MACHINING PROPERTIES OF WOOD:
Tool Wear, Cutting Force and Tensioning of Blades

DOCTORAL THESIS

by

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Skellefteå, Sweden
2013
ABSTRACT

Cutting processes, in general, and wood cutting processes, in particular, are complex to explain and describe with many influencing factors. Wood, in contrast to man-made fabricated materials, is not a homogenous and distinct material, but a multifaceted and nonhomogeneous biological material. A fundamental understanding of wood cutting processes and the machining properties of wood can be obtained by investigating the interaction of wood properties, cutting tools and machining parameters. Such an understanding provides possibilities for improving product quality, increasing production efficiency, or otherwise improving the machining processes. The aim of this thesis was to find ways of improving the machining properties of some wood species, focusing on tool wear, cutting forces and the tensioning of circular sawblades.

The studied wood species were five Mozambican tropical species, namely: *Swartzia Madagascariensis* (ironwood); *Pseudolachnostylis maprounefolia* (ntholo); *Sterculia appendiculata* (metil); *Acacia nigrescens* (namuno); *Pericopsis angolensis* (muanga) and two main Swedish wood species: *Pinus sylvestris* L. (Scots pine); and *Picea abies* (L.) Karst. (Norway spruce).

A series of experimental tests were conducted to determine the suitability of different cutting tool materials when machining these wood species. Machining tropical hardwood and Swedish frozen wood under winter conditions is still a challenge when it comes to the choice of which cutting tool material to use. Tool wear was used as a criterion to evaluate the performance of the cutting tool materials. Additionally, the relationship between tool wear and some chemical and physical properties for Mozambican tropical wood species was analysed. Different wear mechanisms were identified using a scanning electron microscope. It was concluded that tool hardness alone was not the only factor affecting tool wear; a certain amount of tool toughness was also needed to obtain low tool wear. The predominant wearing mechanisms for the tropical wood species tested were abrasion and edge-chipping.

Furthermore, tropical hardwood species were subjected to cutting force tests. A standard single saw tooth, mounted on a piezoelectric load cell, was used to evaluate cutting forces. The theoretical approach used for the prediction of the main cutting forces was based on surface response methodology. Among the studied variables, chip thickness and cutting direction had the greatest effect on the main cutting force level, while wood density, moisture and rake angle had the least effect.

Power consumption using double arbour circular saw machines was investigated. The experiments were carried out, under normal production, in two Swedish sawmills. The climb-sawing model in both sawmills was able to estimate the power consumption better than the counter-sawing model. Climb-sawing had higher power consumption.
than counter-sawing. The lowest power consumption was found using a higher overlap between circular sawblades.

Finally, experimental and theoretical models to improve circular sawblade dynamic lateral stability were developed. Different methods for monitoring flatness and tensioning in circular sawblades for wood cutting were discussed. Additionally, the effects of the magnitude of the roller load, number of grooves and groove positions were tested. The roll-tensioning effects were evaluated by measuring the shift in natural frequencies of several vibration modes. Natural frequencies obtained with the finite element method were in good agreement with the experimental test results. The magnitude of the roller load, number of grooves, and groove positions all affected the natural frequencies.

**Keywords:** cemented carbide, circular sawblade, cutting forces, finite element, natural frequency, power consumption, tensioning, tool wear, tropical wood, vibration, wear mechanisms.
PREFACE

The work presented in this doctoral thesis has been carried out at the Wood Technology, Division of Wood Science and Technology, Luleå University of Technology, Skellefteå, under the supervision of Associate Professor Mats Ekevad and Professor Anders Grönlund. The project was funded by the Swedish International Development Agency (SIDA) through the Technology Processing of Natural Resources for Sustainable Development programme.

I greatly appreciate the support, guidance, advice and encouragement I have received from my supervisors Associate Professor Mats Ekevad and Professor Anders Grönlund.

I would also like to express my gratitude to SIDA for their financial support. I warmly thank Dr. Rui Sitoe, Dr. Carlos Lucas and Dr. José Da Cruz for all the support they have given me.

Many thanks to all the staff of Luleå University of Technology in Skellefteå, for the help and friendship I have received.

Finally, I wish to express my gratitude to my family for their encouragement and their belief in education.

Skellefteå, November 2013

Luís Cristóvão
LIST OF APPENDED PAPERS


The author’s contribution to the papers

- **Paper I**: Planning, experimental test and writing
- **Paper II**: Planning, experimental test and writing
- **Paper III**: Experimental test
- **Paper IV**: Planning and experimental test
- **Paper V**: Planning, experimental test and writing
- **Paper VI**: Data analysis and writing
- **Paper VII**: Experimental test
- **Paper VIII**: Planning, experimental test and writing
1. INTRODUCTION

Cutting processes, in general, and wood cutting processes, in particular, are complex to explain and describe. The cutting process is extremely complex, with many influencing factors, such as material properties, cutting tool geometry and cutting parameters. The primary issue that confounds machining research is the considerable variability of physical and mechanical properties within and between wood species. Cutting tools during interaction with this anisotropic material are subjected to severe loads and transverse vibrations, thus, different wear characteristics and mechanisms are produced. Therefore, a fundamental understanding of wood machining properties, such as cutting tool wear, cutting forces, power consumption, and tensioning of cutting tools, gives the possibility of enhancing product quality, increasing production efficiency, or otherwise improving the machining process.

Tool wear is an important aspect for sawmilling and the woodworking industry. For tropical sawmillers, such as in Mozambique, the major challenge is to increase the service life of the cutting tools. However, some tropical species have mineral inclusions, which develop during growth of the tree. The most common inclusion is silica, and the abrasive action reduces the life of the cutting tool considerably. On the other hand, in Scandinavian countries, sawing frozen timber in winter conditions is still a challenge when it comes to the selection of which cutting tool material to use. Hard cutting tool materials wear less but are more brittle, and softer cutting tool materials wear faster but are tougher.

It is universally acknowledged that different wear mechanisms occur during wood cutting, and the dominant wear mechanism may be different under different cutting conditions. Tool geometry, workpiece properties and cutting parameters influence the wear mechanism greatly.

The performance of the cutting tools varies as they are used. This variation in performance can be monitored by observing the change in the edge geometry of the cutting tool, observing variation in the forces acting during cutting, and variation of power consumption. Wood cutting forces have been studied extensively since the 1950s. Various approaches have been suggested for the evaluation and prediction of cutting forces. Although a considerable amount of research has been carried out in this field, few studies have been done with respect to tropical wood species. A determination of wood cutting parameters may facilitate the optimization of the process, machines and tools when machining these hard-to-cut woods.

Much research has been conducted to increase productivity in sawmills. This involves speeding up the sawline and increasing the cutting speed. However, increasing the feed speed and cutting speed also affects tool wear and cutting tool stability. The
preparation of cutting tools, such as flatness, tensioning and leveling plays an important role in improving the performance, especially when running thin- and large-diameter blades. Tensioning of blades is done to increase dynamic stability, by introducing positive tangential stresses in the outer periphery, which affects the stiffness of the blade. This increases the natural frequencies of the blade and thus makes it possible to use a higher rotating speed in operation, or to have a larger margin between the lowest critical speed and the operational speed. However, this preparation of cutting tools widely relies on the skills of the sawfilers whose know-how remains mainly empirical to date.

The aim of this doctoral thesis is to increase the understanding of machining properties of some selected Mozambican wood species, namely: *Swartzia Madagascariensis* (ironwood); *Pseudolachnostylis maprouneafolia* (ntholo); *Sterculia appendiculata* (metil); *Acacia nigrescens* (namuno); *Pericopsis angolensis* (muanga) and two main Swedish wood species: *Pinus sylvestris* L. (Scots pine) and *Picea abies* (L.) Karst. (Norway spruce). In addition, circular sawblades’ cutting stability is investigated by monitoring different methods of flatness, tensioning and leveling.

### 1.1 Objectives and limitations

The main objectives of this doctoral thesis were to:

- increase knowledge of machining properties of some selected wood species.
- identify suitable cutting tool materials for machining selected wood species.
- evaluate cutting forces experimentally, and develop predictive models.
- formulate a theoretical model of power consumption, and compare with experimental power consumption during resawing.
- improve circular sawblades’ dynamic stability through tensioning and levelling.

All experimental tests concerning Mozambique tropical species were made in Sweden, which limited the number of samples, owing to the transportation costs, and made it impossible to conduct industrial tests.

### 1.2 Contents of the thesis

This doctoral thesis is comprised of seven chapters and eight appended papers.

Chapter 1 provides an introduction to the area of research. Chapters 2–3 provide background on wood machining, with a special focus on tool wear, cutting force, power consumption and tensioning of cutting tools. Chapter 4 describes the materials and methods used for the evaluation of tool wear, the identification of wear
mechanisms, the evaluation of cutting forces, power consumption and measurements of flatness and tensioning. Chapter 5 presents the main results and a discussion on the experimental procedures described in Chapter 4. This is followed by Chapter 6, which contains a brief summary of the results of the appended papers. Finally, some suggestions for future work are presented in Chapter 7.
2. BACKGROUND

This chapter provides the reader with an overview of Mozambique’s forestry.

Overview of Mozambique’s forestry

Mozambique covers an area of 801,590 square kilometres, and around 70% of the country, or 65.3 million hectares, is covered by forests and other woody formations. According to the National Directorate of Land and Forest (NDLF), the forested area covers about 40.6 million hectares (51% of the country), while woods — that is, shrubs, bushes and forests subject to shifting cultivation — cover about 14.7 million hectares, or 19% of the country (NDLF, 2007).

The productive forest for industrial logging covers approximately 26.9 million hectares, or 67% of the total forest area. Thirteen million hectares are not suitable for the production of wood, and most of these are located within national parks, reserves and other conservation areas (NDLF, 2007).

The forestry industry in Mozambique plays an important role in the livelihoods of many communities and the economy’s development. However, efforts to realize the full potential of this natural resource have been far from satisfactory, undermining the potential for enhancing employment and income for the country.

In comparison, Sweden has a total land area of 450,295 square kilometres, and about 66% of the country is covered by forest and other wooded areas. Productive forest land amounts to approximately 22.5 million hectares, with an annual increment of 100 million cubic metres (www.skogsstyrelsen.se). Spruce and pine are the predominant wood species in Swedish forests.

Mozambican forest is characterized by mixed wood species, with a large range of properties. Timber harvesting has been characterized by extremely selective logging of a few high-value species. According to NDLF (2007), the country has a total of 118 commercial species. However, only 18 species have been used historically. Most of the exported Mozambican tropical wood timber is in log form, or with very low levels of primary processing. This minimizes the favourable employment effect that would occur with additional domestic processing.

The Mozambican wood industry, made up mainly of small-scale sawmills, is poorly developed. Figure 1 illustrates a typical Mozambican sawmill. The processing of tropical wood species is carried out by trial and error, which in many cases, leads to inefficient results. This directly affects the rational utilization of this resource. The wood industry is, therefore, unable to compete with imported products in the domestic market.
Sawmillers in Mozambique strive continually for sustainable processing, in order to maintain their competitiveness with other materials. There are undesirable effects, such as rapid wear and tool breakages, which result in the deterioration of the surface and dimensional accuracy of finished products. These effects also increase production times.

Mozambique’s tropical wood species are known to exhibit a large diameter and to be very dense, with logs having a non-uniform shape, which affects their yield and machinability. Cutting tool maintenance and the amount of power consumed are important economic factors for wood processing.

The reforestation of tropical species is complex, and the focus has shifted to fast-growing species, especially pines and eucalypts. Forest plantation for timber production has been growing, but at a slower pace. Therefore, there are still huge gaps between wood supply and demand. There is no pulp and paper industry in Mozambique, and that is one of the reasons harvesting is considered wasteful, since all tops and branches are left in the forest.

Recently, studies of Mozambican tropical wood species have started, in order to find their end use. Uetimane (2010) studied the anatomy, drying behaviour and mechanical properties of lesser-used wood species. Ali (2011) reported on the physical-mechanical properties and natural durability of lesser-used wood species. Furthermore, Lhate (2011) reported on the chemical composition and machinability of selected tropical wood species. Recently, Shenga et al. (2013) presented a comprehensive review of a Mozambican wood-exploitation map of the processing chain. Unlike anatomical, chemical, physical and mechanical features of the lesser-used species, studies on wood machining properties are limited.

\textbf{Figure 1: Sawmill in Mozambique: a) Circular sawblade; b) Band sawblade.}
3. THEORY

This theory chapter contains a basic explanation of wood machining and a literature review, with a special focus on tool wear, cutting forces, power consumption and tensioning of cutting tools.

3.1 Tool wear and wear mechanisms

Tool wear is extremely important in sawmilling and the woodworking industry. Generally, tool wear is used to evaluate the performance of the cutting tool, owing to its direct impact on surface quality, cutting force, power consumption, etc.

To remove a wood chip from a workpiece (timber) a certain amount of force is required. This unwanted material is removed by a cutting tool, which is harder than the workpiece. Preferably, the ideal cutting tool materials should have hardness resistance, toughness resistance, oxidation resistance, abrasion resistance, corrosion resistance, as well as the ability to maintain these properties at high temperature. However, there is no cutting tool material that unifies all the required characteristics. Some of these characteristics are mutually exclusive. For example, as hardness increases the toughness is reduced. In addition to these tool material properties, one has to consider other parameters in the selection of tool materials, such as: price and grindability, etc.

A wide variety of cutting tool materials are used in the wood industry: carbon tool steel; stellite; high speed steels; cemented carbide; and diamond. The development of these cutting tool materials were made in response to productivity, quality and cost concerns. Cemented carbides, possibly the widest utilized cutting materials, are the most versatile hard materials, owing to their unique combination of toughness and hardness within a wide range.

Comprehensive reviews on cemented carbides have been conducted by Ramasamy and Ratnasingam (2010), and Ratnasingam et al. (2013). They pointed out that mechanical, thermal and chemical interactions between cutting tool and workpiece are important factors for tool wear. A detailed review on wood cutting tool wear was made by Klamecki (1979). He pointed out that the chemical nature of wood may play a large part in cutting tool wear rates. Furthermore, Noack and Frühwald (1977) reported that even low-density woods are difficult to machine when their silica content is high.

During wood machining multiple wear mechanisms may, in most cases, be present simultaneously, which makes a study of tool wear very complex. Among these wear mechanisms are abrasion, chipping, corrosion, oxidation, fatigue, and adhesion. The predominant wear mechanisms change depending on cutting parameters, tool geometry and workpiece properties. Much research on wood cutting tools has been done. However, processing of tropical species with high silica content is still a challenge for the woodworking industry. Figure 2 shows an example of abrasion
chipping, which occurred in the corner of cemented carbide, during the machining of Mozambican wood species.

![Figure 2](image1.png)

**Figure 2:** Example of tool wear for cemented carbide when machining tropical species: a) namuno; b) muanga; c) ntholo.

Various parameters have been used by researchers to evaluate tool wear and bluntness of the cutting edge, such as nose width, edge recession in rake face, edge recession in clearance face, edge radius, etc. There is, however, some disagreement as to which wear parameter is the most representative of the state of bluntness of the cutting tool (Sheikh-Ahmad and McKenzie, 1997). Figure 3 illustrates the most common parameters used to evaluate tool wear in the wood industry.

![Figure 3](image2.png)

**Figure 3:** Parameters used to measure tool wear ($\alpha =$ rake angle, $\beta =$ wedge angle, $\gamma =$ clearance angle, ER = edge recession in rake face, ERF = edge recession in clearance face, NW = nose width, $r =$ edge radius).

The shape of a cutting tool edge is determined by the rake angle, wedge angle and clearance angle. The optimum shape depends primarily upon the cutting direction (CD) and wood species properties. The cutting tool shape directly affects the surface quality and productivity of the machining operation. Also, the tool shape defines the magnitude and direction of the cutting force.
3.2 Mechanics of wood cutting

The importance of cutting forces in sawmilling and the woodworking industry has long been recognized. The evidence is the extensive number of studies conducted since 1950. In spite of this, the modelling, analysing and prediction of machining properties — such as, tool wear, cutting force, power consumption and surface quality — are still a challenge for sawmilling and woodworking. The issue that confounds machining research is the extreme anisotropy and heterogeneity of wood. Consequently, tool wear, cutting forces, power consumption and surface quality will change with the \( CD \). These machining properties are also influenced by moisture content.

In wood machining there are three main cutting directions, namely: 90°–90° (rip sawing); 0°–90° (veneer cutting); and 90°–0° (planing); see Fig. 4. According to Kivimaa (1950), the first number indicates the orientation of the cutting edge with respect to the wood grain, and the second number indicates the direction of the movement of the cutting tool with respect to the wood grain. Also, two modes of cutting exist for each direction depending on annual ring direction.

\[ \text{(a)} \quad \text{(b)} \]

*Figure 4: Cutting directions, according to Kivimaa (1950): a) Mode I; b) Mode II.*

It has been reported by Koch (1964), that researchers prefer mode I for \( CD \)s 90°–90° and 0°–90°, and mode II for \( CD \) 90°–0°, because these \( CD \)s minimize the confounding effect of growth rings of varying density.

Several works analyse and discuss the dependence of cutting forces, with respect to cutting geometry, cutting parameters, and workpiece properties. Among these factors are the following: rake angle; clearance angle; edge radius; kerf width; chip thickness; feed speed; wood grain; wood species; wood density; moisture content; and mechanical properties. Kivimaa (1950), Axelsson et al. (1993) and Goli et al. (2009) discussed the change of the cutting force with different wood grain angles. Eyma et al. (2004) presented a model of cutting forces for thirteen tropical wood species in milling processes. The model considers mechanical (hardness, fracture toughness, shearing,
compression parallel to the grain) and physical (specific gravity, shrinkage) parameters. Recently, Moradpour et al. (2013) investigated the effect of wood moisture content and CDs on the cutting forces, in the bandsaw processing of oak and beech wood. They showed that wood moisture content and CD have a great influence on cutting forces.

Comprehensive reviews on cutting force modelling for wood cutting have been conducted by Marchal et al. (2009) and Wyeth et al. (2009). They pointed out that cutting forces are closely related to the material selections, tool life, quality of machined surfaces, chip formation, the geometry of the cutting tool edges and the cutting conditions.

During machining, detailed knowledge of the magnitude and variation of cutting force is very important, because a change in cutting force is directly related to the changes in cutting condition. The need to understand and model wood cutting process is driven by a number of factors, among them, the need to know how to select cutting tool material, how to design cutting tools, how to estimate cutting accuracy, how to determine machinability of workpiece. These needs have driven researchers to conduct experiments and develop models that can explain the mechanisms of the wood cutting process. Researchers have developed a large number of models for wood cutting since the 1950s, including, Kivimaa (1950), Franz (1958), McKenzie (1961), Koch (1964), Axelsson et al. (1993), Scholz et al. (2009), Eyma et al. (2004), Chuchala et al. (2013). Many of these investigations on cutting forces models have been made using a single cutting tool.

There are at least three different approaches used to model the main cutting force. Kivimaa (1950) and Scholz et al. (2009) calculated the main cutting force, based on specific cutting resistance. Orlowski et al. (2013) developed a cutting force model, based on modern fracture mechanics. Axelsson et al. (1993) established a predictive model, using multivariate methods such as multiple linear regression. A few attempts were made to predict wood cutting force using numerical methods, such as finite element methods (FEM). Taking into account the variation of grain angle and change of wood properties along the CD, this is still a challenge when it comes to modelling.

The cutting forces acting in a workpiece may be resolved in three components: main cutting force ($F_p$); feeding force ($F_N$); and lateral force ($F_L$). Each of these cutting forces is influenced by a range of factors, such as: workpiece properties, cutting geometry and cutting parameters. Several methods have been used to measure these cutting forces. These include dynamometers (Franz, 1958; Woodson, 1979; Moradpour et al., 2013), piezoelectric transducers (Axelsson et al., 1993; Cooz and Meyer, 2006; Ekevad et al., 2012) and strain gauges (Porankiewicz et al., 2008). Also, indirect methods to measure main cutting force are used; e.g., measurement of power.
in motor, torque in the shaft (Andrews, 1955). Although a considerable amount of research has been carried out in this field, few studies have been made with respect to tropical wood species.

Wood chips are removed from the workpiece by fracture. The chip geometry formed during structural failure and the cutting forces depend, among other things, on wood properties, cutting tool geometry and cutting parameters. Important works on chip formation were made by Franz (1958), Mckenzie (1961) and Koch (1964). They interpreted the process of chip formation through photographic and direct observation. Franz (1958) classified three types of chip formation when machining wood parallel to the grain, or at small angles to the grain, as follows: Type I, Type II and Type III. When machining different wood species, different chip forms might be formed under the same condition. Recent studies of chip formation in wood cutting were carried out by Ekevad et al. (2012). They observed and interpreted chip types by high-speed camera, during the machining of pine, namuno and ironwood.

Circular sawblades and band sawblades are common cutting tools used in the sawmill industry. During sawing, band sawblades cut in a $90^\circ$–$90^\circ$ CD. Depending on the relative motion between a log and a circular sawblade, two feeding modes can be observed: counter-sawing and climb-sawing. The selection of the feeding mode has important effects on the mechanics of the process, such as the type of chip, surface quality, mode of chip transportation, tool wear, cutting forces and power consumption.

When circular sawblades are used, the $CD$ changes during each cut (see Fig. 5). For instance, in counter-sawing, the forces gradually increase from zero, cutting approximately in direction $90^\circ$–$0^\circ$, at the beginning of the cutting tool engagement to a maximum when the cutting edge leaves the workpiece, cutting approximately in a $90^\circ$–$90^\circ$ CD. The chip thickness generated is non-uniform, depending of the position of the edge.

