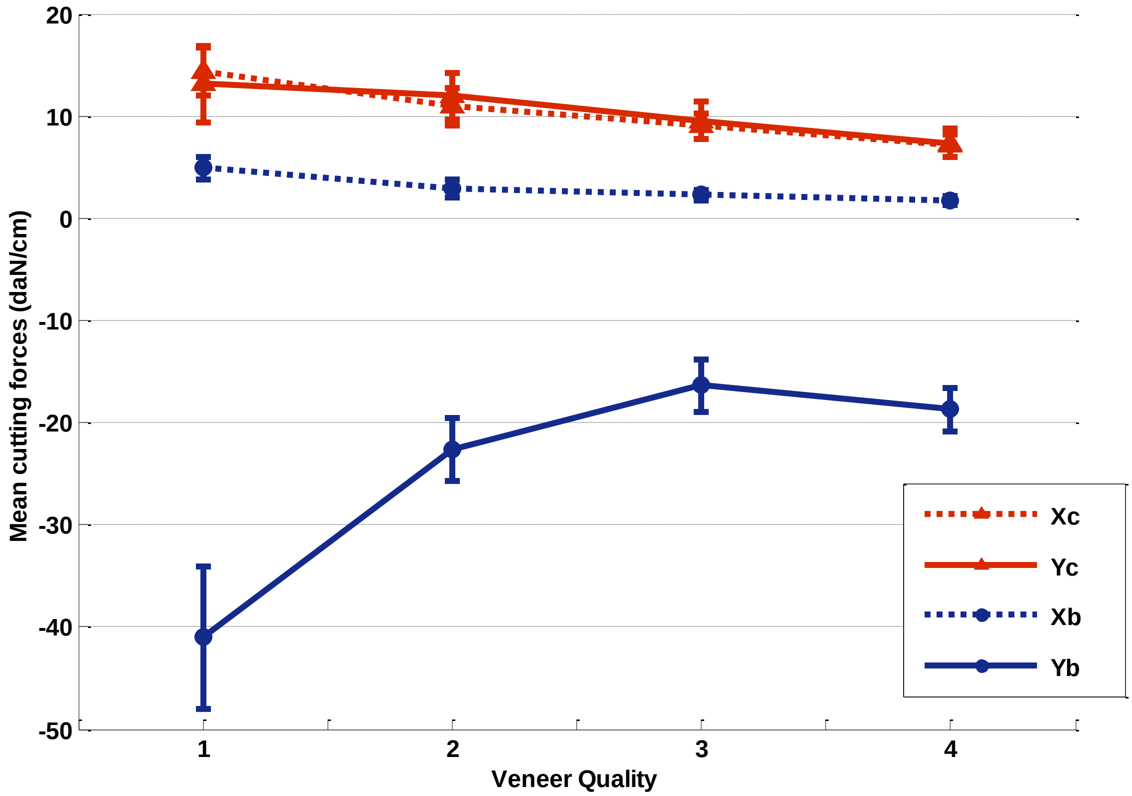

Fig. 10. Mean cutting forces versus visual veneer quality. The cutting conditions were a roller pressure bar, 2.5-mm veneer thickness, 45 m/min speed, and 80 °C. The standard deviations of the forces are represented by the error bars.

Lower compression rates resulted in superior veneer quality. In addition, the variability of the results, as indicated by the standard deviation in Table 2, was less when lower compression ratios were used. This result demonstrates that low compression rates work best for cutting cocowood veneer, unlike when cutting homogeneous woods during which the use of a relatively high compression ratio (τ > 10%) limits crack propagation and maintains satisfactory surface roughness.

Table 2 illustrates the veneer ribbon qualities as assessed using the SMOF system. The average check depth was not significantly affected by the compression rate.

Table 2. Veneer Quality Assessments Using the SMOF System for Different Compression Rates Trialed

Compression rate (%)	Mean Check Depth (mm)	Median Distance Between Checks (mm)
5 *(N=8)*	1.30 *(0.26)*	2.94 *(1.27)*
10 *(N=5)*	1.21 *(0.19)*	4.08 *(3.31)*
20 *(N=2)*	1.21 *(0.22)*	2.03 *(0.29)*

The cutting conditions were a roller pressure bar, 2.5-mm veneer thickness, 45 m/min speed, and 80 °C. N is the number of discs peeled. The standard deviations are shown in parenthesis.