(a)    (b)

*Figure 5: Mode of feeding: a) counter-sawing; b) climb-sawing ($\alpha_1 = \text{entry angle}$, $\alpha_2 = \text{exit angle}$, $\phi =$ sawblade diameter, $\omega =$ angular frequency).*
3.2 Power consumption

The power consumption in wood cutting is related to the cutting force: the higher the cutting force, the greater the power consumption, (Orlowski et al. 2013; Aguilera and Martin 2001; Kováč and Mikleš 2010). Aguilera and Martin (2001) predicted the power consumption of climb-sawing and counter-sawing by measuring the main cutting force, and determined power consumption from the known cutting speed. Kováč and Mikleš (2010) determined the power consumption of the wood cutting process using circular saws, and studied the influence of different cutting tool geometries. Orlowski et al. (2013) compared power consumption, which was calculated based on modern fracture mechanics and specific cutting resistance. Ramasamy and Ratnasingam (2013) showed a close relationship between tool wear pattern and power consumption. Recently, Sitkei (2013) used standard dimensional analysis to develop an equation for the estimation of saws’ power consumption as a function of wood species and operational parameters. Although much attention has been given to developing models using a single saw, little is known about power consumption using double arbor circular sawblades.

The total theoretical power consumption in a circular sawblade is given by:

\[ P_{\text{total}} = \frac{z \cdot n}{360} \sum_{i=1}^{360} P_i \]  

where \( z \) is the total number of teeth engaged and \( n \) is the number of circular sawblades in the arbor. A detailed expression of theoretical power consumption is described in appended Paper VI. The momentary theoretical power \((P_i)\) required to remove a chip from a workpiece using one tooth is:

\[ P_i = F_{pi} \cdot v_i + \frac{H \cdot k \cdot S \cdot d \cdot v_i^2}{2} \]

where \( F_{pi} \) is the main cutting force (N), \( H \) is the depth of the cut (mm), \( S \) is the feed speed (m min\(^{-1}\)), \( v_i \) is the cutting speed (m s\(^{-1}\)), \( k \) is the saw kerf width (mm), and \( d \) is the wood density (kg m\(^{-3}\)). The first term in Equation 2 refers to the power required to cause a failure, and the second term is the power required to accelerate a chip, which can be seen as the change in kinetic energy of the accelerated chips during a specified time interval. The chip acceleration expression is described by Koch (1964) and Orlowski et al. (2013).

As mentioned before, the main cutting force, \( F_{pi} \), can be calculated, based on specific cutting resistance, modern fracture mechanics or from multivariate statistical models.
3.4 Dynamic stability of wood cutting tools

Sawmills continue to strive to increase productivity, recovery and surface quality. This ongoing challenge entails raising the feed speed, reducing kerf width and increasing cutting tool rotation speed. Okai (1998) and Lister et al. (1997) highlighted that an improvement in one factor can only be achieved at the expense of one or both of the other two. For instance, reducing kerf width means reducing the thickness of the cutting tool, which results in lower natural frequencies. This, in turn, increases the risk of running into resonances. Running a cutting tool close to resonances causes increased vibration amplitudes, which increases the kerf width and causes poor dimensional accuracy. For a rotating saw, this resonance vibration phenomenon occurs when the minimum back-travelling wave frequency in any mode is equal or very close to zero (Parker and Mote 1991). The pre-stressing process known as tensioning is the most common method for raising natural frequencies and improving sawing accuracy and sawing speed, especially when running thin- and large-diameters blades. Tensioning is the intentional introduction of a favourable residual stress state in a saw through plastic deformation, typically by hammering, rolling and thermal tensioning (Szymani and Mote, 1977). Its goal is to increase natural frequencies and all critical speeds. It has been pointed out by Schajer (1986) that increased tensioning increases the critical speed margin, but such tensioning also reduces the zero nodal diameter natural frequency. Thus, too much tensioning causes the sawblade to buckle (dishing), and unsuitable tensioning may reduce natural frequency (Schajer and Kishimoto 1996). Detensioning is sometimes carried out, in order to reduce the tensioning of sawblade that has been tensioned too much. It should be emphasized that measuring tensioning means measuring the residual stresses, but since they are hard to measure directly, their effect on the stiffness of sawblades is measured. Sawblade stiffness can be measured statically by bending the sawblade, or dynamically by measuring the natural frequencies of the sawblade. Figure 6 shows the measurement of natural frequencies with an electromagnet.

Figure 6: Circular disc excited by a magnet. Resonance for three nodal diameters shown with salt powder.
Schajer et al. (2011) designed and built a prototype system that measures the natural frequencies, and also identifies the mode shapes by using two microphones; one fixed and one rotating. The natural frequencies and mode shapes of a saw are characterized by the number of nodal diameters (ND) and the number of nodal circles (NC). Figure 7 illustrates mode shapes for different natural frequencies. The introduction of holes and wiper slots change the ND and NC.

\textbf{Figure 7a}: Mode shape for natural frequency 150 Hz, ND=2, NC=0, Diameter=450mm, calculated with \textit{FEM}.

\textbf{Figure 7b}: Mode shape for natural frequency 190 Hz, ND=3, NC=0, Diameter=450mm, calculated with \textit{FEM}.

FEM is commonly used to predict natural frequencies and mode shapes. Generally, the modes shapes with the lowest frequencies are the most important, because the largest vibration amplitudes appear for modes with lower numbers of nodal diameters and zero nodal circles.
4. MATERIALS AND METHODS

This chapter describes various material and methods used in this thesis. Section 4.1 shows the methodology used to evaluate tool wear, during the machining of different wood species. This is followed by sections 4.2 and 4.3 which present the approach used to evaluate and analyse the cutting forces and power consumption, respectively. Section 4.4 illustrates the materials and methods used to improve dynamic lateral stability of circular sawblades through tensioning.

4.1 Tool wear and wear mechanisms

The wood species ironwood, ntholo, metil, namuno and muanga were studied. Lack of knowledge concerning their machining properties has been an obstacle to their wider use. The samples were collected in Northern Mozambique, namely in the Cabo Delgado province.

Tool wear was used as a criterion to evaluate the performance of the cutting tool. The test was carried out on a shaper with a mechanical feeding mechanism, as shown in Fig. 8. The workpieces were machined using a single standard sawtooth. Each cutting edge was examined carefully through a microscope before the experiment, to ensure the cutting edge was free of defects.

The cutterhead had two cutting tools to avoid the effects of imbalance caused by having only one insert, but one was deliberately blunted (so as not to cut), while the other was sharp (Fig. 9).

The cutterhead rotation was 2900 rpm, diameter of cutterhead 154 mm, feed speed 3 m min⁻¹, kerf width 3.9 mm, depth of cut 1 mm, cutting length 12.41 mm, rake angle 30°,
clearance angle 15º, direction of cutting 90º–0º (milling parallel to grain), and a counter-cutting mode.

**Figure 9:** Cutterhead with tool and counterweight.

In Paper I, a very dense material, *Swartzia Madagascariensis* (ironwood), was machined using six different cemented carbide tools, here denoted as 214, 021, 160, 701, 046, and 242. Table 1 illustrates the specifications of the cutting tools materials.

<table>
<thead>
<tr>
<th>Grade</th>
<th>214</th>
<th>701</th>
<th>242</th>
<th>021</th>
<th>160</th>
<th>046</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness (HV30)</td>
<td>1950</td>
<td>1600</td>
<td>1150</td>
<td>1400</td>
<td>1600</td>
<td>1480</td>
</tr>
<tr>
<td>Toughness (K\textsubscript{1C})</td>
<td>9.5</td>
<td>11</td>
<td>17</td>
<td>14</td>
<td>12.7</td>
<td>15.4</td>
</tr>
</tbody>
</table>

The dimensions of the wood samples were 1000x200x70 mm in the fibre, tangential and radial direction, respectively. In this test, tool wear was evaluated by measuring the nose width (\(NW\)) of the tool, as illustrated in Fig. 3. The cutting tests were interrupted at 288 m, 576 m, 864 m, 1152 m, 1440 m, 1728 m, and at 2016 m cutting length for the evaluation of \(NW\). Images of the cutting edge were recorded before and after the experimental test.

In Paper II, experimental tests were carried out on *Pseudolachnostylis maprounaefolia* (ntholo), *Sterculia appendiculata* (metil), *Acacia nigrescens* (namuno) and *Pericopsis angolensis* (muanga). Wood specimens were prepared to dimensions 1000x200x1200 mm in the fibre, tangential and radial direction, respectively. Carbide tool 701 was selected to machine these tropical species, based on the first test (Paper I). The experiment was conducted under the same cutting condition as the first test (Paper I). The chemical and physical analyses were performed on samples from the same logs. Methods and standards used for the evaluation of wood mineral and chemical content are described in Paper II, in the Appendix.
In this test, tool wear was evaluated by means of edge radius \((r)\) and edge recession \((ER)\), to obtain a meaningful representation of tool wear. These characteristics are shown in Fig. 3. \(ER\) and \(r\) were measured at a cutting length of 4896 m.

In Paper III, four tests were conducted in normal production in a Swedish sawmill in winter conditions. Sawing frozen logs in Scandinavia winter months is challenging when it comes to the choice of which cemented carbide grade to use. Both Pine and spruce were the materials that were machined, in both frozen and unfrozen conditions. Carbide tools denoted 242, 701 and 214 were selected from the six grades in the earlier preliminary test (Table 1). A double arbor sawblade was used for the tests. It had six circular sawblades for cutting two center boards and two side boards, as shown in Fig. 10. The sawblade diameter was 350 mm, sawblade thickness 2.6 mm, kerf width 3.6 mm, number of teeth 33, rake angle 30º, clearance angle 10º and the rotation speed was 3300 rpm.

Figure 10: Saw blade positions in the double arbor saw.

Four teeth on each tested circular sawblade were marked and checked after sawing a number of logs. The mean edge radii \((r)\) of the 4 teeth were measured and the 4 teeth were photographed. The thickness of the sawn boards was measured at the top end, root end and in the middle of 10 boards, on each occasion. The standard deviation of the thickness was calculated. Four tests were conducted from March 2009 til August 2010, with the sawblades of different teeth material in different positions. A detailed description of the test results is given in Paper III, in the Appendix.
4.2 Cutting forces

In Papers IV and V, cutting forces were measured using piezoelectric sensors. The cutting machine had a fixed single cutting tool (see Fig. 11). During the experiment, measuring signals were recorded with a sampling frequency of 25 kHz. Data were analysed with the LabVIEW software (Anonymous, 2005).

![Cutting machine used to measure cutting force.](image1.png)  
![Cutting force direction.](image2.png)

Figure 11a: Cutting machine used to measure cutting force.  
Figure 11b: Cutting force direction.

The cutting force during wood machining does not exhibit a steady behaviour. Figure 12 illustrates a sample plot of cutting forces data. In this thesis, only the main cutting force will be analysed. The values of main cutting forces were calculated as an average value of the force level that is roughly the horizontal part of the curve. The cutting speed has very small effect on cutting force values (Kivimaa, 1950). Thus, a constant cutting speed of 15 m s\(^{-1}\) was adopted.
The kerf width was constant at 3.9 mm and the clearance angle was constant at 15º. The wood samples had dimensions 160 mm in the tangential direction, 70 mm in radial direction and 70 mm in the longitudinal direction for the CDs $0^\circ$–$90^\circ$ and $90^\circ$–$0^\circ$, and 70 mm in the tangential direction, 70 mm in radial direction and 160 mm in the longitudinal direction for the CD $90^\circ$–$90^\circ$. Wood density was evaluated by computer tomography scanning, and moisture content was determined by a standard oven-dry method at a temperature of 103ºC.

Measurements of cutting force were divided into two parts:

The first part (Paper IV), was an evaluation of cutting forces for *Pseudolachnostylis maprounaefolia* (ntholo), *Sterculia appendiculata* (metil), *Acacia nigrescens* (namuno) and *Pericopsis angolensis* (muanga) and a comparison of their machinability. Generally, there are 4 basic parameters used to study machinability: namely, tool wear, cutting forces, surface quality and chip formation. In this thesis, only cutting forces and tool wear are discussed. Thus, better machinability means that there is less tool wear and less force per produced volume. The tests were conducted with a constant edge radius of 25 µm. Rake angle was 20º and 30º, and the chip thickness was constant at 0.15 mm. The CDs were $90^\circ$–$0^\circ$ (milling) and $90^\circ$–$90^\circ$ (rip sawing).

In the second part (Paper V), main cutting force models were developed, based on important factors, such as: edge radius ($r$); wood density ($D$); rake angle ($\alpha$); chip thickness ($t$); moisture content ($MC$); and cutting direction ($CD$). The materials that were machined were *Pseudolachnostylis maprounaefolia* (ntholo) and *Swartzia Madagascariensis* (ironwood).
Research design was made by MODDE (Anonymous, 2008). A D-optimal design was used, with three levels and six parameters (wood density was uncontrollable variable). The selected parameters and values of each level are summarized in Table 2. The chosen design comprised 32 runs per wood species. For comparison purposes, the values of the main cutting forces were expressed per mm edge width.

**Table 2: Attribution of the parameter levels.**

<table>
<thead>
<tr>
<th>Level</th>
<th>Chip thickness ((t))</th>
<th>Rake angle ((\alpha))</th>
<th>Edge radius ((r))</th>
<th>Moisture content ((MC))</th>
<th>Cutting direction ((CD))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>10</td>
<td>5</td>
<td>8</td>
<td>(90°–90°) 0</td>
</tr>
<tr>
<td>2</td>
<td>0.50</td>
<td>20</td>
<td>25</td>
<td>24</td>
<td>(90°–0°) 1.57</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>30</td>
<td>50</td>
<td>40</td>
<td>(0°–90°) 3.14</td>
</tr>
</tbody>
</table>

The explained variance, \(R^2\), and predicted variance, \(Q^2\), were used to evaluate the model at a confidence level of 0.95.

### 4.3 Power consumption

In Paper V, two tests were conducted in normal production in two Swedish sawmills, denoted Sawmill A and Sawmill B. The tests were performed in the second saw for resawing (resaw). The resaw machine cut two main boards (2ex) in sawmill B, and three main boards (3ex) in sawmill A. A schematic representation of the two sawmills is shown in Fig. 13.

![Figure 13: Cutting geometry in climb-sawing and counter-sawing: (a) Sawmill A; (b) Sawmill B.](image)

The resaw machines had four motors: two for climb-sawing; and two for countersawing. Each motor drives 2 circular sawblades. The machined material in both
sawmills was Scots pine. The cant heights were 154 mm and 206.5 mm for sawmills A and B, respectively.

The cutting edges for both sawmills were made of tungsten carbide, denoted 242. The cutting edges were sharpened to a similar condition, and were carefully examined before the experiments, to ensure that the cutting edges were free of defects. A standard microscope was used to examine the edge radii of the cutting tools before and after the test. Edge radius tests were measured only in sawmill A. However, in sawmill B, the tool edges were sharp at the beginning of the test. Based on experience, the edge radii were assumed to be 5 µm at the beginning and 50 µm at the end of the tests.

**Experimental power consumption**

The experimental tests were performed during one shift, which lasted approximately 8 h, as shown in Fig. 14. The power consumption of a circular sawblade was measured using a Fluke 1375 Power Logger, with the capability to measure average active power and maximum active power. Power consumption was recorded every 2 s for both sawmills. After recording, the logger was disconnected and the data were downloaded to a computer and reviewed. For comparison purposes, only the average maximum active power is reported here. The sawn boards were analysed and the saw mismatch was measured.

![Figure 14: An example of the measurement of maximum and average power consumption.](image)

**Theoretical power consumption**

The total theoretical power consumption in a circular sawblade was calculated using Equations 1 and 2.
The cutting force model developed by Axelsson et al. (1993) was extended to apply other saw kerf width, and used to estimate the power required to cause a failure,

\[
F_p = (7.37 + \delta_m \cdot (0.38 \cdot \delta_8 - 224.5 \cdot \alpha) + 15.61 \cdot KH - 2.6 \cdot KH^3 + 1.31 \cdot r + 0.2 \cdot v_c + U \cdot (0.3 \cdot KH - 0.01 \cdot T)) \cdot \frac{k}{4.25}
\]

where \(\alpha\) is the rake angle (radian), \(\delta_m\) is the average chip thickness (mm), \(k\) is the saw kerf width, \(r\) is the edge radius (µm), \(\delta_8\) is the average density at 8% moisture content (kg m\(^{-3}\)), \(T\) is the temperature (°C), \(KH\) is the grain angle (radian), and \(U\) is the moisture content (%).

The number of sawn logs were 7669 in sawmill A and 6277 in sawmill B. It was assumed an average green moisture content of 80% and an average green density of 840 kg m\(^{-3}\). The wood density at 8% moisture content was calculated using a volumetric shrinkage of 12.4%, which resulted in \(\delta_8 = 548\) kg m\(^{-3}\). All experimental tests were conducted during summer at a temperature around 20°C. One set of tests was conducted in each sawmill, as summarized in appended Paper V.

To calculate theoretical power consumption a program Microsoft Visual Basic C++ was used. Theoretical power consumption was calculated for a complete cycle in 1-degree increments of the cutting-edge position. The models also incorporated the effects of the saw kerf width, overlap, and saw mismatch between circular sawblades. Saw mismatch was incorporated by adding the cutting zone, which is shadowed by the first sawblade. The saw kerf width, used to calculate power consumption in the overlap zone, was the value of mismatch. To understand the effects of overlap between sawblades on theoretical power consumption, only the position of the second sawblade to cut (climb-sawing for sawmill A, and counter-sawing for sawmill B) was varied.

The idling power was subtracted from the experimental power consumption for each sawmill, in order to compare with the theoretical power consumption.

**4.4 Dynamic stability of wood cutting tools**

**Flatness and tensioning of circular sawblade**

In Paper VII, different methods for monitoring flatness and tensioning in circular sawblades were performed. The number of tested circular sawblades was 10 and they were denoted S1, S2, S3, S4, S5, S6, K1, K2, K3 and E1. These circular sawblades had different amounts of tensioning and flatness. The tested sawblades had several radial slots and were intended for use in double arbour saws with collars and no guides. Specifications of the circular sawblades used in the tests are illustrated in appended Paper VII.
Flatness measurements

Three methods for flatness measurement were considered; namely, a manual ruler, an indicator gauge and a dynamic method.

Tensioning measurements

The amount of tensioning in circular sawblades was determined by five methods:

- Method 1: light-gap technique
- Method 2: measurement of natural frequencies acoustically
- Method 3: measurement of natural frequencies with an electromagnet
- Method 4: static bending test
- Method 5: theoretical calculation of the natural frequencies with the FEM.

A detailed explanation of each method is presented in Paper VII.

Roll-tensioning effect on natural frequencies

In Paper VIII, the roll-tensioning effect on natural frequencies in circular sawblades for wood cutting was investigated. The sawblades tested had radius, $R_y$, 350 mm and thickness 3 mm. The tensioning radii for all tests were set within the range of $0.33R_y$ to $0.78R_y$. Seven identical sawblades were tested, and denoted A, B, C, D, E, F, and G. Experimental data were collected from circular sawblades in a non-rotating state. The roller load was applied through a screw mechanism, and the magnitude of the load was measured using a universal load cell, as shown in Fig. 16. The rolling was stopped after each complete revolution, and the sawblade was removed for examination. Each circular sawblade was rolled with a constant roll load, making one to five evenly spaced grooves ($G_r$), from inside to outside. The roller loads used were 10, 13.5, and 19.5kN.

Figure 16: Roll-tensioning of a sawblade.
Two methods for measuring the flatness of the sawblades were considered: namely, an indicator gauge and a light-gap technique.

The amount of tensioning was determined by measuring the natural frequencies of the free sawblades (Method 2), before and after tensioning. The non-rotating sawblade was excited by hitting it moderately with a wooden stick, and then the sound was recorded with a microphone, sampling rate 22050 Hz, 16-bit resolution. Finally, a fast Fourier transform analysis was conducted (16384 points, resolution 1.35 Hz), which showed the natural frequencies as amplitude peaks in the amplitude versus frequency diagram (Fig. 17).

![Image](image.png)

**Figure 17:** Power spectrum of sawblade F after tensioning one groove.

The finite element program Abaqus 6.10 (Simulia 2010) was used to calculate natural frequencies and mode shapes of the circular sawblades (Method 5).
5. RESULTS AND DISCUSSION

This chapter illustrates the main results, and discusses the main findings of this thesis. Section 5.1 presents results and discusses the evolution of tool wear and different tool wear mechanisms. Section 5.2 shows measured cutting forces, and theoretical models to predict cutting forces. Section 5.3 illustrates the main results concerning power consumption, and discusses the relationship between cutting parameters and theoretical power consumption. In section 5.4, tensioning results for circular sawblades are presented and discussed.

5.1 Tool wear and wear mechanisms

From Paper I, the measured nose width ($NW$) when cutting up to 2016 m cutting length is illustrated in Fig. 18. The shape of these $NW$ curves as a function of cutting length depends on the cutting conditions. Although the cutting edges were sharpened before the tests, the initial $NW$s of the cemented carbide grades varied from 3.5 to 18.9 µm. According to Astakhov (2006) and Ratnasingam et al. (2013), three distinctive regions can normally be observed on tool wear curves. The first region is the region of relatively high wear, and is explained by the accelerated wear of the tool layers, damaged during their manufacturing or re-sharpening. The second is the operating region for the cutting tool. The third is known as the tertiary or accelerated wear region. The characteristics of these regions can be seen in Figure 18, except for the third region, because the cutting tools were still not very dull at the end of the test ($NW_{\text{maximum}} = 42.5$ µm). In this thesis, average tool wear ($W$) is defined as the difference between the final nose width and the initial nose width.

![Figure 18: Nose width for different carbide grades.](image-url)
Machining properties of wood: tool wear, cutting force and tensioning of blades

A low-wear rate region is found between 864–1440 m cutting length, where the NW versus cutting length relationship is almost linear with a small slope. Grade 242 has superior toughness among the tested grades, which makes this grade extremely resistant to impact, but it had the highest final NW (42.5 µm) and the highest W (35.2 µm). Grade 214 had low average tool wear (W=11.8 µm). Also, it proved to be too brittle during the experiment (see Fig. 19). The initial NW was large, because it proved to be already brittle during the grinding. In general, as the hardness of the carbide is increased, grindability is sacrificed.

Grades 701 and 160 behaved similarly over the range studied, as was expected, because they have the same hardness and almost the same toughness (see Table 1). Among the tested grades, 701 had the least wear (W = 11.7 µm). Grades 021 and 046 showed good wear resistance, combined with high toughness. The amount of tool wear varies along the cutting edge. This might be explained by the inhomogeneous properties of the wood.

Figure 19: Catastrophic edge breakage of cemented carbide grade 214.

In Paper II, relationships between tool wear and some chemical and physical properties for four Mozambican tropical wood species are presented. Also several degrading tool mechanisms are identified. The average values for chemical, physical properties and tool wear, for muanga, namuno, metil and ntholo, are shown in Table 3.

Table 3: Average values for chemical, physical and tool wear properties of the tested wood species. Values in bracket are standard deviation.

<table>
<thead>
<tr>
<th>Species</th>
<th>Extractive (wt% dry base)</th>
<th>Ash (wt% dry base)</th>
<th>Silica (wt% dry base)</th>
<th>Wood density (kg m⁻³) (MC=8-9%)</th>
<th>Tool wear radius (µm) r</th>
<th>Edge recession (µm) ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muanga</td>
<td>9.07 (0.47)</td>
<td>1.28 (0.41)</td>
<td>0.13 (0.02)</td>
<td>920 (28.5)</td>
<td>15 (4.9)</td>
<td>50 (3.8)</td>
</tr>
<tr>
<td>Namuno</td>
<td>5.19 (0.34)</td>
<td>0.77 (0.14)</td>
<td>0.12 (0.02)</td>
<td>1100 (30.2)</td>
<td>9 (3.8)</td>
<td>55 (5.4)</td>
</tr>
<tr>
<td>Metil</td>
<td>1.98 (0.31)</td>
<td>3.10 (0.29)</td>
<td>0.13 (0.02)</td>
<td>550 (18.0)</td>
<td>5 (2.1)</td>
<td>46 (3.2)</td>
</tr>
<tr>
<td>Ntholo</td>
<td>3.96 (0.75)</td>
<td>3.10 (0.47)</td>
<td>0.40 (0.21)</td>
<td>726 (25.6)</td>
<td>43 (4.1)</td>
<td>93 (5.8)</td>
</tr>
</tbody>
</table>

25
Metil and ntholo had the highest ash content among the wood species tested. The content of extractives differed significantly. Ntholo had the highest silica content among the wood species tested. The range of wood density varied from 550 kg m$^{-3}$ (metil) to 1100 kg m$^{-3}$ (namuno).

The least dense material, metil, showed relatively low $r$ and $ER$, although it had a high ash content. The highest $r$ and $ER$ experienced over the studied range was for ntholo ($r = 43$ μm and $ER = 93$ μm), which had the highest silica content and relatively low wood density. Namuno had higher $ER$ than muanga. However, muanga had higher $r$ than namuno. This finding suggests that $r$ and $ER$ are not always related. It has been suggested by Klamecki (1979) that there are cases where edge recession measurements may not give a true indication of the wear of the cutting tool, with an obvious example being the situation in which edge wear proceeds in such a way as to retain a sharp cutting edge; i.e. self-sharpening. This difference makes the process of evaluating tool wear with a single parameter somewhat questionable. Siklienka & Mišura (2008) reported that one parameter does not always express the total rate of the cutting wedge tool wear, and it is necessary to measure more parameters.

To visualize the connection between wood chemical and physical characteristics, $ER$ and $r$, the experimental data were analysed by multivariate statistical methods, using Umetrics AB SIMCA P+ 12.0 software. Figure 20 illustrates the coefficient plot of the dependence of wood properties and tool wear, $ER$ and $r$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure20.png}
\caption{Dependence of edge recession and tool wear radius on physical and chemical characteristics of wood.}
\end{figure}

Figure 20 shows that the higher the silica content, the higher the $ER$ and $r$. Similar findings were reported by Porankiewicz and Grönlund (1991) and Darmawan et al. (2006). Silica content was the most important factor affecting $ER$ and $r$ for the tested wood species. High ash content resulted also in high $ER$ and $r$. Torelli & Čufar (1995) pointed out that silica and ash are relevant for sawing and machining. For the tested wood species, wood density affected the wearing rate very little. This contrasted with
the expectations before the tests, but the results agree with several similar studies by Porankiewicz et al. (2005, 2006), Okai et al. (2005) and Darmawan et al. (2006). They found that density alone cannot provide a satisfactory explanation of tool wear. It can also be observed from Figure 20 that the higher the amount of extractives, the lower the ER for the tested wood species, but the effect was insignificant on r. McKenzie and Karpovich (1968), and Svensson et al. (2009) reported that wood extractives act as lubricants and lower the coefficient of friction between the cutting tool and the workpiece.

During cutting of namuno, ntholo, metil and muanga, several degrading mechanisms were found on the cutting edges. Wear on cutting tools results from the interaction of many effects. Figure 21 (a, b) illustrates pitting of the WC grains, and the lack of cobalt in the cemented carbide skeleton. The wear pattern shows a rough surface with chipping, in combination with smooth abrasive wear. Corrosion was observed in the cutting edge for metil. Figure 21 (c, d) illustrates that the wear pattern is characterized by traces from chipping of the cemented carbide. No indication of corrosion was observed.

![SEM images of the surface texture of the wear profile along the cutting edge.](image)

**Figure 21:** SEM images of the surface texture of the wear profile along the cutting edge.
The traces from chipping may be associated with undesirable objects present in workpieces, such as stones and sand.

In Paper III, results from industrial tests when sawing pine and spruce revealed that grades 701 and 214 had the least amount of wear. Grade 242, standard grade today, had the greatest wear as was expected before the tests. It was also found that it is possible to use the harder cemented carbide grades 701 and 214 for winter-sawing conditions, instead of the commonly used grade 242, without risking significant edge damage.

It is quite difficult to compare the performance of cutting tools as attempted in this thesis, owing to the different cutting lengths, feeds per tooth, feed speeds, cutting directions, and so on. The largest edge radius during the machining of pine and spruce was 60 µm and 52 µm, respectively. During the machining of tropical woods the highest \( NW \) and \( r \) was around 43 µm for ironwood and ntholo, respectively. It is well known that \( NW \) is a bit smaller than twice the edge radius, but by comparing the number of samples and feed speed it is clear that ironwood or ntholo give faster wear than pine or spruce. In addition, it has been pointed out by Ramasamy and Ratnasingam (2010) that tool wear increases with an increasing moisture content. Thus, the values reported when machining ironwood, namuno, ntholo, metil, muanga might be higher when machined green.

The ability to saw a log consistently within specified thickness can be used as an indicator of sawmills efficiency. The standard deviations for board thicknesses, as a function of the number of logs, are shown in Fig. 22. The standard deviation of the thicknesses of the 10 measured boards was about 0.2 mm, and this value was constant and not affected by the number of logs sawn. Several factors influence the sawing accuracy such as tool wear, lateral stiffness, cutting condition, etc.

![Figure 22](image)

**Figure 22:** Each point is the standard deviation (mm) for thickness at 3 positions for 10 centre boards.
5.2 Cutting forces

In paper IV, the results of the experiments showed that cutting forces increased with density and decreased with an increasing rake angle. Results of cutting forces for metil, muanga, ntholo, namuno are presented in Table 4.

**Table 4: Density, main cutting forces in 90°–90° and 90°–0° of lesser used species from Mozambique. Edge radius 25µm and kerf width 3.9 mm.**

<table>
<thead>
<tr>
<th>Species</th>
<th>Wood density, kg m⁻³ (MC = 6-9%)</th>
<th>Force 90°–90°, N</th>
<th>Force 90°–0°, N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metil</td>
<td>604±16</td>
<td>81 ±7</td>
<td>34±6</td>
</tr>
<tr>
<td>Muanga</td>
<td>926±14</td>
<td>117±8</td>
<td>51±4</td>
</tr>
<tr>
<td>Ntholo</td>
<td>751±28</td>
<td>103±9</td>
<td>43±3</td>
</tr>
<tr>
<td>Namuno</td>
<td>1112±14</td>
<td>188±9</td>
<td>70±9</td>
</tr>
</tbody>
</table>

The range of wood densities of tested wood species varied from 604 kg m⁻³ (metil) to 1112 kg m⁻³ (namuno). Cutting forces varied from 81 N (metil) to 188 N (namuno) in a 90°–90° CD, and from 34 N (metil) to 70 N (namuno) in a 90°–0° CD. Interestingly, low wood density, ntholo, had a high ER and r (Paper II) and low cutting force (Paper IV). This finding suggests that wood species with low density and high mineral content can give a low cutting force and produce high tool wear. In Paper II, the highest r and ER experienced over the studied range was for ntholo, which had the highest silica content and relatively low wood density. Therefore, in wood cutting a single parameter to describe machinability may lead to a poor judgment.

Table 5 illustrates the ratio between wood density and cutting forces, and the ratio between cutting forces in directions 90°–90° and 90°–0°.

**Table 5: Ratio between density and cutting forces, and ratio between cutting forces.**

<table>
<thead>
<tr>
<th>Species</th>
<th>Density ( \frac{F_{90°-90°}}{F_{90°-0°}} ) s² m⁻⁴</th>
<th>Density ( \frac{F_{90°-90°}}{F_{90°-0°}} ) s² m⁻⁴</th>
<th>( \frac{F_{90°-90°}}{F_{90°-0°}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metil</td>
<td>7</td>
<td>17.7</td>
<td>2.37</td>
</tr>
<tr>
<td>Muanga</td>
<td>7.8</td>
<td>18.3</td>
<td>2.32</td>
</tr>
<tr>
<td>Ntholo</td>
<td>7.3</td>
<td>17.3</td>
<td>2.37</td>
</tr>
<tr>
<td>Namuno</td>
<td>6</td>
<td>16</td>
<td>2.69</td>
</tr>
</tbody>
</table>
Surprisingly, the ratio between wood density and cutting forces in $90^\circ$–$90^\circ$ and $90^\circ$–$0^\circ$ CDs were around $7 \text{s}^2\text{m}^{-4}$ and $17.3 \text{s}^2\text{m}^{-4}$, respectively. This suggests that with the same specific condition, by determining the wood density one can have a rough estimation of the cutting force in $90^\circ$–$90^\circ$ and $90^\circ$–$0^\circ$ CD. However, it is well known that, sometimes, two species with the same density give very different cutting forces, or species with completely different densities have similar cutting forces (Eyma et al. 2004). Recently, Chuchala et al. (2013) pointed out that cutting forces are clearly correlated with wood density, even if it is not the only significant factor.

Among the tested wood species, the cutting forces ratio between $90^\circ$–$90^\circ$ and $90^\circ$–$0^\circ$ cutting directions was 2.4. Since cutting force is correlated to power consumption, this implies that the power required to cause a failure during sawing ($90^\circ$–$90^\circ$) is 2.4 times greater than the power required during planing ($90^\circ$–$0^\circ$).

In Paper V, the models to predict the main cutting force required when cutting ntholo and ironwood are given by:

$$F_{p,Ntholo} = -6.55 - 0.08 \cdot \alpha + 0.18 \cdot r + 0.03 \cdot D + 28.94 \cdot t + 0.10 \cdot MC - 4.22 \cdot CD \quad (\text{Nm}^{-1}) \tag{4}$$

$$F_{p,\text{Ironwood}} = 37.4 - 0.021 \cdot \alpha + 0.31 \cdot r + 0.01 \cdot D + 31.21 \cdot t - 0.10 \cdot MC - 4.37 \cdot CD \quad (\text{Nm}^{-1}) \tag{5}$$

where $\alpha$ is the rake angle (degree), $r$ is the edge radius ($\mu$m), $D$ is the wood density ($\text{kgm}^{-3}$), $t$ is the chip thickness (mm), $MC$ is the moisture content (%), and $CD$ is the cutting direction (radian).

Since it is difficult to interpret variables with different scales — i.e., Equations 4 and 5 — scaled and centred coefficients are given in Equations 6 and 7.

$$F'_{p,Ntholo} = 1.94 - 0.04 \cdot \alpha' + 0.21 \cdot r' + 0.24 \cdot D' + 0.66 \cdot t' + 0.09 \cdot MC' - 0.35 \cdot CD' \tag{6}$$

$$F'_{p,\text{Ironwood}} = 2.23 - 0.10 \cdot \alpha' + 0.21 \cdot r' + 0.07 \cdot D' + 0.77 \cdot t' - 0.09 \cdot MC' - 0.39 \cdot CD' \tag{7}$$

The geometry of the cutting tool plays an important role when cutting wood. Equations 6 and 7 illustrate that the main cutting force increases when the edge radius increases. Also, the main cutting force decreases with increased rake angle. Similar findings were reported by Kivimaa (1950), Franz (1958) and Axelsson et al. (1993). The rake angle had a higher impact on the main cutting force when machining ironwood than when machining ntholo.

The cutting forces also (besides tool geometry) depend on wood species, wood density, and moisture content. In this thesis, wood density was used as an important indicator of wood stiffness, strength and hardness. Its advantage is that it can be measured quickly and without great expense. The results showed that the main cutting force increases with increased wood density. This is in agreement with Kivimaa
(1950), McKenzie (1961) and Koch (1964). The wood density had a higher impact on the main cutting forces for ntholo than for ironwood. It seems reasonable to expect that the main cutting force would decrease with increased moisture content, but for ntholo a different pattern of results was observed. However, Koch (1964) highlighted that the effect of moisture content on cutting forces is somewhat obscure, because of complex interactions with other factors. Furthermore, Chardin (1954) suggested that the cutting force decreases when cutting wood with high moisture content, but this did not apply to high density woods. It has also been reported by Loehnertz and Cooz (1998) that the effect of moisture content on the main cutting force might vary with the species studied.

Results revealed that cutting wood with lower chip thickness reduces the main cutting force. However, it has been pointed out by Grönlund (2004) that low values of chip thickness greatly increase the specific cutting work. Also, in Equation 7 and 8, the highest main cutting force occurs with a $CD$ of 90°–90°, while the smallest main cutting force occurs with a $CD$ of 0°–90°. These results agree with studies made by Kivimaa (1950), McKenzie (1961), and Moradpour et al. (2013).

Figure 23 illustrates that the models for both wood species are able to predict the main cutting force in an acceptable way, for almost all runs that were carried out.

![Figure 23: Observed and predicted main force: (a) ntholo; (b) ironwood.](image)

The explained variance for ironwood model was the same as that of the ntholo model ($R^2 = 0.89$). However, the ability to predict new data for ntholo ($Q^2 = 0.83$) was higher than for ironwood ($Q^2 = 0.81$). The difference between $R^2$ and $Q^2$ was small statistically, and the levels of $Q^2$ here indicate fairly strong and valid models.
Machining properties of wood: tool wear, cutting force and tensioning of blades

The highest main cutting forces for these tropical woods were 64.51 N mm\(^{-1}\) for ntholo, and 58.38 N mm\(^{-1}\) for ironwood.

### 5.3 Power consumption

In Paper VI, the experimental and theoretical power consumption, as a function of edge radius, assuming that wear is constant over time, are illustrated in Fig. 24. For both sawmills, an increase in edge radius resulted in higher power consumption. The idling power was 8.5 kW in sawmill A, and 7.2 kW in sawmill B.

Figure 24: The change in power consumption depending on edge radius: (a) sawmill A; (b) sawmill B.

The theoretical model showed lower power consumption than the experimental model. The differences between the theoretical and experimental results might be a result of the presence of wiper slots, back-sawing, motor efficiency, mismatch between sawblades and other losses, owing to interactions of the cutting tool and the workpiece, which were not considered in the theoretical calculation. Climb-sawing consumed more power than counter-sawing in the range tested. Surprisingly, the theoretical and experimental power consumption data converged, with an increase of cutting tool edge radius. The power consumption was higher in sawmill B than in sawmill A, owing to a high saw kerf width, cant height, high mismatch and low overlap between sawblades. In general, the climb-sawing model for both sawmills was able to estimate the power consumption better than the counter-sawing model.

To accelerate a chip, sawmill B required 6.2 kW for climb-sawing and 4.8 kW for counter-sawing. However, sawmill A required 11 kW for climb-sawing and 6.6 kW for counter-sawing. The relatively high values required to accelerate a chip in sawmill A were owing to the high sawblade rotation combined with a high feed speed.

Figure 25 illustrates how variation in overlap affects the theoretical power consumption in each sawmill. The theoretical total power consumption was defined as the sum of theoretical power consumption during climb-sawing, and theoretical power consumption during counter-sawing. In the experimental test, sawmills A and B had 25 mm and 5 mm overlaps, respectively. As the overlap between sawblades increased,
the theoretical power reduced for both sawmills, as result of the change in the angle of tooth entry and exit, grain angle, length of path of tooth engagement, and the number of teeth engaged; i.e., the greater the overlap between sawblades, the shorter the path of tooth engagement, and the fewer the number of teeth engaged in the cut. A potential for reduction in power consumption can be seen in sawmill A, if the overlap is increased.

![Figure 25](image)

**Figure 25**: Theoretical power consumption depending on overlap between sawblades: (a) sawmill A; (b) sawmill B (saw mismatch = 0).

5.4 Dynamic stability of wood cutting tools

Different methods for monitoring flatness and tensioning in circular sawblades

Paper VII’s results for the static and dynamic flatness of circular sawblades S1–S6 and K1–K3 are presented in Fig. 26. The methods differ mainly in the way the circular sawblades are fixed during the rotation.

A flatness value below 120 μm, measured with the static method, is an acceptable value for circular sawblades S1–S6 and K1–K3, according to experience. The two tested methods of flatness measurements gave different results, probably as result of the difference in fixation. However, all sawblades used were flat, and within acceptable limits for usable sawblades.

Electromagnetic excitation measurements for measuring tensioning (method 3) for sawblade E1 resulted in frequencies illustrated in Fig. 27, compared to FEM calculation results (method 5) for an untensioned sawblade (T = 0 C), and a tensioned sawblade (T = 20 C). Natural frequencies calculated with FEM agree well in general with measured frequencies.
Natural frequencies of roll-tensioned circular sawblades

In Paper VIII, sawblade A, B and C were tested with 10kN, 13kN, and 19.5kN tensioning force, respectively. Five tensioning grooves were made for each sawblade, from a tensioning radius of 0.33\(R_y\) to 0.45\(R_y\). The distance between grooves was 10 mm. Results revealed that the natural frequencies for NC = 0 were, in general, raised by tensioning, and the frequencies for NC = 1 were, in general, lowered. A low tensioning force, as in sawblades A and B, gave a small increase in the natural frequencies for NC = 0. The highest rise in natural frequency for NC = 0 was observed when tensioning with a high tensioning force, as in sawblade C (see Fig. 28). For reference, the values of natural frequencies are presented as frequency ratios between tensioned and untensioned sawblades.
Figure 28: Influence of tensioning force on natural frequency for sawblade C (19.5kN).

The values of natural frequencies for ND = 0 for NC = 1 were greatly reduced with tensioning, and in particular, the frequency for ND = 0 dropped to zero (dishing) for circular sawblade C with five grooves. The circular sawblade was also evaluated by the light-gap method, and the predicted dishing of sawblade C, when it was tensioned with five grooves, was also found, in practice, as a maximum flatness deviation observed by a gauge indicator of 0.1 mm. The effect of dishing could be avoided if the tensioning of circular sawblade C was stopped at four grooves. However, it has been reported that sawblades that experience dishing will become flat when running at or above the dishing speed (Schajer and Kishimoto 1996).

Circular sawblade G was tensioned using grooves from 0.67Ry to 0.78Ry. The distance between grooves was 10 mm. Figure 29 illustrates the frequency ratio for ND = 2 to 7 with NC = 0, and how it varies with an increasing number of grooves. The results illustrate the existence of a limit between increasing (tensioning) and reducing (detensioning) the natural frequencies of the circular sawblade.
In this thesis, this limit was called the critical tensioning radius ($R_{tc}$). $R_{tc}$ is different for different modes, and here, it was determined for ND = 2 and ND = 3. The critical value of $R_t$ for the tested sawblades was $0.72R_y$. Tensioning the circular sawblade G to the $R_{tc}$ ($Gr = 3$) resulted in a 33.5% rise in the frequency for ND = 2.
6. CONCLUSIONS

The most important conclusions of this thesis are:

Tool material and tool wear

- Harder carbide grades 701 and 214 can be used in winter-sawing conditions to machine pine and spruce than normally used.
- Carbide grades 701 and 160 are suitable for processing tropical wood species.
- The hardest carbide grade 214 was very difficult to grind.
- The predominant wearing mechanisms, when machining tropical species, were abrasion and edge-chipping.
- Silica content was the most important factor with regard to wearing of cutting tool.
- Wood density alone was not a good estimator of tool wear.

Cutting forces

- When processing tropical species, the highest possible chip thickness with respect to surface quality, edge strength and available power should be used.
- Wood density alone was not a good estimator of cutting force for ntholo and ironwood when moisture content was varied from 8–40%.
- The ratio between wood density and cutting forces in directions 90°–90° and 90°–0° were 7 s^2m^-4 and 17.3 s^2m^-4, respectively.
- The ratio between force for cutting direction 90°–90° and force for cutting direction 90°–0° was 2.4.

Power consumption

- The power consumption was higher in sawmill B than in sawmill A, owing to the large saw kerf width, large cant height and small overlap between sawblades.
- Climb-sawing gave higher power consumption than counter-sawing.
• The cutting force model by Axelsson et al. (1993) was able to predict power consumption better during climb-sawing than during countersawing.

• The smallest power consumption was found using a larger overlap between circular sawblades.

Dynamic lateral stability of circular sawblade

• Experimental and theoretical natural frequencies were in good agreement.

• Natural frequency test made by acoustic microphone was fast and simple to perform.

• The critical tensioning radius was found to be $0.72R_f$ for the tested circular sawblades.
7. FUTURE WORK

All tests concerning tool wear and cutting forces, using tropical wood species, were conducted in a laboratory. Industrial test are planned.

**Tool wear and wear mechanisms:**

- study the influence of cutting direction on tool wear.
- investigate the relation between normal force and tool wear.