However, unlike in homogeneous woods, the median distance between checks was clearly maximized at a compression ratio of 10% (Table 2). These findings suggest a moderate compression rate can limit crack formation in cocowood veneers. The optimum compression rate would be influenced by the diameter of the roller pressure bar used.

Veneer Thickness

The veneer quality was found to be poor when targeting veneer thicknesses below 2 mm. This was due to unacceptable checks, fragmentation, and surface roughness. A microscopic examination showed that very dense and large-diameter bundles (0.5 to 2 mm) surrounded by soft ground tissue influenced deep check formation. On such thin veneers, the checks continued through the soft tissue until they were either stopped by a bundle or passed through the entire veneer, as illustrated in Fig. 11.

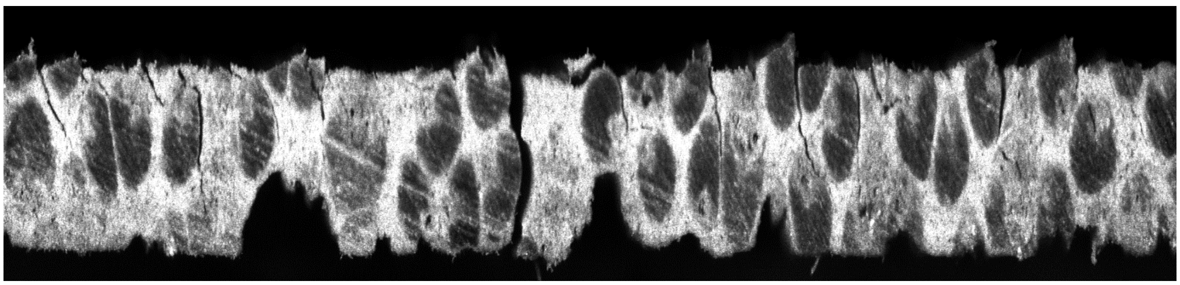

Fig. 11. Deep checks and severe roughness on a 2-mm-thick veneer. The cutting conditions were a roller pressure bar, 2.5-mm veneer thickness, 45 m/min speed, and 80 °C.

When peeling veneers above 3 mm in thickness, the forces on the knife value exceeded 25 daN/cm, above the appropriate force that conventional lathe designs can support (Thibaud 1988). For subsequent trials, a target veneer thickness of 2.5 mm was chosen.

Basic Density

A linear regression analysis established that the basic density of the cocowood measured on the ribbon could be predicted with statistical significance, as could the average knife cutting forces (Fig. 12). For Y_c, $F(1, 97) = 25.411$ and $p < .0005$; for X_c, $F(1, 97) = 69.707$ and $p < .0005$. Density accounted for 40.4% and 65.6% of the explained variability in the knife cutting forces, Y_c and X_c, respectively.

The variability in cutting forces during peeling was observed to be cyclic with disc revolution (Fig. 3). Similar variations are occasionally observed when cutting other high-density woods and are believed to be related to cutting refusal or tool dive (Marchal and Negri 1997). Cyclic variability can also be connected to variations in density, as displayed in Fig. 13, in which circumferential cocowood density induced force variation within a single revolution.

In the peripheral region of the disc containing high-density cocowood, cutting refusal and circumferential density variation can both occur. The cyclic variability in cutting forces could be simply due to the shape of the stem. Assuming circumferential homogeneity of coconut wood, ovality induces asymmetric removal of same quality coconut wood during rounding. As a consequence the cylindrical bolt that produces the continuous veneer ribbon displays a gradient of density along its circumference.