**Cutting force:**

- apply different approaches to predict cutting forces, such as specific cutting resistance and modern fracture mechanics.
- investigate the relation between cutting parameters and chip formation when cutting tropical wood species.

**Power consumption:**

- study effect of back-sawing, owing due to curve sawing on theoretical power consumption.
- analyse resaw machines with thicker saw kerf widths for climb-sawing, and thinner ones for counter-sawing, or vice versa.

**Dynamic lateral stability of wood cutting tools:**

- study the effect of different geometry of circular sawblades.
- investigate stresses in circular sawblades, owing to tensioning, centrifugal force and cutting forces.
REFERENCES


Paper 1
Brittleness of cutting tools when cutting ironwood

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ABSTRACT

Mozambique possesses tropical tree species that have renowned commercial value, but little is known about primary and secondary processing characteristics of these materials. For that reason, a better understanding of wood cutting-tool materials is necessary to optimize the production process, reduce exports of raw timber and stimulate industrial transformation.

The aim of this work was to study tool wear behaviour when cutting ironwood (Swartzia Madagascariensis). The experiments were carried out on a shaper. Six different cemented-carbide grades for woodworking were tested, and the cutting parameters were fixed.

Results obtained showed good correlation between tool wear and tool physical properties. Results also indicate that tool wear differed greatly among the tested cemented-carbide grades.

Keywords: cutting tools, tool wear, ironwood, hardwood

INTRODUCTION

The wear of woodcutting tools is generally the process that makes a tool unfit for continued use. The replacement of the worn cutter by either reconditioning or substitution of a new one represents a necessary cost that can be minimized by controlling tool wear (Klamecki 1979).

The tool materials used in wood industry are carbon steels, high speed steels, stellite, cemented carbide, and diamonds. Carbon steels were used at early phase and were replaced by high speed steels and stellite. Further development of wood industry the need of harder and high resistance to cut woods led to wide use of cemented carbides. Cemented carbides are the most versatile hard materials due to their unique combination of high hardness and toughness within a wide.

The evaluation of tool wear has been monitored in studies either by observing the change in the edge geometry of the cutting tool, or by observing variation in the forces acting during cutting. Chardin and Froidure (1969) used photographic tools before and after cutting-tool use, measuring edge recession, made casts of the tool edges, and observed readily apparent tool characteristics, e.g., colour change.

Edge recession is, in general, non-uniform along the tool edge, and usually some average value is measured. A way of accounting for the non-uniformity of edge recession is to specify the projected area of tool blunting representing the recession of the edge. Although cutting-edge recession is an
easily measured characteristic of tool wear, the question of what the worn edge profile (viewed along the cutting edge) is remains unanswered by such measurements (Klamecki 1979).

The aim of this work was to study tool-wear behaviour when cutting *Swartzia Madagascariensis* (ironwood). Processing this hardwood is difficult. The design of new specific and strong tools will allow more acceptance of wood from these species in the Mozambique market and improve export income.

**EXPERIMENTAL**

**Measurements and analysis**

Tool wear was determined by measuring the nose width (NW) of the tool at specific positions along the cutting edge (Fig. 1). The cutter head that was used was equipped with two cutting tools so as to avoid out of balance effects caused by having only one insert, but one was deliberately blunted (so as not to cut) and the second was sharp (Fig. 2). All cutting-machine parameters were fixed (Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutterhead</td>
<td>2900 rpm</td>
</tr>
<tr>
<td>Feed speed</td>
<td>3 m/min</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>1 mm</td>
</tr>
<tr>
<td>Tool carbide grade</td>
<td>Sandvik 214, 701, 242, 021, 160, 046</td>
</tr>
<tr>
<td>Diameter of cutter head</td>
<td>154 mm</td>
</tr>
<tr>
<td>Cutting length per cut</td>
<td>12.41 mm</td>
</tr>
<tr>
<td>Number of tests per grade</td>
<td>7</td>
</tr>
<tr>
<td>Rake angle</td>
<td>30°</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>15°</td>
</tr>
<tr>
<td>Mean density</td>
<td>1100 kg/m³</td>
</tr>
<tr>
<td>Kerf width</td>
<td>3.9 mm</td>
</tr>
<tr>
<td>Direction of cutting</td>
<td>90°–0°</td>
</tr>
<tr>
<td>Mode of cut</td>
<td>counter-cutting</td>
</tr>
</tbody>
</table>

The test started with measurements of the initial nose width of the new tools, and after that, the nose width was tracked after 288, 576, 864, 1152, 1440, 1728 and 2016 meters of cutting length. Cutting length was defined as the distance the cutting tool was in contact with the wood sample. NW was measured at four positions along the cutting edge, the first being at the corner, then at 1.3, 2.6 and 3.9 mm from the corner.

Fig. 1 Determination of tool wear by measuring the nose width (NW). | Fig. 2 Carbide tooth inserted in a cutter head.
Material

Ironwood (*Swartzia Madagascariensis*) samples were prepared with dimensions of 1000 x 200 x 70 mm in the fibre, tangential and radial directions, respectively. The specimens were chosen from butt logs that had been felled and sawn the previous year in Northern Mozambique, namely in the province of Cabo Delgado. Special care was taken to select samples as free as possible of knots or other defects. The evaluation of average wood density was made by computer tomography scanning (Fig. 3).

![Fig. 3 Greyscale digital image of the density.](image)

The specimens were stored several months in laboratory climate, and during this time, an average moisture content of about 12 percent was reached. Immediately after the cutting, the moisture content of some the test pieces in each test was checked.

Tools
The six different carbides tools used for the experiment were 214, 701, 242, 021, 160, 046 provided by the company Sandvik Hard Materials. The cutting edges were checked prior to cutting, and those with a nose width of more than 20 microns were rejected.

Shaper
An SCM shaper machine was used for this test (Fig. 4). Table 1 shows more details of the test setup.

Microscope
An optical microscope Leica Qwin V3 with digital picture capturing and measurement capabilities was used for measurement of the nose width (Fig. 5). Wear ($W$) is defined as the difference between the initial nose width and the final nose width.
RESULTS AND DISCUSSION

Very often, grade selection involves finding the best compromise between hardness (abrasion resistance) and toughness (impact resistance), though in some cases, strength and corrosion resistance can be important factors in grade selection.

The results reported for each cutting length are the average values of the nose width from the four positions (Table 2).

Table 2 Average NW for all six cemented–carbide tools tested at 0, 288, 576, 864, 1152, 1440, 1728 and 2016 metres.

<table>
<thead>
<tr>
<th>Grade</th>
<th>0 m</th>
<th>288 m</th>
<th>576 m</th>
<th>864 m</th>
<th>1152 m</th>
<th>1440 m</th>
<th>1728 m</th>
<th>2016 m</th>
<th>Wear (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>18.9</td>
<td>20.9</td>
<td>21.8</td>
<td>23.5</td>
<td>25.8</td>
<td>28.3</td>
<td>29.5</td>
<td>30.7</td>
<td>11.8</td>
</tr>
<tr>
<td>021</td>
<td>3.5</td>
<td>6.8</td>
<td>12.8</td>
<td>14.0</td>
<td>16.3</td>
<td>18.9</td>
<td>20.8</td>
<td>28.3</td>
<td>24.8</td>
</tr>
<tr>
<td>160</td>
<td>1.8</td>
<td>3.5</td>
<td>7.0</td>
<td>9.0</td>
<td>11.5</td>
<td>11.8</td>
<td>12.8</td>
<td>13.8</td>
<td>12.0</td>
</tr>
<tr>
<td>701</td>
<td>3.5</td>
<td>5.3</td>
<td>7.0</td>
<td>9.0</td>
<td>11.5</td>
<td>12.3</td>
<td>14.0</td>
<td>15.2</td>
<td>11.7</td>
</tr>
<tr>
<td>046</td>
<td>3.5</td>
<td>4.5</td>
<td>9.0</td>
<td>19.0</td>
<td>23.5</td>
<td>25.8</td>
<td>28.3</td>
<td>30.7</td>
<td>27.2</td>
</tr>
<tr>
<td>242</td>
<td>7.3</td>
<td>21.0</td>
<td>23.8</td>
<td>25.5</td>
<td>28.3</td>
<td>30.5</td>
<td>40.2</td>
<td>42.5</td>
<td>35.2</td>
</tr>
</tbody>
</table>

The results of the study show the basic relationships between tool wear versus hardness of the tools and tool wear versus toughness of the tools (Figures 6 and 7). There was a positive correlation between tool wear and toughness, and the hardness of the material was negatively correlated to the tool wear. These findings were expected as already several authors have reported a similar result. The coefficient of determination was $R^2 = 0.86$ for tool wear versus toughness and $R^2 = 0.73$ for tool wear versus hardness.
The graph in Figure 8 shows the NW for six different carbide grades as a function of cutting length.

According to Astakhov (2006), three distinctive regions can normally be observed on tool wear curves. The first region is the region of primary or initial wear. Here we have a relatively high wear rate, and it is explained by accelerated wear of the tool layers damaged during its manufacturing or re-sharpening. The second region is the region of steady-state wear. This is the normal operating region for the cutting tool. The third is known as the tertiary or accelerated wear region. The characteristics of these regions can be seen in the plot above, except for the third region, because the tools were still quite sharp at the end of the tests ($NW_{\text{maximum}} = 42.5 \mu m$).

The cemented-carbide grade 242 has superior toughness, which makes this carbide extremely resistant to impact, but it had the greatest wear ($W = 35.2 \mu m$) (Table 2). The initial tool wear for this grade was higher ($W = 13.8 \mu m$) than the total wear for grades 214, 160 and 160.
Grades 701 and 160 behaved similarly over the range studied, as was expected, because both have the same wear resistance (hardness) and almost the same toughness (Table 2). The 701 grade had the least wear of all grades ($W = 11.7 \mu m$).

Grades 021 and 046, which are more versatile, showed good wear resistance combined with high toughness.

The 214 grade had low wear ($W = 11.8 \mu m$). However, it proved to be too brittle during the experiment (Appendix). The grade started with a large nose width, because it proved to be brittle already during the grinding. In general, as the hardness (wear resistance) of carbide is increased, grindability is sacrificed.

CONCLUSIONS

The main conclusions arrived at are:
- The carbide-cemented grade 214 was too brittle, which led to catastrophic failure (see Appendix) during the fourth test (at 1152 meters) and from the point of view of maintainability, it is very difficult to grind this grade.
- Grades 701 and 160 are most suitable for processing ironwood.
- Cemented-carbide grades 021 and 046 can be used in the woodworking industry for processing this hard-to-cut wood, but are not as sustainable as 701 and 160 from the point of view of tool life and edge quality.

In the next step of research, relations between wood chemical properties and tool wear will be considered. In addition, other species will be considered.

REFERENCES

APPENDIX

The appendix shows the edge profiles for the different cemented-carbide grades, *i.e.*, the initial and final shapes.

![Carbide 214-0 m](image1) ![Carbide 701-0 m](image2)
![Carbide 214-2016 m](image3) ![Carbide 701-2016 m](image4)

![Carbide 242-0 m](image5) ![Carbide 021-0 m](image6)
![Carbide 242-2016 m](image7) ![Carbide 021-2016 m](image8)

![Carbide 160-0 m](image9) ![Carbide 046-0 m](image10)
![Carbide 160-2016 m](image11) ![Carbide 046-2016 m](image12)
Paper II
Tool wear for lesser known tropical wood species

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Abstract
This study investigated the relationship between tool wear and some chemical and physical properties for four different Mozambican lesser known tropical species: *Pseudolachnostylis maprouneafolia* (ntholo), *Sterculia appendiculata* (metil), *Acacia nigrescens* (namuno) and *Pericopsis angolensis* (muanga). Tool wear is an important aspect for sawmilling and for the woodworking industry. For Mozambique, the utilization of available lesser known wood species will help to increase domestic industry and the economic usage viability of sustainable forest management. A set of experiments was performed on a shaper with a mechanical feed mechanism. Tools of a cemented carbide grade for woodworking were used, and the cutting parameters were fixed. Edge recession and tool wear radius were measured for monitoring tool wear. The wear mechanism was investigated using a scanning electron microscope. The experimental results showed that the chemical properties of the wood species have a great effect on tool wear. Wood silica content was the most important factor affecting tool wear. Wood density and extractives had a low influence on tool wear. The highest tool wear was observed in ntholo, which also had the highest ash and silica contents. A single parameter for evaluation of tool wear was not sufficient to describe the amount of total tool wear.

Keywords: Cemented carbide, tool wear, tropical species, wear mechanisms.

Introduction

Much research on wood-cutting tools has been done. However, processing of tropical species with a high silica content is still a challenge for the woodworking industry. To improve this situation, knowledge of fundamental wear mechanisms is an important factor in determining the type of tool materials that should be used. Mechanical, thermal and chemical interactions between cutting tool and workpiece are important factors in tool wear. Wear from abrasion has been considered to be the dominant degrading mechanism. Cemented tungsten carbide has provided improvements in tool life because of superior abrasion resistance compared with carbon steels, high-speed steels and cast cobalt alloys.

Several parameters have been used by researchers to determine tool wear and bluntness of the cutting edge. There is, however, some disagreement as to which wear parameter is the most representative of the state of bluntness of the cutting tool (Sheikh-Ahmad & McKenzie, 1997). The chemical nature of wood may play a large part in cutting tool wear rates (Klamecki, 1979). McKenzie and Karpovich (1968) highlighted that extractives in wood act as lubricants and effectively decrease the coefficient of friction in the sliding of wood over steel. Porankiewicz and Grönlund (1991) pointed out that rapid mechanical wearing of tools has often been attributed to the presence of silica content and other abrasive agents in wood. Machinability of wood is decisively influenced if the silica content is above 0.5% (Rowell, 1984) or 1–3% (Gottwald, 1973). Even low-density woods are difficult to machine when their silica content is high (Noack & Frühwald, 1977). The work of Kirbach and Chow (1976) emphasizes the complexity of the tool-wear problem inherent in the multicomponent
nature of the wood and tool materials. Their proposed mechanism of carbide tool wear involves chemical attacks on the tool material binder and mechanical failure of the exposed carbide grains. Thus, the nature of both the wood and the tool determines wear rates.

The forests of Mozambique contain lesser known species (LKS), sometimes with similar properties to well-known commercial species; these LKS are less exploited and used because of their poorly known properties (Ali et al., 2008). Utilization of available LKS will help to expand domestic sawmilling and woodworking industries and also the economic usage viability of sustainable forest management. Data on physical, chemical, mechanical and cutting properties are important for promotion of these species. The available volumes of LKS are several times higher than the well-known commercial species (DNTF, 2007).

The aim of this work was to gain insight into the effects of wood chemical and physical properties on the mechanism of woodcutting tool wear and to evaluate methods of measurement of cutting edge tool wear. Edge recession and tool wear radius were measured for monitoring tool wear, as the tool wear pattern and phenomena differ between species.

**Materials and methods**

Four Mozambican lesser known tropical species were studied: ntholo, metil, namuno and muanga.
Wood specimens were prepared to dimensions 1000 × 200 × 120 mm in the fibre, tangential and radial directions, respectively. Table I shows the common name, scientific name and family of the wood species studied.

The wood samples for the experiments were taken from heartwood selected from butt logs. The ratio of heartwood to sapwood was not measured in the logs felled for the study of machinability. Sapwood would have better machinability than heartwood, owing to its lower density.

The chemical and physical analyses were performed on samples from the same log. The samples were collected in Cabo Delgado Province (latitude 12°45′0″S, longitude 39°30′0″E, with an annual rainfall 1400–1800 mm). The specimens were stored for several months in a laboratory climate before the tests, during which time an average moisture content of 8–9% was reached. The selected moisture content is an acceptable level for hardwood interior furnish. Immediately after cutting, the moisture content of some test pieces in each test was determined by a standard oven-dry method and found to be the same.

The results reported for wood mineral content are the average values for inner heartwood and outer heartwood. For further information on the wood mineral content, the collected data set and the experimental methods, refer to Lhate et al. (2010).

The tool-wear experiments were carried out on a shaper with a mechanical feed mechanism (Figure 2) under the following conditions: tool carbide grade Sandvik 701, cutterhead rotation rate 2900 rpm, diameter of cutterhead 154 mm, feed speed 3 m min⁻¹, depth of cut 1 mm, cutting length per cut 12.41 mm, cutting width 3.9 mm, rake angle 30°, clearance angle 15°, direction of cutting 90°–0° (milling parallel to grain) and a counter-cutting mode. The workpieces were machined using a single standard saw tooth AA. Wood machining studies using a single sawtooth help to elucidate the cutting process. Using a single sawtooth eliminates extraneous variables such as vibration of the cutting tool and saw machine components that obscure variables involved in the cutting process.

The cutterhead was equipped with two cutting tools to avoid effects of imbalance caused by having only one insert, but one was deliberately blunted (so as not to cut) and the other was sharp (Figure 3). Carbide cemented grade 701 was provided by Sandvik Hard Materials. This grade incorporates 10% cobalt, 89.5% tungsten carbide (WC) and 0.5% other compounds. Vickers hardness (HV30) was 1600 and Rockwell hardness (HRA) was 92.1.

In this study, tool wear was evaluated by means of tool wear radius (TW) and edge recession (ER) to

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash content</td>
<td>Gravimetric</td>
<td>SS18717:1</td>
</tr>
<tr>
<td>Extractives</td>
<td>Gravimetric/Soxhlet extraction (acetone)</td>
<td>SCAN-CM 49:03</td>
</tr>
<tr>
<td>Silica</td>
<td>Atomic absorption spectrophotometry (flame)</td>
<td>ALC2038-201</td>
</tr>
</tbody>
</table>
obtain a meaningful representation of tool wear. Tool wear radius measurements were taken in an evaluation area in the middle position of the cutting edge with the aid of micro-CAD (Figure 4a).

The length of the evaluation area was 2 mm along the cutting edge and the length around the cutting edge was 1.5 mm. The results reported are the average values from 400 measurements of edge profile taken in the evaluation area for each tool. An optical microscope with digital picture capturing and measurement capabilities was used for measurement of the edge recession on the rake surface (Figure 4b) at four equidistant positions in the same evaluation area as for TW. ER and TW were measured at a cutting length of 4896 m. Cutting length was defined as the distance the cutting tool was in contact with the wood sample. The cutting edge was also studied by scanning electronic microscope (SEM) to classify the wear mechanisms.

Since the initial geometry of the cutting tool seems to have a significant effect on tool wear, the cutting edges were checked before cutting; after cutting, the tools were cleaned to eliminate the influence of dust on the accuracy of the results.

Statistical analyses of the experimental data were performed by multivariate statistical methods, using Umetrics AB SIMCA P+ 12.0 software (Anon., 2008).

**Results**

From Table III, it can be seen that metil and ntholo had the highest ash content. The content of extractives obtained by the acetone method among the wood species differed significantly. Ntholo had

---

Figure 4. (a) Tool wear radius evaluation area; (b) edge recession and tool wear radius.

Figure 5. Scanning electron micrograph images of the surface texture of the wear profile along the cutting edge: (a) metil; (b) namuno; (c) muanga; (d) ntholo.
the highest silica content among the wood species studied. The range of wood densities of LKS tested here varied from 550 kg m\(^{-3}\) (metil) to 1100 kg m\(^{-3}\) (namuno).

As already mentioned, tool wear was evaluated based on the average of the several measurements of a wear parameter made in a specific predetermined region. The least dense material, metil, showed relatively low TW and ER, although it had a high ash content. The highest TW and ER experienced over the studied range was for ntholo (TW = 43 μm and ER = 93 μm), which had the highest silica content and relatively low wood density.

Figure 5(a, b) illustrates pitting of the WC grains and lack of cobalt in the cemented carbide skeleton. The wear pattern shows a rough surface with chipping in combination with smooth abrasive wear. Corrosion was observed in the cutting edge for metil. Figure 5(c, d) shows that the wear pattern is characterized by traces from chipping of the cemented carbide. No indication of corrosion was observed.

Figure 6 shows the corner of the tool edge for different species. The cutting edge in the corner showed deep distortions of the chipping and abrasive wear pattern. Metil showed a different type of wear, with very little ER and TW except for chipping in the corner (Figure 6a).

Wear mechanisms on cutting tools result from the interaction of many effects. During the cutting process, several wear mechanisms can occur at the same time. The SEM analysis indicated that the main mechanical wear mechanism was a combination of abrasion and tool edge chipping.
To visualize the connection between wood chemical and physical characteristics, ER and TW, the experimental data were analysed by multivariate statistical methods using Umetrics AB SIMCA P+ 12.0 software. Coefficient plots of the dependence of wood chemical and physical characteristics, ER and TW are shown in Figure 7. Figure 7 shows that high ash and silica content resulted in both high ER and high TW for the tested wood species. Density and extractive content had a small effect on tool wear and they were somewhat negatively correlated with tool wear for the tested wood species.

Table III. Average values for chemical, physical properties and tool wear properties of the tested wood species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Extractive (wt% dry base)</th>
<th>Ash (wt% dry base)</th>
<th>Silica (wt% dry base)</th>
<th>Wood density (kg m(^{-3}))</th>
<th>Tool wear radius (μm)</th>
<th>Edge recession (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muanga</td>
<td>9.07 ± 0.47</td>
<td>1.28 ± 0.41</td>
<td>0.13 ± 0.02</td>
<td>920 ± 28.5</td>
<td>15 ± 4.9</td>
<td>50 ± 3.8</td>
</tr>
<tr>
<td>Namuno</td>
<td>5.19 ± 0.34</td>
<td>0.77 ± 0.14</td>
<td>0.12 ± 0.02</td>
<td>1100 ± 30.2</td>
<td>9 ± 3.8</td>
<td>55 ± 5.4</td>
</tr>
<tr>
<td>Metil</td>
<td>1.98 ± 0.31</td>
<td>3.10 ± 0.29</td>
<td>0.13 ± 0.02</td>
<td>550 ± 18.0</td>
<td>5 ± 2.1</td>
<td>46 ± 3.2</td>
</tr>
<tr>
<td>Ntholo</td>
<td>3.96 ± 0.75</td>
<td>3.10 ± 0.47</td>
<td>0.40 ± 0.21</td>
<td>720 ± 25.6</td>
<td>43 ± 4.1</td>
<td>93 ± 5.8</td>
</tr>
</tbody>
</table>

Note: Data are shown as mean ± SD.

Discussion

Metil had the best machinability, i.e. the lowest TW and ER; however, it had the lowest extractive content. This finding is based on the acetone extractive content only and not the total extractives. Namuno had higher ER than muanga; however, muanga had higher TW than namuno (Table II). This finding suggests that TW and ER are not always related. It has been mentioned by Klamecki (1979) that there are cases where edge recession measurements of wear may not give a true indication of the value of the cutting tool, an obvious example being the situation in which edge wear proceeds in such a way as to retain a sharp cutting edge, i.e. self-sharpening. It was also pointed out by McKenzie and Cowling (1971) that the tool wear radius tends to stabilize at a particular value and does not increase with further increases in cutting distance. The traces from chipping may be associated with undesirable objects present in workpieces, such as stones and sand.

Figure 7 illustrates that the higher the wood silica content, the higher the ER and TW. Similar findings were reported by Porankiewicz and Grönlund (1991) and Darmawan et al. (2006). Wood silica content was the most important factor affecting ER and TW for the tested wood species. High ash content resulted also in high ER and TW. This is in line with a study done by Torelli and Cufar (1995), who pointed out that wood silica and ash are of relevance for sawing and machining. For the tested wood species, high wood density means low ER and TW. This was in contrast with expectations before the tests, but the results agree with several similar studies by Porankiewicz et al. (2005), Okai et al. (2005) and Darmawan et al. (2006). They found that wood density alone cannot provide a satisfactory explanation of tool wear. It can also be observed from Figure 7 that the higher the amount of wood extractives, the lower the ER for the tested wood species, but the effect was insignificant on TW. This difference makes the process of evaluating tool wear with a single parameter somewhat questionable.

In conclusion, the main findings of this work for the tested wood species can be summarized as follows:

- Tool wear did not increase with increase of wood density.
- Wood silica content was the most important factor for wearing of the cutting tool.
- Abrasive wear and tool edge chipping were the most dominant mechanical wear mechanisms.
- Ntholo species caused the cutting tool to wear quickly owing to its high content of silica.
- Metil species had the best machinability of the four wood species studied, but this species had the lowest extractive content, based on the acetone method.
- The lesser known tropical species muanga, namuno and metil would appear to be more profitable than ntholo based on tool life.

The relation between tool wear and cutting forces will be considered in future research.

Acknowledgements

The authors express their gratitude to AB Sandvik Company for supplying the cemented carbide grades
for this study. Part of the test was carried out in AB Sandvik Company; special thanks to Mr Stefan Ederyd. Thanks also to the Swedish International Development Agency (SIDA), Department for Research Cooperation (SAREC) for funding the research.

References


Paper III
Wear of teeth of circular saw blades

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Abstract

Measured wear data is presented for three different carbide grades. The data were collected during rip sawing wood with a double arbour saw. The purpose of the test was to determine the suitability of different grades for sawing frozen timber. A set of circular saw blades of diameter 350 mm was equipped with teeth comprised of three different cemented carbide grades, denoted A, B and C. The double arbour saw was equipped with six saw blades for cutting two centre boards and two side boards. The six saw blades with different teeth were mounted in a mixed manner on the arbours, and after sawing a number of logs the wear of teeth was measured. The thickness of boards was also measured and the standard deviation was calculated. The results showed that grade A had the highest wear and grades B and C the lowest wear. There was no significant edge damage during the tests. Grade C did not suffer problems of chipping from cutting edges and was found to be suitable for sawing frozen timber. The thickness standard deviations were constant at about 0.2 mm, and not a function of the number of logs sawn.

Keywords: Cemented carbide, circular sawblade, tool wear.

Introduction

Circular saw blades with cemented tungsten carbide teeth are normally used in Swedish saw mills for the rip-sawing of logs. Different kinds (grades) of cemented carbides can be used, from softer and tougher ones to harder but more brittle ones. Winter conditions in Scandinavia, in combination with green logs which contain much icy sapwood, are particularly challenging when it comes to the choice of which cemented carbide grade to use. Hard grades wear less but are more brittle, and softer grades wear faster but are tougher. Greater brittleness results in greater damage to the teeth edges, such as corners or small parts (chips) of the edges breaking off. Wear can be measured by measuring the edge radius, see Figure 1. Also by inspecting the edge in order to identify broken off parts of the edge.

Wear of cutting edges in general has been studied extensively and is caused by a combination of chemical, physical and mechanical processes (McKenzie and Karpovich 1968, McKenzie and Cowling 1971, Kirbach and Chow 1976, Klamecki 1979, Porankiewicz and Gronlund 1991, Sheikh-Ahmad and McKenzie 1997, Okai et al. 2005, Porankiewicz et al. 2006, 2005). Mechanical wear is due to high stresses, friction and partly due to hard particles imbedded in the wood. Chemical wear is due to chemical content in the wood which reacts with the edge material. High temperatures affect wear, since mechanical and chemical properties and reactions are greatly affected by temperature.

In this study, three different cemented carbide grades are compared. The three grades were tested in circular saw blades used in normal production in a Swedish saw-mill under winter conditions. The purpose was to decide whether it was possible to use harder carbide grades during winter sawing than those normally used. Edge wear, edge damage and the accuracy of board dimensions were registered as a function of the number of logs that were sawn.

Material and methods

A double arbour saw (with vertical arbours) was used for the tests. It was run under normal saw mill production but equipped with test saw blades in different configurations. It had six saw blades (three
on each arbour) for cutting two centre boards and two side boards, see Figure 2. The geometry of the saw blades that were used are shown in Figure 3. The diameter was 350 mm, the thickness was 2.6 mm, the kerf width was 3.6 mm, the number of teeth was 33, the rake angle was 30°, the clearance angle was 10° and the rotation speed was 3300 rpm.

Four teeth on each tested saw blade was marked and checked after sawing a number of logs. The mean edge radii of the four teeth were measured and

Table I. Description of tests.

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 4</th>
<th>Test 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start date</td>
<td>9 March 2009 (spruce),</td>
<td>5 October 2009</td>
<td>18 March 2010</td>
<td>20 August 2010</td>
</tr>
<tr>
<td>Log material</td>
<td>Spruce + pine</td>
<td>Pine</td>
<td>Spruce</td>
<td>Spruce</td>
</tr>
<tr>
<td>Log condition</td>
<td>Frozen spruce-unfrozen</td>
<td>Unfrozen</td>
<td>Frozen</td>
<td>Unfrozen</td>
</tr>
<tr>
<td>Feeding speed (m/min)</td>
<td>70 (spruce)</td>
<td>76</td>
<td>66</td>
<td>68</td>
</tr>
<tr>
<td>Centre board dimension</td>
<td>47 × 150 (spruce)</td>
<td>50 × 150</td>
<td>63 × 150</td>
<td>50 × 150</td>
</tr>
<tr>
<td></td>
<td>63 × 155 (pine)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Position 1</td>
<td>B No 4</td>
<td>B No 4</td>
<td>C No 7</td>
<td>C No 7</td>
</tr>
<tr>
<td>Position 2</td>
<td>A No 1</td>
<td>A No 1</td>
<td>A No 1</td>
<td>A No 3</td>
</tr>
<tr>
<td>Position 3</td>
<td>B No 5</td>
<td>B No 5</td>
<td>B No 5</td>
<td>B No 4</td>
</tr>
<tr>
<td>Position 4</td>
<td>A No 2</td>
<td>A No 2</td>
<td>C No 8</td>
<td>C No 8</td>
</tr>
<tr>
<td>Position 5</td>
<td>B No 6</td>
<td>B No 6</td>
<td>B No 4</td>
<td>B No 6</td>
</tr>
<tr>
<td>Position 6</td>
<td>A No 3</td>
<td>A No 3</td>
<td>A No 2</td>
<td>A No 1</td>
</tr>
<tr>
<td>Number of logs sawn at first stop</td>
<td>2908 spruce</td>
<td>5303</td>
<td>3120</td>
<td>2870</td>
</tr>
<tr>
<td>Number of logs sawn at second stop</td>
<td>5 spruce</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Number of logs sawn at third stop</td>
<td>5062 spruce</td>
<td>5303 + 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of logs sawn at fourth stop</td>
<td>5062 spruce + 1607 pine (20 May 2009)</td>
<td>5303 + 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Action after test</td>
<td>Regrinding</td>
<td>Accident + regrinding</td>
<td>Accident + regrinding</td>
<td>Accident + regrinding</td>
</tr>
<tr>
<td></td>
<td>Minor edge damages in grade B</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
the four teeth were photographed. The blades were then put back into production. After an additional period of time the blades were removed, inspected, ground and used again for sawing. The thickness of the sawn boards was measured at the top end, root end and in the middle of 10 boards for each occasion. The standard deviation of the thicknesses were calculated.

The normal grade used in Sweden for wintersawing is relatively soft and tough and was here denoted grade A, with a critical stress intensity factor $K_{IC} = 11$ MNm$^{-3/2}$ and hardness 1600 HV30 (ISO K10). Grade B was harder and more brittle, $K_{IC} = 9.5$ MNm$^{-3/2}$, hardness 1950 HV30 (ISO K01). Grade C was even harder and more brittle $K_{IC} = 9.5$ MNm$^{-3/2}$, hardness 1950 HV30 (ISO K01). These three grades were chosen out of six grades in an earlier preliminary laboratory test.

Four tests were conducted from March 2009 until August 2010 with the saw blades of different teeth material in different positions, see Table I. Both pine and spruce logs were sawn, in both frozen and unfrozen conditions. Blade numbers 1 to 3 were equipped with grade A teeth, blade numbers 4–6 had grade B teeth and blades 7–9 had grade C teeth.

Results

The standard deviations for board thicknesses are shown in Table II and Figure 4. The edge radii are shown in Table III and Figure 5a–c. Edge damage was not found after inspection after normal sawing in test 1 and test 5, except after test 1 where minor edge damage (small chips broken off) were found for grade B. Accidents that stopped test 2 and test 4 (jammed log in sawing machine) resulted in severe blade failure but were not of interest in this study.

Analysis, discussion and conclusions

Figure 4 and Table II show that the standard deviation of the thicknesses of the 10 measured boards was about 0.2 mm, and that this value was constant and not affected by the number of logs sawn.

Figure 5a–c and Table III show that edge radii for all grades in general increased with the number of logs sawn. Also that grade B and C resulted in the least amount of wear. Grade A presented the greatest wear as was expected before the tests. Since the data points were taken from different tests conducted on different occasions, for both pine and spruce logs

<table>
<thead>
<tr>
<th>Test 1</th>
<th>Stop 1</th>
<th>Stop 2</th>
<th>Stop 3</th>
<th>Stop 4</th>
<th>Stop 5</th>
<th>Stop 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>5062 logs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40 B</td>
<td>52 A</td>
<td>38 B</td>
<td>54 A</td>
<td>69 B</td>
<td>55 A</td>
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<tr>
<td>Test 2</td>
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<td>Stop 2</td>
<td>Stop 3</td>
<td>Stop 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5303 logs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60 A</td>
<td></td>
<td></td>
<td></td>
<td>35 B</td>
<td></td>
</tr>
<tr>
<td>Test 4</td>
<td>Stop 1</td>
<td>Stop 2</td>
<td>Stop 3</td>
<td>Stop 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 logs</td>
<td>20 C</td>
<td>16 A</td>
<td>30 B</td>
<td>20 C</td>
<td>30 B</td>
</tr>
<tr>
<td></td>
<td>26 C</td>
<td>27 A</td>
<td>33 B</td>
<td>26 C</td>
<td>33 B</td>
<td>27 A</td>
</tr>
<tr>
<td>Test 5</td>
<td>Stop 1</td>
<td>Stop 2</td>
<td>Stop 3</td>
<td>Stop 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2870 logs</td>
<td>43 C (not</td>
<td>48 A</td>
<td>43 B</td>
<td>43 C (not</td>
<td>48 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>reground)</td>
<td></td>
<td></td>
<td>reground)</td>
<td></td>
</tr>
</tbody>
</table>
and for both frozen and unfrozen wood, the edge radii did not consistently increase with the number of logs sawn. The edge radii at the start after grinding were not measured except for test 4, and were possibly different in the other tests. There was no significant edge damage to the cutting edges (chips broken off) for any of the grades. The edge radii directly after grinding were controlled in test 4 (see Table III). The values were 16, 30 and 30 μm for grades A, B and C respectively, which indicates that cemented carbide teeth are difficult to grind to a high degree of sharpness (i.e. a small edge radius) and that especially the harder the grades are the more difficult to grind they are. It was concluded that it is possible to use the harder grades B and C for wintersawing conditions instead of the commonly used grade A without risking significant edge damage.

Acknowledgements

The authors express their gratitude to the European Regional Development Fund, Objective 2, Northern Sweden via Tillväxtverket (the Swedish Agency for Economic and Regional Growth) and Vinnova (the Swedish Agency for Innovation Systems) for financial support.

References

Paper IV
Cutting Forces for Wood of Lesser Used Species from Mozambique

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\textsuperscript{2}Department of Wood Science and Technology, Luleå University of Technology, SE-931 87, Skellefteå, Sweden

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ABSTRACT

The present study was aiming at measuring cutting forces for wood of lesser used species from Mozambique such as \textit{Acacia nigrescens} Oliv (Namuno), \textit{Pericopsis angolensis} Meeweven (Muanga), \textit{Pseudolachnostylis maprounaefolia} Pax (Ntholo) and \textit{Sterculia appendiculata} K. Schum (Metil). Another aim was to use an expeditious method to compare performance of the species when cut. A machinability index calculated using Digraph and Matrix Methods was used for ranking the species. The density was measured with a Siemens CT scanner in 16 slices per sample. Two different cutting tools 20° and 30° rake angle were used. Before cutting, the edge radius of the tools was measured. Main cutting force in 90°–90° and 90°–0° cutting directions were measured by piezoelectric gauge. The results of the experiments show that cutting forces followed normal trends to increase with density and decrease with increasing rake angle. The most difficult species to be machined was Namuno, whereas the easiest species to be machined was Metil.

INTRODUCTION

Mozambique is an African country with vast forestry resources, including native tropical wood species with high commercial value that are recognised internationally. Thus, exportation of timber is a commercial option of considerable value for the country. The Mozambican forest comprises 118 usable wood species but only 15 of these with already known properties and uses are exploited due to their high commercial value in selective logging systems, DNFFB \cite{1}. In fact, in the Mozambican forests only a few commercial species are harvested because of lack of technical information and less popularity in the market place of many others wood species.
Evidence of the selective logging practices can be found in a report from the Ministry of Agriculture stating that only three wood species represented 78% of the total wood exploited in Mozambique in 2004, Marzoli [2]. Other reasons for research on Mozambican lesser used (LU) and unexploited wood species are the need to increase the resource base in the country and reduce the pressure on the better known wood species. Characterization of anatomical, chemical, physical and mechanical features of selected native species has started in order to find their end uses, Uetimane Jr et al., Lhate et al. and Ali et al. [3, 4, 5, 6].

Basic aspects of machining such as chip formation, surface quality, and tool life can be better understood with knowledge of the cutting forces needed during orthogonal cutting, Woodson [7]. Some cutting forces models have been elaborated, to understand the mechanical behaviour of the materials tested and others to characterise the machinability of different wood materials, Marchal et al. [8].

The present study was aiming at measuring cutting forces of LU species such as metil, muanga, namuno and ntholo. Another aim was to use an expeditious method to compare performance of the species when cut. The most difficult species to be machined was Namuno, whereas the easiest species to be machined was Metil.

MATERIAL AND METHODS

Sites and Sampling

Scientific and vernacular names of the species considered in this study were as given in table 1. Two trees per species were obtained from open dry forest subjected to frequent fires set by local people as a result of shift cultivation and traditional hunting routines in the sampling stand. Each stem of the considered species was cut to three logs of 1.2 m length depicted as bottom, middle and top log. All logs were through-and-through sawn to 80 mm thick planks.

<table>
<thead>
<tr>
<th>Scientific name</th>
<th>Vernacular name</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acacia nigrescens</em></td>
<td>Namuno</td>
<td>Leguminosae</td>
</tr>
<tr>
<td><em>Pericopsis angolensis</em></td>
<td>Muanga</td>
<td>Fabaceae-Faboideae</td>
</tr>
<tr>
<td><em>Pseudolachnostylis</em></td>
<td>Ntholo</td>
<td>Bopyroidea</td>
</tr>
<tr>
<td><em>Pseudolachnostylis</em></td>
<td><em>maprouneafolia</em></td>
<td></td>
</tr>
<tr>
<td><em>Sterculia appendiculata</em></td>
<td>Metil</td>
<td>Sterculiaceae</td>
</tr>
</tbody>
</table>

Note: a lesser used species  b emerging species

Samples Preparation

All samples for cutting forces experiments were taken from butt log that was cut 0.7- m from the ground. A main plank was through-and-through sown from each butt log for samples. Smaller planks sized 80x80x1200 mm were air dried and then cut to 70x70 x 160 mm. In each end of the sample, 7 kerfs were cut either using a tool with rake angle 20º or 30º, for rip sawing (90º–90º) and planing (90º–0º), Figure 1. Cutting directions were as defined in [8].
All samples contained only mature heartwood. This study considered only main cutting force.

**Density Measurement**

Wood density measurements were made by a computer tomography scanner (CT-scanner) (Table 2) as made by Lindgren et al. [10]. The depth of each kerf was adjusted to cover the thickness of a slice in order to allow replication or repetition of the experiments. Density was read once per kerf (7 times per cross section) using Image J software, version 1.42. Tomograph images were also used to check for defects in samples. All kerfs were cut in slices free of defects.

**Table 2 - Grey scales CT - images showing density level of LU species from Mozambique**

<table>
<thead>
<tr>
<th></th>
<th>Metal</th>
<th>Nholo</th>
<th>Muanga</th>
<th>Nanuno</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1101</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>936</td>
<td></td>
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<tr>
<td>772</td>
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</tr>
<tr>
<td>608</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>443</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Tool Edge Radius Measurement**

Before each cutting of two samples (one sample per tree), the edge radius of the tool was measured. The measurements were performed with the aid of Leica Qwin Microscope. The microscope was endowed with the capacity of digital image capturing. Tool edge radius was designed to be equal to 25 μm, (Figure 2).
Wearing Tests

The four species, namuno, muanga, ntholo and metil were also tested for tool wear properties by Cristóvão et al. [11]. The findings on tool wear were used in the results and discussion of current study (Table 3). The values on tool wear radius were obtained after a cutting length of 4896 m.

Cutting Forces Measurement

Cutting forces were measured on 8 samples selected from 4 wood species (two samples per species and one sample per tree) using piezoelectric sensors. Cutting forces were read 11 times per kerf (77 times per cross section). Schematic view of the equipment and cutting conditions were as given in Figure 3 and Table 3. Main force measurement followed the methodology by Axelsson et al. [12].

![Figure 3 - Schematic view of the measuring equipment](image)

**Table 3 – Cutting parameters**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Value</th>
<th>Designation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting direction</td>
<td>90°-90°, 90°-0°</td>
<td>Cutting speed</td>
<td>15 m/s</td>
</tr>
<tr>
<td>Chip thickness</td>
<td>0,15 mm</td>
<td>Kerf width</td>
<td>3.9 mm</td>
</tr>
<tr>
<td>Rake angle</td>
<td>20° and 30°</td>
<td>Moisture content</td>
<td>6-9%</td>
</tr>
<tr>
<td>Edge radius</td>
<td>25 μm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The data on cutting forces and density measurements were collected and analysed using SAS, Version 9.2 [13].

Digraph and Matrix Methods for Machinability Evaluation

In order to compare species’ performance when cut, a machinability index was used. The machinability index was calculated using Digraph and Matrix methods. Machinability attributes considered in current study were as given in Figure 4, tool wear (TW), cutting forces in direction 90°-0° (CF1) and cutting forces in direction 90°-0° (CF2).
In current work every attribute was considered non-beneficial to machinability. Eq. 1 gave matrix representation of machinability attributes taking into account the number of variables in present work (3 variables). Eq. 2 was the expression of machinability function considering the dimension of the matrix in Eq. 1. The permanent of matrix $A$, i.e., $\text{per}(A)$ is defined as universal machinability function. The permanent is a standard matrix function and is used in combinatorial mathematics, Rao & Ghandi [14].

The values of attributes $D_i$ had to be normalized in order to use the scale, from 0 to 10. For non-beneficial attributes, the attribute value 0, on the scale 0 to 10, was assigned to the worst range value $D_{iu}$ and the value of 10 was assigned to the best range value $D_{il}$. The other intermediate values $D_{ij}$ of the machinability attribute were assigned values in between 0 and 10 as per the following:

$$\begin{align*}
D_{iu} &= 10\left[1 - \frac{D_i}{D_m}\right] & \text{for } D_{iu} = 0 \\
D_{ij} &= 10\left[\frac{(D_m - D_{ij})}{(D_m - D_i)}\right] & \text{for } D_{ij} > 0
\end{align*}$$

The relative importance between $i$, $j$, and $j$, $i$ was distributed on the scale 0 to 10 and was defined as:

$$a_{ij} = 10 - a_{ji}$$

**RESULTS AND DISCUSSION**

Overall, measurements of density and main cutting forces showed differences between species. The results of the experiments showed that cutting forces followed normal trends to increase with
density and decrease with increasing rake angle. Cutting forces ranged from 80.98 N, for Metil, to 187.50 N, for Namuno, in direction $90^\circ$–$90^\circ$ and from 34.17 N to 69.59 N, for Metil and Namuno, respectively, in $90^\circ$–$0^\circ$ direction (Table 4). Density varied from 603 to 1112 kg/m$^3$, for Metil and Namuno, respectively (table 4).