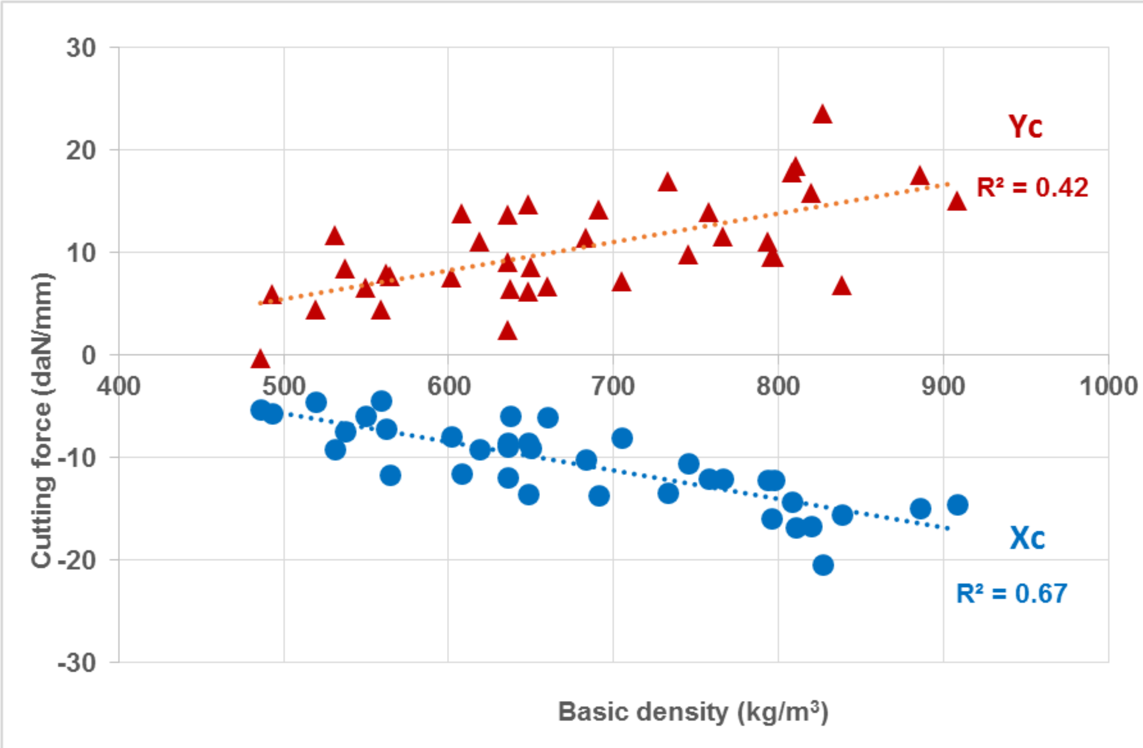

Fig. 12. Average knife cutting forces (3 revolutions) *versus* cocowood density. The cutting conditions were a roller pressure bar, 2.5-mm veneer thickness, 45 m/min speed, and 80 °C.

Fig. 13. Circumferential cocowood density variation

CONCLUSION

1. The study was successful in establishing the cutting characteristics of rotary-peeled coconut wood on the basis of sequential trials. This approach, although not exhaustive, was beneficial in providing practical and useful information. The outer part of the trunk was targeted because it contained high-density wood thought to have the greatest potential to produce high quality structural or appearance veneer.
2. Heating the logs above 70 °C was necessary to significantly reduce the cutting forces observed, improve surface quality, and limit premature knife damage. However, these cutting forces are still substantial compared to usual wood cutting forces.

3. The use of a roller nose bar and a relatively low compression rate (around 10%) provided a favourable effect on most of the critical processing parameters, including cutting forces, checks, and surface quality.
4. The minimum peelable veneer thickness (around 2 mm) is limited by the size of the fibrovascular bundles.
5. The high density of cocowood requires a positive clearance angle to limit the forces on the clearance face of the knife.
6. Due to the abrasive nature of the cocowood and its extremely hard fibrovascular bundles, the use of a micro-bevel knife is expected to improve the knife service life and potentially reduce cutting forces (Feihl 1986).
7. The friction phenomenon observed when using an angular nose bar highlights the unusual cutting characteristics of coconut wood. In future studies, it would be relevant to analyse the choice of knife alloys to optimize the cutting properties (Djouadi *et al.* 1999).
8. These observations should be confirmed using an industrial lathe with a large-diameter roller pressure bar to enhance the positive effect of the bar on the checking mechanism.

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