**Table 4- Density, main cutting forces in $90^\circ$–$90^\circ$ and $90^\circ$–$0^\circ$ and tool wear radius of lesser used species from Mozambique. Standard deviation (STD) shown in parentheses**

<table>
<thead>
<tr>
<th>Species</th>
<th>Density Kg/m$^3$</th>
<th>$F_{90^\circ-90^\circ}$ (N)</th>
<th>$F_{90^\circ-0^\circ}$ (N)</th>
<th>Tool wear radius * (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metil</td>
<td>603.75</td>
<td>80.98</td>
<td>34.17</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(16.32)</td>
<td>(6.92)</td>
<td>(5.61)</td>
<td></td>
</tr>
<tr>
<td>Muanga</td>
<td>925.50</td>
<td>117.22</td>
<td>50.56</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>(14.26)</td>
<td>(7.73)</td>
<td>(4.29)</td>
<td></td>
</tr>
<tr>
<td>Ntholo</td>
<td>751.18</td>
<td>102.57</td>
<td>43.35</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>(28.09)</td>
<td>(8.59)</td>
<td>(3.26)</td>
<td></td>
</tr>
<tr>
<td>Namuno</td>
<td>1112.26</td>
<td>187.59</td>
<td>69.59</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>(13.66)</td>
<td>(8.79)</td>
<td>(8.76)</td>
<td></td>
</tr>
</tbody>
</table>

A thorough explanation of Digraph and Matrix Method has been reported in literature, Rao & Ghandi [14].

It is standard to use density to estimate cutting forces, however it is well known that sometimes, two species with the same density need very different cutting forces, or species with completely different densities need similar cutting forces, Eyma et al. [15, 16]. The range of cutting forces earned by Metil partially overlaps with the range of Scots Pine by Axelsson et al. [12]. Recorded differences are due to differences in density.

**Table 5- Machinability attributes values ($D_i$)**

<table>
<thead>
<tr>
<th>Species</th>
<th>Tool wear radius</th>
<th>Cutting forces $90^\circ$–$0^\circ$</th>
<th>Cutting forces $90^\circ$–$90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metil</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Muanga</td>
<td>7.37</td>
<td>5.37</td>
<td>6.57</td>
</tr>
<tr>
<td>Ntholo</td>
<td>0</td>
<td>7.41</td>
<td>7.97</td>
</tr>
<tr>
<td>Namuno</td>
<td>8.95</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 6 - Relative importance values of machinability attributes ($a_i$)**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Cutting forces $90^\circ$–$90^\circ$</th>
<th>Cutting forces $90^\circ$–$0^\circ$</th>
<th>Tool wear radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting forces $90^\circ$–$90^\circ$</td>
<td>-</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Cutting forces $90^\circ$–$0^\circ$</td>
<td>5</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Tool wear</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

The current study adopted the approach of Rao & Ghandi [14], for assignment of relative importance value for tool wear.
**Machinability Indexes and Ranking:**

<table>
<thead>
<tr>
<th>Species</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metil</td>
<td>1730</td>
</tr>
<tr>
<td>Muanga</td>
<td>788</td>
</tr>
<tr>
<td>Ntholo</td>
<td>478</td>
</tr>
<tr>
<td>Namuno</td>
<td>303</td>
</tr>
</tbody>
</table>

Machinability index was calculated by Eq. 2. The coefficients of relative importance $a_{ij}$ were object of subjective judgement for their assignment. In current work two machining process output variables were considered: cutting forces and tool wear.

The ranking of machinability showed that the easiest species to be machined was Metil and the most difficult species to be machined was Namuno. Namuno was highly penalized in terms of machinability due to its high cutting forces.

**Sensitivity Analysis**

The sensitivity analysis was aiming at judging the effect of relative importance values assignment on species ranking, since there was no consensual approach in literature about the assignment. The sensitivity analysis showed that the ranking was kept the same for the whole range of values for the relative importance coefficient.

**CONCLUSIONS**

The present study was aiming at determining cutting forces of LU species such as namuno, ntholo, metil and muanga. Another aim was to use an expeditious method to compare the performance of the species when cut. A machinability index calculated through Digraph and Matrix Method was used. The main findings of this work can be summarized as follows:

- Cutting forces followed normal trend to increase with increasing density;
- The most difficult species to be machined was Namuno, whereas the easiest species to be machined was Metil;
- Cutting forces earned by Namuno seemed to have been affected by anatomical features not measured in current study;
- Sensitivity analysis showed that in this study variation of relative importance coefficient affected only similarity between species, and not the ranking.

**ACKNOWLEDGMENTS**

Special acknowledgments and thanks are due to Swedish International Development Agency (SIDA), Department for Research Cooperation (SAREC) for funding the research project entitled “Improving Wood Utilization in Mozambique” in which this study is an integrant part. The authors would also like to thank the Universidade Eduardo Mondlane for providing this opportunity, Swedish University of Agricultural Sciences and Luleå University of Technology for supervision and hosting of the study. The authors express their appreciation to Birger Marklund for his indispensable assistance throughout the experiments.
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Paper V
Main cutting force models for two species of tropical wood

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2Department of Mechanical Engineering, Eduardo Mondlane University, Maputo, Mozambique

Abstract
The aim of the study was to evaluate the main cutting force for two species of tropical Mozambican wood and to develop predictive models. Cutting these hardwoods is difficult. Determination of cutting parameters is required to optimize cutting processes, machines and tools in the cutting operations. This determination would enable the forestry and wood sector to achieve higher financial results. Samples of a lesser-known wood species Pseudolachnostylis maprounaefolia (ntholo) and a well-known wood species Swartzia madagascariensis (ironwood) were machined in a test apparatus. A standard single saw tooth mounted on a piezoelectric load cell was used to evaluate the main cutting force. Data were captured using an A/D converter integrated with National Instruments LabVIEW software. The measured signals were recorded at a sampling frequency of 25 kHz. The experimental set-up used response surface methodology for developing predictive models. The experimental clearly determined the relationship between the main cutting force and edge radius, wood density, rake angle, chip thickness, moisture content (MC) and cutting direction (CD). Among the studied variables, chip thickness and CD had the highest effect on the main cutting force level while wood density, MC and rake angle had the lowest effect.

Keywords: Cutting force, Pseudolachnostylis maprounaefolia, Swartzia madagascariensis.

Introduction
Wood cutting forces have been investigated since the 1950s. Various approaches have been suggested for cutting force evaluation. Although a considerable amount of research has been carried out in this field, few studies have been made with respect to tropical wood species.

Comprehensive reviews on cutting force modelling for wood cutting have been conducted by Marchal et al. (2009) and Wyeth et al. (2009). They pointed out that tool material selections, tool life, quality of machined surfaces, chip formation, the geometry of the cutting tool edges and cutting conditions are closely related to the cutting forces.

Cutting forces have often been considered as the main output parameter for physical description of the cutting process. Other parameters, such as vibration, sound, temperature, cutting power, deformation, surface quality and chip quality, have normally been neglected (Marchal et al. 2009).

Eyma et al. (2004) presented a model of cutting forces for 13 tropical wood species in milling processes. The model considers mechanical (hardness, fracture toughness, shearing, compression parallel to the grain) and physical (specific gravity, shrinkage) parameters.

Porankiewicz et al. (2007) developed a cutting forces model for two low-density wood species using cutting edge dullness, average angle between wood grains and cutting plane, cutting speed, feed per edge and moisture content (MC) as parameters. Scholz et al. (2009) presented an integrated model for prediction of wood cutting forces. Detailed information concerning the mechanics of chip formation and factors that contribute to cutting forces and work required for cutting was given by Wyeth et al. (2009). Goli et al. (2009) analysed and discussed the dependence of the cutting forces with respect on the cutting geometry.

In the past, forest harvesting in Mozambique has been extremely selective and mostly confined to a
of these selective harvesting practices and recently has been backing the promotion and utilization of lesser-known species to promote sustainable use of forest resources (DNTF 2008). Recently, Lhate et al. (2011) have measured the cutting forces for four lesser-known species from Mozambique. Difficulties experienced by tropical sawmill operators are related to cutting tool design, tool material, machine operation and maintenance of the cutting tools (Loehnertz and Cooz 1998). A determination of wood cutting parameters may facilitate optimization of processes, machines and tools when cutting these hard-to-cut woods. The government believe that this optimization will in turn contribute to increasing financial results in the forestry and wood sectors.

The aim of this study was to evaluate the woodcutting forces of two tropical species and their relation to some important parameters, such as edge radius (r), wood density (D), rake angle (α), chip thickness (t), moisture content (MC) and cutting direction (CD).

Material and methods

Cutting force measurement

The cutting force measurements were performed on special equipment, developed at Luleå University of Technology, fitted with a fixed single carbide symmetric standard tooth (Figure 1a). The cutting forces were measured in the main (F_P), normal (F_N) and lateral (F_L) directions (Figure 1b). A rotating arm moved a wood block past a cutting tool in a 1 m diameter circle. A detailed description of the basic structure of the apparatus was reported earlier by Axelsson et al. (1993).

The edge condition and edge radius of each tool were evaluated under an optical microscope (Figure 2). Data on cutting forces are computed using National Instruments LabVIEW (Anon 2005). During the experiments, measuring signals were recorded with a sampling frequency of 25 kHz. The cutting force during wood machining does not exhibit a steady behaviour. Figure 3 shows a sample plot of cutting-force data. In this study, the values of the cutting forces are calculated as an average value of the force level that is roughly the horizontal part of the main force curve. In this study only the main cutting force will be analysed because of its importance in determining the power consumption, tool geometry and tool material when cutting these hard-to-cut woods.

Wood samples

Two wood species, ironwood (*Swartzia madagascariensis*) and ntholo (*Pseudolachnostylis maprouneafolia*) were studied. Four trees per species were harvested in the Northern part of Mozambique, latitude 12° 45’ 0” S and longitude 39° 30’ 0” E, with annual rainfall between 1400 and 1800 mm. All samples were heartwood taken from butt logs. No significant defects, such as compression wood and knots were visible in the samples. Butt logs were through-and-through sawn. The test samples were prepared in the dimensions of 160 mm in the...
tangential direction, 70 mm in radial direction and 70 mm in the longitudinal direction for the CD s $0^\circ / C_1 90^\circ$ and $90^\circ / C_1 0^\circ$ and 70 mm in the tangential direction, 70 mm in radial direction and 160 mm in the longitudinal direction for the CD s $90^\circ / C_1 90^\circ$ and $0^\circ / C_1 90^\circ$. Each test sample was denoted with a code consisting of a number and a letter describing the direction of cutting and the MC, respectively. All experiments were conducted at room temperature of 20°C.

Measurement of density and MC

The evaluation of average wood density was made by computer tomography scanning (Figure 4) as described by Lindgren et al. (1992). The density given is the average density of the kerf material. After the wood density evaluation, MC was determined by a standard oven-dry method at a temperature of 103°C.

Experimental design

The experimental set-up was made by MODDE (Anon 2008). A D-optimal design was used, with three levels and six parameters (one uncontrollable). The parameters to be studied and the value of each level are shown in Table I. Wood density was an uncontrollable variable. The chosen design comprised 32 runs per species. The number of samples was eight per tree. All sets of experiments were conducted to determine the relation between the main cutting force and various wood machining parameters. The main cutting force reported is the average force for 15 cuts for each cutting condition repeated on the same sample. The cutting width was constant at 3.9 mm and the clearance angle was constant at $15^\circ$. For comparison purpose, the values of the main cutting forces were expressed per edge width.

The CD for the tested tropical species was mode I (Figure 5) for CD s $90^\circ - 90^\circ$ and $0^\circ - 0^\circ$ and mode II (Figure 5) for CD $90^\circ - 0^\circ$. It has been reported by Koch (1964), that these directions minimize the confounding effect of growth rings of varying density although for the tested tropical wood species the differences were negligible.

To describe the relationship $F_0 = f(a, r, t, D, MC, CD)$ a linear and a non-linear model with and without interaction were analysed. A partial least squares method was applied to build and evaluate

![Figure 3. Example of signal measurement of a single cut.](image)

![Figure 4. Greyscale digital image of the wood density.](image)

![Table I. Attribution of the parameters levels.](table)

<table>
<thead>
<tr>
<th>Level</th>
<th>Chip thickness ($t$) mm</th>
<th>Rake angle ($a$) degree</th>
<th>Edge radius ($r$) μm</th>
<th>Moisture content (MC) %</th>
<th>Cutting direction (CD) radian</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>10</td>
<td>5</td>
<td>8</td>
<td>(90 - 90') $0^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>0.50</td>
<td>20</td>
<td>25</td>
<td>24</td>
<td>(90 - 0') 1.57</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>30</td>
<td>50</td>
<td>40</td>
<td>(0 - 90') 3.14</td>
</tr>
</tbody>
</table>

![Figure 4. Greyscale digital image of the wood density.](image)

![Figure 5. Cutting directions according to Kivimaa (1950): (a) Mode I.](image)

![Figure 5. Cutting directions according to Kivimaa (1950): (b) Mode II.](image)
where and predicted variance, $Q^2$, were used to evaluate the model at a confidence level of 0.95. The cutting speed has no effect on cutting force values (Kivistäm 1950). Thus, a constant cutting speed of 15 m/s was adopted.

The order of the experimental runs was not randomized for practical reasons: they would take much time; setting the unit would incur great cost as would resetting of the machinery.

Results

The results allow establishment of relationships between the main cutting force generated during the cutting of the selected hard-to-cut wood species and the various wood cutting parameters.

The predictive models established above are given by:

\[
F_P{\text{Ntholo}} = -6.55 - 0.08 \cdot z + 0.18 \cdot r + 0.03 \cdot D
+ 28.94 \cdot t + 0.10 \cdot MC
- 4.22 \cdot CD \quad \text{N mm}^{-1}
\]

\[
F_P{\text{Iron wood}} = 8.16 - 0.18 \cdot z + 0.17 \cdot r + 0.01 \cdot D
+ 31.21 \cdot t - 0.10 \cdot MC
- 4.37 \cdot CD \quad \text{N mm}^{-1}
\]

where $z =$ rake angle, degree, $r =$ edge radius, $\mu$m, $D =$ wood density, kg m$^{-3}$, $t =$ chip thickness, mm, $MC =$ moisture content,%, $CD =$ cutting direction, radian.

The regression coefficients of the two models (1) and (2) are unscaled and refer to the original measurement scale of the factors. They are difficult to interpret because different factors are on different scales. For interpretation purpose the models (1) and (2) are shown with scaled and centred coefficients in Equations (3) and (4). Those scaled and centred coefficients make it possible to compare and see the impact of each factor within each model.

\[
F_P{\text{Ntholo}} = 1.94 - 0.04 \cdot z + 0.21 \cdot r + 0.24 \cdot D'
+ 0.66 \cdot t' + 0.09 \cdot MC'
- 0.35 \cdot CD' \quad \text{N mm}^{-1}
\]

\[
F_P{\text{Iron wood}} = 2.23 - 0.10 \cdot z + 0.21 \cdot r' + 0.07 \cdot D'
+ 0.77 \cdot t' - 0.09 \cdot MC'
- 0.39 \cdot CD' \quad \text{N mm}^{-1}
\]

There is no non-linear model in this article.

Figure 6 illustrates that the models for both species in an acceptable way are able to predict the main cutting force for almost all runs that were carried out.

The explained variance for the ironwood model was the same as that for the ntholo model ($R^2 = 0.89$); however, the ability to predict new data for ntholo ($Q^2 = 0.83$) was higher than for ironwood ($Q^2 = 0.81$).

Discussion

The difference between $Q^2$ and $R^2$ was small statistically and the levels of $Q^2$ here indicate fairly strong and valid models. There is no model that includes interaction between variables, so the assertion about interaction between variables is groundless.

The highest main cutting forces for these hard-to-cut woods were 64.51 N mm$^{-1}$ for ntholo and 58.38 N mm$^{-1}$ for ironwood. It is quite difficult to compare cutting forces as attempted in this work due to different cutting conditions, densities, and so on. The main cutting forces recorded by Woodson

![Figure 6. Observed and predicted main force: (a) ntholo; (b) ironwood.](image-url)
were 3.86 and 7.53 N mm\(^{-1}\) for yellow poplar (Liriodendron tulipifera L.) and Southern red oak (Quercus falcata Michx.), respectively. Lhate et al. (2011) measured cutting forces of four tropical species. Among the tested wood species the largest average main force recorded was 48.1 N mm\(^{-1}\) cutting dry namuno (Acacia nigrescens). Eyma et al. (2004) also measured cutting forces for 13 tropical wood and found that the largest value was 6.14 N mm\(^{-1}\) cutting Boco (Bocoa prouacensis Aubl.). The highest values of the main force observed during the cutting tests of these dense woods can be used when designing machine and tool, and when selecting material for tools. Thus, a sustainable processing can be achieved.

The geometry of the cutting tool plays an important role when cutting wood. Figure 7 shows that the main cutting force increases when the edge radius increases. A similar finding was reported by Kivimaa (1950), Franz (1958), and Axelsson et al. (1993). Figure 7 also illustrates that the main cutting force decreases with increased rake angle. However, this effect is smaller than that of edge radius. The effect of the rake angle on main cutting force is also shown by Kivimaa (1950), Franz (1958), and Axelsson et al. (1993). They report that at low or negative rake angles cutting force is high, and at high rake angles the cutting force is decreased. The rake angle had higher impact on main cutting force when testing ironwood than when testing ntholo.

When using different cutting conditions, the tool geometry which generates the least force is expected to be the most effective in cutting when the aim is to use least power. From Figure 7, it may be seen that the largest rake angle, \(a = 30^\circ\), combined with the sharpest tool, \(r = 5\mu m\), gave the least main cutting force. However, larger rake angles reduce the strength and fracture toughness of the tool as well as tool life.

In this study, wood density was used as an important indicator of wood stiffness, strength and hardness. Its advantage is that it can be measured quickly and without great expense.

The experimental results showed that ntholo samples had the lowest density and the highest density variability of the samples studied \((D_{\text{min}} = 700.20 \text{ kg m}^{-3}, \ D_{\text{max}} = 1112.27 \text{ kg m}^{-3})\). The sample with the greatest density was of the ironwood species \((D_{\text{max}} = 1251.98 \text{ kg m}^{-3})\) (Figure 8).

For the same experimental set-up, the values of the main force for the lesser-known species (ntholo) were slightly higher than for the well-known species (ironwood). Ratio of main cutting force and wood density suggested that differences in main cutting force are due to factors other than wood density. It has been recently reported by Cristóvão et al. (2011) that ntholo causes the cutting tool to wear quickly (and tool wear is correlated to cutting force) due to the high content of silica although it has low density.

Figure 8 clearly indicates that the main cutting force increases with increased wood density. This is also in agreement with Kivimaa (1950), McKenzie (1961), and Koch (1964). The wood density had higher impact on the main cutting force for ntholo than for ironwood. Also, in Figure 8, cutting wood with lower chip thickness reduces the main cutting force. However, it has been pointed out by Gronlund (2004) that low values of chip thickness greatly increase the specific cutting work.

Figure 9 illustrates the influence of CD and MC on the values of main cutting force. The experimental results showed that the three directions generate different levels of main cutting force. The highest main cutting force occurs with a CD of \(90\text{–}90^\circ\) (0 rad). The smallest main cutting force occurs with a CD of \(0\text{–}90^\circ\) (3.14 rad). These results agree with studies made by Kivimaa (1950), McKenzie (1961), and Koch (1964). Also, in

![Figure 7](image-url) Relationship between main force on edge radius and rake angle: (a) ntholo, (b) ironwood.
Figure 9, it seemed reasonable to expect that the main force would decrease with increased MC, but for ntholo a different pattern of results was observed. This might be associated with the small differences between the levels of MC used in this test. However, Chardin (1954) suggested that the force decreases when cutting wood with high MC, but this did not apply for high density woods. Furthermore, it has also been reported by Loehnertz and Cooz (1998) that the effect of MC on main force might vary with the species studied. No attempt was made to predict the main force of both species with one joint model due to the different effect of the MC.

**Industrial applications**

The relationship between the main cutting force and wood cutting parameters has important implications for tropical sawmillers. Knowledge and awareness of this relationship facilitates improved cutting performance. However, machining properties are usually a compromise between the power consumption, the quality of finished surface and the rate of wear of the cutting tool. This study suggests that cutting these tropical wood species may be improved by such measures as adjusting chip thickness, rake angle and edge radius. These adjustments must be carried out simultaneously if maximum benefit is to be achieved. A significant difference existed between the force levels generated at three different chip thicknesses. Small changes in chip thickness greatly affect the main cutting force (Figure 8). This implies that a small chip thickness of 0.15 mm should be chosen but this leads to low feed speed and consequently low levels of productivity and high wear per produced volume. For the efficient processing of the wood species tested, edge radius of 5–25 μm should be chosen, which leads to a low main cutting force. Of the rake angles tested 20° was deemed to be optimal compared with rake angles of 10° and 30°, which is a good compromise between power consumption and the strength of the cutting edge.
The following conclusion may be drawn from the results:

- Wood density alone was not good estimator of main cutting force for the tested wood species.
- Wood density, MC and rake angle showed the lowest effect on the main cutting force in all three CDs for both species.
- The chip thickness had the greatest impact on the main cutting force for both species.
- The effect of MC on the main cutting force did not show the same pattern for both species.
- A lower rake angle generated a higher main cutting force for both species.
- The effect of density and rake angle is slightly different for ntholo and ironwood. Rake angle effect was higher for ironwood, whereas density effect was higher for ntholo and vice versa.
- The greatest main cutting force was found at a CD 90–90° for both species.
- The lowest main cutting force was found at a CD 0–90°.
- When processing these hard-to-cut woods it is necessary to use small chip thickness and use sharp edge radius to achieve low cutting force.

The relation between normal force and wood cutting parameters will be considered in future research.

References


Main cutting force models 149

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Paper VI
Industrial Sawing of *Pinus sylvestris* L.: Power Consumption

Luís Cristóvão,* Mats Ekevad, and Anders Grönlund

The wood industry continues to strive to reduce production costs and increase productivity to remain competitive. Knowledge of the effect of wood cutting parameters on power consumption could increase energy efficiency, reducing operating costs and increasing profitability. Measuring power consumption also provides information about other variables, such as tool edge wear, occurrence of catastrophic failures, and other parameters that affect the quality of the sawn boards and the momentary efficiency of the breakdown process. In this work, power consumption during sawing of *Pinus sylvestris* L. using a double arbor circular saw was investigated. Both climb-sawing and counter-sawing were considered. The experiments were carried out under normal production circumstances in two Swedish sawmills. The relationship between cutting parameters and theoretical power consumption was investigated. The experimental power consumption increased by 11 to 35% during an 8-h shift, mainly due to an increase in the tooth radius. Additionally, this study showed that climb-sawing consumed more power than counter-sawing.

Keywords: Climb-sawing; Counter-sawing; Cutting force; Power consumption

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INTRODUCTION

Large numbers of logs are machined in sawmills every day, and the prediction of power consumption is becoming an increasingly important economic factor throughout all processing stages. Understanding the effect of wood cutting parameters on power consumption could increase energy efficiency, reduce operating costs, and enhance profitability.

Predicting power consumption and cutting forces is very complex, with many interacting phenomena. It requires a fundamental understanding of the interaction between wood properties, the cutting tool, and machining parameters. The primary issue that confounds machining research is the extreme anisotropy and heterogeneity of wood. The cutting force direction and its magnitude also change due to the cutting tool rotation. Cutting is interrupted as each tooth enters and leaves the workpiece.

In Sweden, modern sawmills normally use double arbor circular sawblades for the resaw (deal saw). A resaw on a modern high-production saw line has an installed power in the range of 1 MW. Compared to a single arbor circular sawblade, a double arbor blade offers the advantage of increasing the sawing accuracy and reducing the kerf losses to minimize sawdust waste. Double arbor saws are also able to run at high feed speeds with small variations of accuracy. Depending on the relative motion between the log and the circular sawblade, two feeding modes can be observed: counter-sawing and climb-sawing. The selection of feeding mode has important effects on the mechanics of the
process, such as the type of chip, surface quality, mode of chip transportation, cutting forces, power consumption, and tool wear.

Important works for predicting power consumption were written by Aguilera and Martin (2001) and Kováč and Mikleš (2010). Aguilera and Martin (2001) predicted the power consumption of climb-sawing and counter-sawing by measuring the main cutting force and determined power consumption from the known cutting speed. Kováč and Mikleš (2010) determined the power consumption of the wood cutting process using circular saws and studied the influence of different cutting tool geometries. Although much attention has been given to developing models using a single cutting tool, little is known about power consumption using double arbor circular sawblades.

The aim of this study was to analyze how different geometrical parameters affect the power consumption in a double arbor circular sawblade during sawing of Pinus sylvestris L. Another aim was also to compare how well theoretical calculation can mimic measurements in full industrial production.

THEORETICAL BACKGROUND

Mechanics of the Sawing Process

The power consumption when cutting with a circular sawblade is cyclic and depends on the position angle of the tooth, \( \phi \) (Fig. 1).

![Fig. 1. Cutting zone for counter-sawing (\( \phi_1 \) = entry angle, \( \phi_2 \) = exit angle, \( KH \) = angle between the cutting speed vector and the wood grain)](image)

The momentary power \( P_i \) is given by,

\[
P_i = \frac{dE}{dt}
\]

where \( E \) is the energy and \( t \) is the time. For a circular sawblade rotating at angular frequency \( \omega \), the tooth engaged in the cutting zone repeats cutting after a time interval of \( 2\pi/\omega \), which is denoted \( T \), the period required to make one complete cycle. Thus, the total energy per revolution is the result of the following integral:

\[
E_{\text{total}} = \int_0^T P_i \cdot dt = \int_0^{2\pi/\omega} \frac{P_i}{\omega} \cdot d\phi
\]
If the total number of teeth engaged is \( z \) and the increment is \( \Delta \phi = 1^\circ \), the total energy per revolution can be approximated:

\[
E_{\text{total}} = z \sum_{i=1}^{360} \frac{P_i}{60} \Delta \phi
\]

Substituting this result in Eq. 1, the following can be obtained,

\[
P_{\text{total}} = \frac{z \cdot n}{360} \sum_{i=1}^{360} P_i
\]

where \( n \) is the number of circular sawblades in the arbor. The momentary power \( (P_i) \) is computed according to the general laws \((\text{force} \times \text{velocity})\) with an additional term describing the energy needed for the chip acceleration as described by Koch (1964) and Orlowski et al. (2013),

\[
P_i = F_{pi} \cdot v_i + \frac{H \cdot k \cdot S \cdot d \cdot v_i^2}{2}
\]

where \( F_{pi} \) is the main cutting force \((\text{N})\), \( H \) is the depth of the cut \((\text{mm})\), \( S \) is the feed speed \((\text{m/min})\), \( v_i \) is the cutting speed \((\text{m/s})\), \( k \) is the saw kerf width \((\text{mm})\), and \( d \) is the wood density \((\text{kg/m}^3)\).

In wood machining, there are three different approaches used to model the main cutting force. Kivimaa (1950) and Scholz et al. (2009) calculated the main cutting force based on specific cutting resistance. Orlowski et al. (2013) developed a cutting force model based on modern fracture mechanics. Axelsson et al. (1993) and Cristóvão et al. (2011) established a predictive model using multivariate methods such as multiple linear regression and partial least squares regression. In order to calculate \( P_i \) and proceed with the modeling operations, \( F_{pi} \) is needed and it can be computed according to Equation 6 proposed by Axelsson et al. (1993),

\[
F_{pi} = -7.37 + \delta \alpha - (0.38 \cdot d8 - 224.5 \cdot \alpha) + 15.61 \cdot KH - 2.6 \cdot KH^2 + 1.31 \cdot r + 0.2 \cdot v_i + U \cdot (0.3 \cdot KH - 0.01 \cdot T)
\]

where \( \alpha \) is the rake angle \((\text{radian})\), \( \delta \alpha \) is the average chip thickness \((\text{mm})\), \( r \) is the edge radius \((\mu \text{m})\), \( d8 \) is the average density at 8% of moisture content \((\text{kg/m}^3)\), \( T \) is the temperature \((^\circ \text{C})\), \( KH \) is the grain angle \((\text{radian})\), and \( U \) is the moisture content \((\%)\).

Figure 1 illustrates the angle between the wood grain and the cutting speed vector. The equation 6 was used to predict the main cutting forces when cutting Scots pine with kerf width 4.25 mm. To extend the range of application, the Equation 6 was multiplied by the ratio of tested saw kerf width \( k \) to 4.25 as shown in Equation 7.

\[
F_{pi} = (-7.37 + \delta \alpha - (0.38 \cdot d8 - 224.5 \cdot \alpha) + 15.61 \cdot KH - 2.6 \cdot KH^2 + 1.31 \cdot r + 0.2 \cdot v_i + U \cdot (0.3 \cdot KH - 0.01 \cdot T)) \cdot \frac{K}{4.25}
\]

Cristóvão et al. (2013). “Sawblade power consumption.” BioResources 8(4), 6044-6053. 6046
EXPERIMENTAL

Materials and Methods

The experimental tests were carried out under normal circumstances in two Swedish sawmills, named A and B. The tests were performed in the second saw for resawing (resaw). The resaw machine cuts two main boards (2ex) in sawmill B and three main boards (3ex) in sawmill A. The machined material in both sawmills was Scots pine (*Pinus sylvestris* L.). The cant heights were 154 mm and 206.5 mm for sawmills A and B, respectively. It has been reported by Sehlstedt-Persson (2008) that the green moisture content for Scots pine vary considerably between sapwood and heartwood; it is approximately 150% for sapwood and 40% in heartwood. Wood density, like moisture content, is extremely varied; it was measured from 550 kg/m$^3$ for sapwood to 980 kg/m$^3$ for heartwood by Esping (1992). Equation 7 made it possible to predict the main cutting force for a workpiece with average moisture content and density measured at 8% moisture content. Therefore, it was assumed in this study that the average green moisture content was 80% and the average green density was 840 kg/m$^3$. The wood density at 8% moisture content was calculated using volumetric shrinkage of 12.4% which resulted in $d_8=548$ kg/m$^3$. All experimental tests were carried out during summer at a temperature around 20 °C. One set of tests was conducted in each sawmill, as summarized in Table 1.

A double arbor saw with a horizontal arbor was used in the second saw (resaw) test for both sawmills. In sawmill A, the first sawblade to cut was the counter-saw (lower sawblades), while in sawmill B, the first sawblade to cut was the climb-saw (upper sawblades). The resaw machines were equipped with four motors: two for climb-sawing and two for counter-sawing. A schematic representation of the two sawmills is shown in Fig. 2.

The inserts of the circular sawblades for both sawmills were made of tungsten carbide, denoted 242. The cutting edges were sharpened with similar condition and carefully examined before the experiment to ensure the cutting edge was free of defects. A standard microscope was used to examine the edge radii of the cutting tools before and after the test. Edge radius tests were performed only in sawmill A. However, in sawmill B, the tool edge was sharp at the beginning of the test. Based on experience, the edge radius was assumed to be 5 μm at the beginning and 50 μm at the end of the test.
Table 1. Sawing Conditions in the Two Sawmills

<table>
<thead>
<tr>
<th>Cutting Parameters</th>
<th>Sawmill A</th>
<th>Sawmill B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawblade diameter, mm</td>
<td>540</td>
<td>510</td>
</tr>
<tr>
<td>Sawblade thickness, mm</td>
<td>2.6</td>
<td>2.9</td>
</tr>
<tr>
<td>Saw kerf width, mm</td>
<td>3.8</td>
<td>4.2</td>
</tr>
<tr>
<td>Rake angle, degree</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Gullet area, mm^2</td>
<td>519</td>
<td>432</td>
</tr>
<tr>
<td>Initial edge radius, μm</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Number of teeth</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Feed speed, m/min</td>
<td>119.2</td>
<td>64.0</td>
</tr>
<tr>
<td>Overlap between blades, mm</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Bite/tooth, mm</td>
<td>1.07</td>
<td>0.71</td>
</tr>
<tr>
<td>Blade rotation, rpm</td>
<td>3100</td>
<td>2500</td>
</tr>
<tr>
<td>Number of sawn logs</td>
<td>7669</td>
<td>6277</td>
</tr>
</tbody>
</table>

The experimental tests were performed during one shift, which lasted approximately 8 h, as shown in Fig. 3. The power consumption of a circular sawblade was measured using a Fluke 1375 Power Logger with the capability to measure average active power and maximum active power. The power consumption was measured separately for upper sawblades motor (climb-sawing) and lower sawblades motor (counter-sawing). Power consumption was recorded every 5 s for both sawmills. After recording, the logger was disconnected and the data were downloaded to a computer and reviewed.

For comparison purposes, only the average maximum active power was reported in this study. During sawing with a double arbor, the upper sawblades are usually not in perfect alignment with the lower sawblades on the other arbor. As result, a slight saw mismatch occurs in the sawn boards. The sawn boards were analyzed and the saw mismatch was measured in this study.

To understand the effects of the cutting parameters on power consumption, theoretical power consumption was modeled using Equations 4, 5, and 7 and then compared with the experimentally measured power. The calculation was made for a complete cycle in 1-degree increments of the cutting edge position. The chip thickness, main force, and power consumption were a function of the cutting edge position.

The program Microsoft Visual Basic C++ was used to build the models. The models also incorporated the effects of the saw kerf width, overlap, and saw mismatch between circular sawblades.

The cutting force model developed by Axelsson et al. (1993) was extended to apply other saw kerf width and used to estimate the power required to cause a failure (Equation 7). Saw mismatch was incorporated by adding the cutting zone, which is shadowed by the first sawblade (Fig. 4). The saw kerf width used to calculate power consumption in the overlap zone was the value of mismatch. A change in the overlap between sawblades affected the angle of tooth entry and exit, the path length of tooth engagement, the number of teeth engaged, etc. (Fig. 4).

To understand the effects of overlap between sawblades on theoretical power consumption, only the second sawblade to cut (climb-sawing for sawmill A and counter-sawing for sawmill B) was varied in the distance between workpiece and axis of sawblades rotation (Fig. 4).
RESULTS AND DISCUSSION

The experimental and predicted results of power consumption, as a function of edge radius, assuming that wear is linear, are presented in Fig. 5. The idling power was 8.5 kW in sawmill A and 7.2 kW in sawmill B. For both sawmills, an increase in edge radius resulted in higher power consumption.

Fig. 3. An example of the measurement of maximum and average power consumption

For comparison purposes between experimental and theoretical power consumption, the idling power was subtracted from the experimental power consumption for each sawmill.

Fig. 4. Mismatch zone and overlap between sawblades: (a) sawmill A, (b) sawmill B

Fig. 5. The change in power consumption depending on edge radius: (a) sawmill A, (b) sawmill B (mismatch=0)
The predicted model showed lower power consumption than the experimental. The differences between the predicted and experimental results might be due to the presence of wiper slots, back sawing, motor efficiency, and other losses between the interaction of the cutting tool and workpiece, which were not considered in this study. Climb-sawing consumed more power than counter-sawing in the range tested. The difference between climb-sawing and counter-sawing was more pronounced in sawmill B. Surprisingly, the theoretical and experimental power consumption data converged with an increase of cutting tool edge radius. The power consumption was higher in sawmill B than in sawmill A due to a high saw kerf width, cant height, high mismatch, and low overlap between sawblades.

In general, the experimental test showed an increase of power around 35% in sawmill A during counter-sawing and of 30% in sawmill B during climb-sawing. The lowest increase in the experimental data was 11%, observed in sawmill B during counter-sawing. Additionally, the power consumption in sawmill A during the experimental test had an increase of 24% when climb-sawing. It should be emphasized that the edge radius was not measured in sawmill B. In general, the climb-sawing model for both sawmills was able to estimate the power consumption better than counter-sawing.

To accelerate a chip, sawmill B required 6.2 kW for climb-sawing and 4.8 kW for counter-sawing. Alternately, sawmill A required 11 kW for climb-sawing and 6.6 kW for counter-sawing. The relatively high values required to accelerate a chip in sawmill A were due to the high sawblade rotation combined with a high feed speed (Equation 6).

Wood is an anisotropic and heterogeneous material and when machined using circular sawblade, each tool edge engaged is cutting at different wood grains that result in different cutting forces direction and magnitude. Figure 6 illustrates the predicted power consumption as a function of grain angle for a single sawblade. The theoretical power consumption was computed using Equations 4, 5 and 7. During counter-sawing, the theoretical power consumption gradually increased from the beginning of the cut to a maximum when the cutting tool left the workpiece. However, in climb-sawing, the theoretical power consumption reached a maximum at the beginning of the cut and gradually decreased until reaching the exit angle. The variation of chip thickness for each sawmill is shown in Fig. 2 and 4.

![Fig. 6. Theoretical power consumption depending on grain angle for a single sawblade: (a) sawmill A; (b) sawmill B (saw mismatch=0)](image-url)
It is important to note that counter-sawing starts to cut at a grain angle of 0° (90-0° mode), while climb-sawing starts to cut at around 125° (approximately 90-90° mode). Kivimaa (1950), Goli (2009), and Axelsson (1993) found that the main cutting forces are slightly smaller at grain angles between 0 and 90° than they are between 90 and 180°. Therefore, changes in chip thickness, grain angle, and cutting length explain the differences in power required to remove a chip via climb-sawing and counter-sawing.

Figure 7 illustrates how variation in overlap affects the theoretical power consumption in each sawmill. In the experimental test, sawmills A and B had 25 mm and 5 mm overlaps, respectively. As the overlap between sawblades increased, the theoretical power reduced for both sawmills due to the change in the angle of tooth entry and exit, grain angle, length of path of tooth engagement, and the number of teeth engaged, i.e., the greater the overlap between sawblades was, the shorter the path of tooth engagement and the fewer the number of teeth engaged in the cut.

![Fig. 7. Theoretical power consumption depending on overlap between sawblades: (a) sawmill A, (b) sawmill B (saw mismatch=0)](image)

A potential reduction in power consumption can be seen in sawmill A, where the sawblades had 25 mm of overlap.

![Fig. 8. Theoretical power consumption depending on the mismatch between sawblades: (a) sawmill A (overlap = 25 mm), (b) sawmill B (overlap = 5 mm)](image)

During sawing, the blades are subjected to severe loads and vibrations that lead to poor surface quality and reduced cutting accuracy. Figure 8 illustrates the effect of saw mismatch on theoretical power consumption in sawmill A and B. The experimental tests revealed the highest values of saw mismatch to be 2.5 mm in sawmill B and 1.75 mm in sawmill A. These saw mismatch values are quite high; the average values were much
smaller. The theoretical results showed that an increase in saw mismatch resulted in high power consumption. Interestingly, the changes in power consumption in sawmill B due to saw mismatch were negligible. This is because the overlap was only 5 mm.

As expected, the power required to accelerate a chip when the saw mismatch was 2.5 mm increased by 0.8 kW in sawmill B; with a saw mismatch of 1.75 mm in sawmill A, the power required was 2.8 kW. This value in sawmill A was due to the long cutting length in the overlap zone between sawblades.

From Figs. 7 and 8, it is reasonable to conclude that sawmills that use thinner sawblades that are prone to instability should consider using less overlap between sawblades. However, the choice of operating conditions in a sawmill is not based exclusively on power consumption; it is a compromise between productivity, lumber recovery, and sawing accuracy. In the future, more controlled experimental tests are planned. Resaw machines with thicker saw kerf widths for climb-sawing and thinner ones for counter-sawing, or vice versa, will be considered.

CONCLUSIONS

1. The cutting force model by Axelsson et al. (1993) was able to estimate power consumption better during climb-sawing than in counter-sawing.

2. The lowest difference between experimental and theoretical power consumption was 7.4 kW observed at the end of the test during climb-sawing (sawmill B) while the greatest difference was 38 kW observed at beginning of the test during counter-sawing (sawmill A).

3. The power consumption was higher in sawmill B than in sawmill A, due to a high saw kerf width, cant height, and low overlap between sawblades.

4. Power consumption increased by 11 to 35% in the experimental test.

5. Climb-sawing required more power than counter-sawing.

6. The lowest theoretical power consumption was found using greater overlap.

ACKNOWLEDGMENTS

The authors would like to sincerely thank the European Regional Development Fund, Objective 2, Northern Sweden via Tillväxtverket (the Swedish Agency for Economic and Regional Growth), Vinnova (the Swedish Agency for Innovation Systems), and SIDA (Swedish International Development Cooperation Agency) for their financial support.

This article first appeared in the proceedings of the 21st International Wood Machining Seminar (IWMS-21), which was held in Tsukuba, Japan (August 4-7, 2013).
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Article submitted: August 14, 2013; Peer review completed: September 21, 2013; Revised version received and accepted: October 1, 2013; Published: October 4, 2013.
Different methods for monitoring flatness and tensioning in circular-saw blades

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ABSTRACT

The performance of a circular-saw blade during sawing depends greatly on the mechanical and geometrical properties of the individual saw blade in question. In order to characterize an individual saw blade when manufacturing saw blades or when doing maintenance of the saw blades, flatness and tensioning are important aspects. Flatness and tensioning influence the lateral stability of the saw blade during sawing and thus affect the sawing result, e.g., the accuracy of the dimensions of the sawn timber.

Tests and comparisons of different methods for characterizing individual saw blades were done. New and used saw blades with different amounts of tensioning and flatness were used. The tested saw blades had several radial slots and were intended for use in double-arbour saws with collars and no guides. The methods that were compared were static and dynamic flatness measurements, natural-frequency measurements and theoretical finite-element calculations with different excitation methods and boundary conditions.

The results show some of the qualities of the different methods and show benefits and disadvantages. Especially tensioning can be accurately measured and predicted from natural frequency measurements and from finite-element calculations.

Keywords: circular-saw blade, tensioning, flatness, finite element, ripsawing, stability
INTRODUCTION

Flatness and tensioning of circular-saw blades are important aspects for the characterization and performance of circular-saw blades. Measuring these aspects, maximizing flatness and finding the best amount of tensioning are important when manufacturing new saw blades or maintaining and sharpening used saw blades (see, for example, Schajer (1984)). In this paper, different experimental and theoretical methods for measuring flatness and tensioning are discussed, and results are shown for various circular-saw blades intended for ripsawing in double arbour saws with collars and no guides. The principle for these kinds of saw machines is shown in Figure 1. The rotational direction of the saw blades may be switched so that these sawing machines can be used for both counter-cutting and climb-cutting.

![Figure 1. Principle for ripsawing logs with a double arbour saw.](image)

The species that were cut with the blades used in this paper were mainly the Scandinavian species Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*). Most of the tested saw blades (see Figure 2) had several radials slots. The slots were equipped with cutting edges in order to clean the cut surfaces of sawdust. One reason for having these clean-cutting slots is that the logs are frozen during wintertime, and ripsawing frozen timber presents special problems, such as sawdust sticking to the saw blades or to the cut surfaces of the sawn timber.

Flatness is measured by measuring the axial movement of points on the surface of a saw blade when rotating the blade. Using a saw blade that is much out of flat (*i.e.*, skewed) may result in such unwanted phenomena as vibrations, sound emissions and fluctuating cutting forces, as a result of which the dimensions of the sawn timber may lose accuracy (Mote & Szymani 1977; Holoyen 1997).

Tensioning of saw blades is done in order to increase their dynamic stability by introducing tangential tension stresses in the outer periphery of the blades. This increases the natural frequencies of the blades and thus makes it possible to use a higher rotating speed in operation or to have a larger margin between the lowest critical speed and the operational rotational speed.
Tensioning also makes the blades become less susceptible to heating in the outer periphery, since heating causes compressive tangential stresses in the outer periphery. Too much tensioning make the blade too “loose”, and this means that the saw blade will buckle or be close to buckling when stationary. Tensioning is done by rolling the blade between rollers at some positions (e.g., circular grooves) in between the outer and inner periphery (see Figure 2) and thus introducing plastic deformations that produce internal (residual) stresses. By introducing these plastic deformations in suitable places, the blade will be internally stressed and will acquire the desired tangential tension stresses in the outer periphery. Detensioning is sometimes done in order to reduce the tensioning of a saw blade that has been tensioned too much. This is done by rolling the outer periphery of the saw blade, thus reducing the tangential tension stress at the outer periphery (Szymani & Mote 1974, 1979).

![Figure 2. Geometry of circular-saw blades S1–S6 and K1–K3. Two times three slots in geometry. Three grooves for tensioning.](image1)

![Figure 3. Circular disc E1 excited with magnet. Resonance for three nodal diameters shown with salt powder.](image2)

Tensioning affects the natural frequencies of the saw blades (Szymani & Mote 1974, 1979; Schayer & Mote 1983, 1984). The natural frequencies and mode shapes of a plane, circular disc (a saw blade with no teeth and slots) are characterized by the number of nodal diameters and the number of nodal circles due to the circular symmetry. The introduction of teeth, holes or slots will change these characteristics, since the structure will become rotationally periodic and not circularly symmetric, but the natural frequencies may still be characterized by the number of nodal diameters. The theoretical basis for vibrations of rotationally periodic structures was described by Wildheim (1981) and the specific effects of slots in circular-saw blades were described by Mote & Yu (1987) and by Nishio & Marui (1996). The natural frequencies are raised by rotational and centrifugal forces. Also, clamping of the centre by a collar will raise the natural frequencies compared to a completely free blade, especially for low nodal diameters. Tensioning introduces internal (residual) stresses in the saw blade, and internal stresses in general can both raise and lower natural frequencies, depending on the specific residual-stress condition. Normally, tensioning is introduced in such a way that the natural frequencies are raised.
Resonance for a saw blade rotating at a variable speed appears at certain critical rotational speeds (Mote and Szymani 1977). A resonance condition is characterized by high amplitude of vibration. The resonance condition of a circular disc due to a single, constant and stationary point force acting in the direction of the rotational axle (transverse to the plane of the saw blade) is theoretically given by the critical rotational speed

\[ f_{rot} = \frac{f_{mn}}{n} \]

where \( f_{rot} \) is the critical rotational frequency (Hz) at which there is resonance, and \( f_{mn} \) is the natural frequency (Hz) of the disc with \( m \) nodal circles and \( n \) nodal diameters. Saw blades also have resonances at the same critical speeds, but there may also be resonances at other rotational speeds (Wildheim 1981) due to the periodicity of the number of teeth, the number of grooves and the number of holes. There may also be resonances at other critical rotational speeds due to excitation from other distributed and/or time-varying stationary forces and from air turbulence varying in a random manner. In operation, the saw blades treated here normally rotate well below the lowest critical speed given by Eq. 1.

In this paper, a summary of a large amount of experimental data and FEM-calculated data is shown for a number of circular-saw blades. The purpose is to show and compare how flatness and tension in circular-saw blades can be detected in various ways.

**METHODS**

**Flatness measurements**

Three methods for flatness measurement were considered. The first method consists of using a ruler and observing the light between the saw blade and the ruler at a number of different positions. This is a manual and qualitative method that can only detect large deviations from flatness, and the method is not treated further in this paper.

The second method, a static one, involves placing the blade horizontally on a fixed collar and slowly rotating the blade, which slides on the collar, and at the same time measuring the vertical displacement with an indicator gauge placed at some radius, often near the outer radius. The difference between the maximum and minimum readings when rotating one full turn is registered as the flatness value.

The third method, a dynamic one, uses an automatic machine that measures flatness as the difference between the maximum and minimum displacement value at the outer radius when rotating one full turn at slow speed (100 rpm) with the blade fixed to an arbour with a collar.

**Tensioning measurements**

The tensioning of different saw blades was tested by using several methods. Measuring tensioning means measuring the internal stresses, but since they are hard to measure directly, their effect on the stiffness of the blades was measured instead. Blade stiffness can be measured statically by bending the saw blade or dynamically by measuring the natural frequencies of the saw blade.
Method 1 was a manual test with a ruler. By looking at the light showing between the ruler and the blade and at the same time bending the blade slightly, a skilled person can feel and see the stiffness and thus decide whether the blade is tensioned or not and possibly also how much it is tensioned. Results of this method are not shown here.

Method 2 was a natural frequency test done by impacting the blade with a hammer, using a microphone to get the sound spectrum and a frequency analyzer to determine the natural frequencies, but not necessarily all natural frequencies. This method was used on both free blades and blades fixed to an arbour with a collar. The method did not give information about the mode shapes.

Method 3 was a natural-frequency test done by exciting fixed blades with an electromagnet and finding resonance frequencies and the corresponding mode shapes using salt powder (Figure 3). The resonance frequencies were the natural frequencies, but not necessarily all natural frequencies were found. This test was done with the blade fixed with a collar in the centre.

Method 4 was a static bending test of a blade fixed with a collar in the centre. The blade was bent with two point forces at the outer periphery 180° apart (at the top and bottom of Figures 4a and 4b) which led to a certain displacement (10 mm in the example in Figure 4). At the same time, the displacement of the blade at two points 90° apart from the points of force application was measured. A tensioned blade bends in the same direction as the forces (Figure 4a). An untensioned blade bends in the opposite direction to the direction of the forces (Figure 4b). The tensioning values presented below are these displacement values for a constant force presented as nondimensional values. Positive values indicate that the blade is tensioned. An untensioned blade will have a small negative value.

Method 5 was a theoretical calculation of the natural frequencies with the finite element method (FEM). The commercial FEM programme ABAQUS, with quadratic linear elastic elements, was used, and calculations for free, fixed, tensioned, untensioned, stationary and rotating saw blades were done. All natural frequencies and corresponding mode shapes (below the chosen frequency) were obtained. The tensioning method in the FEM calculations was to set a higher temperature in the areas where the tension was applied (see the circular grooves in Figure 2) and to set a radial thermal expansion coefficient for the material. The tensioning temperature \( T \) (see Table 1) was determined by adjusting the FEM result to fit the test result for the lowest natural frequency. \( T = 0 \) means no tensioning. Figures 11a and 11b show an example of a mode shape and the mesh that was used.
RESULTS

The data for the saw blades are shown in Table 1, and the geometries are shown in Figures 2 and 3. Nine circular-saw blades with slots and with the same overall geometry except for thickness, but with different amounts of tensioning, were named S1 to S6 and K1 to K3. E1 was a circular-saw blade without teeth and without slots (i.e., a circular disc).

<table>
<thead>
<tr>
<th>Name</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
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<td>yes</td>
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<tr>
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Flatness measurements

Flatness was measured for blades S1 to S6 and K1 to K3 with the static and the dynamic method. The methods differ mainly in the way the blades are fixed during the rotation. Figure 5 shows the measured flatnesses versus each other. A flatness value below about 120 μm measured with the static method is an acceptable value for blades S1–S6 and K1–K3 according to experience.

![Figure 5. Flatness values for blades S1–S6 and K1–K3.](image)

![Figure 6. Natural frequencies for blade E1 calculated with FEM and measured with magnetic excitation. Fixed in centre. Branches for 1, 2 and 3 nodal circles.](image)

Tensioning measurements and calculations

Results from static tensioning measurements with method 4 (static bending) for blades S1–S6 and K1–K3 are shown in Table 1. Blades S1–S6 have three different tension values, and blades K1–K3 have two different tension values.

Electromagnetic excitation measurements (method 3) for blade E1 resulted in frequencies shown in Figure 6 compared to FEM calculation results (method 5) for an untensioned blade (T = 0) and a tensioned blade (T = 20). Figure 3 shows an example of a measured mode shape. Figure 7 shows both free and fixed natural frequencies for blade E1 from both FEM calculations and experiments.
Figure 7. Natural frequencies for blade E1 calculated with FEM (fixed and free) and measured with magnetic excitation (fixed) and impact test (free).

Figure 8. Free natural frequencies for S1–S6 as a function of tensioning value. From impact test.

Results of impact tests (method 2) for free blades are shown in Figure 8 for blades S1–S6 and in Figure 9 for blade S1, which has a low value of tensioning, and in Figure 10 for blade S6, which has a higher value of tensioning. The mode shapes for the tested natural frequencies were not determined directly by the test results, but were determined by comparing with the frequencies from the FEM calculations (method 5). Figures 11a and 11b show the FEM-calculated free mode shape for blade S6 and n = 3 at 165.7 Hz. This mode was measured as lying at 163.8 Hz (-1.2%).

Figure 9. Free natural frequencies for blade S1. Experimental values from impact test and calculated values with FEM.

Figure 10. Free natural frequencies for blade S6. Experimental values from impact test and calculated values with FEM.
FEM-calculated free natural frequencies for blade K1 are shown in Figures 12 and 13 with and without tensioning and with and without slots.

**ANALYSIS AND DISCUSSION**

The two tested methods of flatness measurement two give different results, probably due to the difference in fixation (Figure 5). The dynamic method may be influenced by play or skewness of
the rotating axle. However, all blades used here were flat within acceptable limits for usable blades.

For fixed blades, tensioning increases the lowest natural frequencies, especially for nodal diameters 2, 3, 4 and 5. For nodal diameters 0 and 1, tensioning lowers the natural frequencies, and for nodal diameters 6 and higher, the effect of tensioning is a smaller increase (Figures 6 and 7). For free blades, the influence of tensioning is to raise the natural frequencies for \( n = 2 \) and 3 significantly, 10% or more (Figure 8). This shows that the level of tensioning can be measured by measuring the natural frequencies of the blade.

The three-fold periodicity of the slots makes the (double) natural frequencies for \( n = 3, 6, 9, \ldots \) split in two. Slots lower all natural frequencies (Figures 12 and 13).

Natural frequencies calculated with FEM agree well in general with measured frequencies (Figures 6–10). Using FEM for tensioned blades with the tensioning method described here gave errors typically in the frequency of < 2% for \( n = 2, 3 \) and 4 and < 5% for \( n < 10 \) (Figures 9 and 10). The combination of FEM calculations and impact tests is very attractive. Impact tests are very fast and simple to perform, but give only frequencies, and not necessarily all frequencies. FEM gives all frequencies and mode shapes. With a combination of those two methods, all the natural frequencies and mode shapes may be found. Thus, the tensioning level and the quality of tensioning may be measured.

Future research in this area will be directed towards understanding how and where best to tension the blades in order to achieve certain changes of the natural frequencies (i.e., to control the tuning of the blades).
REFERENCES


Paper VIII
Roll-tensioning effects on natural frequencies in circular sawblades for woodcutting were investigated. Adequate knowledge of these effects will enable a more precise and repeatable tuning of natural frequencies, which will ease manufacturing and maintenance of sawblades. With natural frequencies tuned to not create resonance under running conditions, longer running times and more accurate cutting are made easier. The aim of this study was to find the optimum, or most suitable, tensioning parameters for a series of tested circular sawblades and also to draw general conclusions. The effects of the magnitude of the roller load, number of grooves, and groove positions were tested. The magnitude of the roller load was measured by using a universal load cell. The roll-tensioning effects were evaluated by measuring the shift in natural frequencies of several vibration modes. Finite element analysis was performed to model natural frequencies. The magnitude of the roller load, number of grooves, and groove positions all affected the natural frequencies. Natural frequencies obtained with the finite element method were in good agreement with the experimental test results.

Keywords: Roll tensioning; Finite element; Natural frequency; Vibration

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INTRODUCTION

A large amount of low-value sawdust is produced in sawmills during log conversion and lumber production. Much research has been conducted to increase lumber recovery by reducing the kerf width while maintaining productivity (feed speed) and dimensional accuracy. Reducing kerf width means reducing the thickness of the sawblades, which lowers natural frequencies, which, in turn, increases the risk of running into resonances (Lister et al. 1997). Running close to resonances causes increased vibration amplitudes, which increases the kerf width and causes poor dimensional accuracy. Tensioning of circular sawblades plays an important role for the performance, especially when using thin and large diameter blades. Its goal is to increase natural frequencies and thus, the gap between exciting frequencies during cutting and natural frequencies. However, excessive tensioning causes the sawblade to buckle (dishing) and unsuitable tensioning may reduce natural frequencies (Schajer and Kishimoto 1996).

Tensioning means introducing a state of residual stress, which affects the stiffness of the sawblade. Residual stresses are hard to measure directly, but since stiffness affects natural frequencies, the natural frequencies are an indirect measure of residual stresses and thus, tensioning (Szymani and Mote 1979). The natural frequencies and mode shapes...
define the dynamics of any structure. The number of nodal diameters (ND) and the number of nodal circles (NC) characterizes the mode shape for circular saw blades (Fig. 1). Natural frequencies of circular saw blades can be measured acoustically by using a microphone as a vibration sensor. Schajer et al. (2011) recently designed and built a prototype system that measures the natural frequencies and also identifies the mode shapes by using two microphones, one fixed and one rotating.

![Graph of natural frequencies vs nodal diameters and circles](image)

**Fig. 1.** Vibration mode shapes of sawblade after tensioning one groove: a) branches of nodal circles; b) illustration of ND = 4 and NC = 0

The largest vibration amplitudes appear for modes with a low number of nodal diameters and zero nodal circles. Mote and Szymani (1977) reported that the dominating sawblade vibration modes most often have zero to six nodal diameters and zero nodal circles. There are several ways of tensioning saw blades by either mechanical or thermal means. Roll-tensioning is widely used in sawblade factories and in sawmills. It has been reported by Stakhiev (1999) that the effectiveness of the roll-tensioning process depends on the diameter of the rolled track circle, the profile (cross section) of the rolls, the number of passes in a groove, the number of grooves, and the force of the rolls pressing against the sawblade. Also, a thermal tensioning process is possible, where stresses due to the temperature difference between the central area and outer rim were shown to improve the stability and cutting accuracy of clamped saws (Mote et al. 1981).

The purpose of this work was to find the optimum roll-tensioning parameters by varying the magnitudes of the roller load, tensioning radius, number of grooves, and distance between grooves. Here, finding the optimum means finding the right method, the right amount, and the right place to tension the blade in order to increase the margin to resonance as much as possible.
EXPERIMENTAL

Experimental data were collected from circular sawblades in a non-rotating state. The roller load was applied through a screw mechanism, and the magnitude of the load, \( F \), was measured using a universal load cell as shown in Fig. 2a. A schematic illustration of a sawblade with radius \( R_y \) and thickness \( t \) being tensioned with the roller load \( F \) at tensioning radius \( R_t \) is shown in Fig. 2b.

The dimensions of circular sawblades tested were: radius, \( R_y \), 350 mm, thickness, \( t \), 3 mm, bore diameter, \( d \), 126 mm, and rake angle and clearance angle 15°. The tensioning radii, \( R_t \), for all tests were set within the range of 117 mm (0.33\( R_y \)) to 273 mm (0.78\( R_y \)). Seven identical sawblades were tested and denoted A, B, C, D, E, F, and G. The sawblades tested had no inserted carbide tips. Schajer and Mote (1983) showed that saw teeth have negligible influence on the natural frequencies of circular sawblades and thus, the carbide tips must have negligible influence on natural frequency. The roller used for tensioning had a crown radius and a roll radius of 19.5 mm and 48 mm, respectively. The rolling was stopped after each complete revolution, and the blade was removed for examination. Each sawblade was rolled with a constant roll load, making one to five evenly spaced grooves (\( G_r \)) from inside to outside. Results were collected after each groove was rolled. The roller loads used were 10, 13.5, and 19.5kN.
Two methods of measuring the flatness of the sawblades were considered, namely an indicator gauge and a light-gap technique. The indicator gauge technique entails measuring the vertical displacement around the circumference when rolling the blade on a fixed plane near the center hole, as shown in Fig. 3. The light-gap technique entails measuring the flatness around the diameter with a ruler and manually looking at the light gap between the ruler and the blade. The indentation depth and groove width ($e$) left after tensioning of each sawblade was measured.

In this study, the amount of tensioning was determined by measuring the natural frequencies of the free blades, as shown in Fig. 4, before and after tensioning. The non-rotating sawblade was excited by moderately hitting it with a wooden stick, and then the sound was recorded with a microphone, sampling rate 22050 Hz, 16 bit resolution. Finally a FFT (fast Fourier transform) analysis was conducted (16384 points, resolution 1.35 Hz) which showed the natural frequencies as amplitude peaks in the amplitude versus frequency diagram (Fig. 5).
The natural frequencies of the sawblades were measured up to 500Hz. Mode shapes (number of nodal diameters and nodal circles) were not revealed directly by this method alone, but were instead determined by comparison with calculated mode shapes.

The FE (finite element) program Abaqus 6.10 (Simulia 2010) was used to calculate natural frequencies and mode shapes of the sawblades. Quadratic linear elastic elements were used and the boundary conditions were those of a completely free sawblade. Figure 1 shows an example of a mesh that was used. Tensioning was simulated by using a higher temperature in the grooves to represent the effect of residual stresses introduced by the rolling procedure. The groove widths in the calculations were set to the measured values 4.0 mm, 4.2 mm, and 4.5 mm for 10 kN, 13 kN, and 19.5 kN, respectively. A suitable temperature difference to use to simulate tensioning was determined by adjusting the calculated result to fit the test result for the lowest natural frequency, which had two nodal diameters and zero nodal circles. The temperature differences determined and used were 5°C, 35°C, and 75°C for tensioning forces of 10kN, 13.5kN, and 19.5kN, respectively. A detailed description of the tensioning method, using this approach, was reported earlier by Ekevad et al. (2009). The material properties used were an elastic modulus of $2.1 \times 10^{11}$ Pa, a Poisson's ratio of 0.3, a mass density of 7800 kgm$^{-3}$, and a coefficient of thermal expansion of $12 \times 10^{-6}$ C$^{-1}$.

Nodal diameters and nodal circles in the experiments were determined by comparing test results with calculation results. As only lower order vibration modes are of interest in the present analysis, the lowest eight nodal diameters were used.

RESULTS AND DISCUSSION

The untensioned sawblades were nearly identical when it came to untensioned natural frequencies ($\leq 1$ Hz difference in frequencies for the frequencies used for ND = 2), but they had some initial residual stresses, probably due to the manufacturing process. Frequency shifts due to these initial stresses were equal to or less than 8.0 Hz for ND = 2. This was revealed by comparing calculated frequency results with test results, and also qualitatively by using the opinion of a skilled sawblade filer who used his “feeling” for the sawblades. The effect of tensioning force on natural frequencies is presented in Figs. 6 through 8 for sawblades A, B, and C, which were tested with 10kN, 13kN, and 19.5kN, respectively. Five tensioning grooves were made for each sawblade from a tensioning radius of 117 mm (0.33Ry) to 157 mm (0.45Ry). The distance between grooves was 10 mm. For reference, the values of natural frequencies are presented as frequency ratios between tensioned and untensioned sawblades.

The frequencies for NC = 0 were in general raised by tensioning, and the frequencies for NC = 1 were in general lowered. A low tensioning force, as in sawblade A, gave a small increase in the natural frequencies for NC = 0. The highest rise in natural frequency for NC = 0 was observed when tensioning with a high tensioning force as in sawblade C. This highest tensioning force resulted in an indentation depth of less than 0.01 mm on each side of the sawblade and a groove width ($e$) of 4.5 mm. The rise in natural frequencies for NC = 0 produced by rolling five grooves in sawblade A was less than the change produced by a single groove rolled with 13kN, as in sawblade B. Also,
the rise in natural frequencies for NC = 0 produced by rolling five grooves in sawblade B could be achieved by rolling two grooves in sawblade C.

It is interesting to observe that the values of natural frequencies for ND = 0 for NC = 1 were reduced very much with tensioning, and in particular the frequency for ND = 0 drops to zero (dishing) for blade C with five grooves. In contrast, the change in natural frequencies due to tensioning for NC = 2 in the tested sawblades was negligible.
The natural frequencies measured are compared with those obtained from the numerical simulations. It can be seen that the natural frequencies obtained from the experiment were in reasonably good agreement with those obtained from the simulation.
The dishing phenomenon was observed in sawblade C during tensioning of the fifth and last groove, $Gr = 5$ in Fig. 8. Excessive tensioning in its central area caused this phenomenon. It can be seen that the relative change in natural frequency for $ND = 0$ with $NC = 1$ with respect to the number of grooves was non-linear and was highest, 0.32, when tensioning from the fourth to the fifth groove (Fig. 9).

The sawblade was also evaluated by the light-gap method and the predicted dishing of sawblade C when it was tensioned with five grooves was also found in practice as a maximum flatness deviation observed by a gauge indicator of 0.1 mm. The allowed flatness deviation for sawblades of 350 mm radius was 0.18 mm, according to the tolerance stated by the sawblade manufacturer. The effect of dishing could be avoided if the tensioning of sawblade C was stopped at four grooves. However, it has been reported that sawblades that experience dishing will become flat when running at or above the dishing speed (Schajer and Kishimoto 1996).

Rolling loads of 13kN and 19.5kN were chosen as suitable for practical use for these sawblades. The choice of rolling load entails a compromise between the shifts in natural frequencies, time taken to perform the tensioning procedure, and avoidance of dishing. For example, the rise in natural frequencies produced by two grooves in sawblade C was similar to the rise produced by five grooves in sawblade B (Figs. 7 and 8). For practical reasons, it would take more time to achieve the same increase in frequencies by rolling a sawblade with 13kN (greater number of grooves) compared to rolling it with 19.5kN. Therefore, a tensioning force of 19.5kN was chosen for testing sawblades D, E, F, and G.

Sawblade D was tensioned between 175mm (0.5 $R_y$) and 215mm (0.61 $R_y$), that is, farther outwards compared to sawblades A, B, and C. The distance between grooves was 10 mm. The results are shown in Fig. 10.

![Fig. 10. Number of grooves and frequency ratios of sawblade D](image)
The frequency ratios for five grooves for ND = 2 and 3 with NC = 0 became 1.79 and 1.50, respectively. The frequency ratio for ND = 0 with NC = 1 became 0.57. For the tested sawblade, the greatest change in natural frequencies was observed during tensioning with the first three grooves. The magnitude of the change in frequency ratio given by grooves 4 and 5 was very small (≤ 0.08 for ND = 2). In general, sawblade D had smaller changes in natural frequency than sawblade C when they were both tensioned with the same force. The simulation results are also shown for reference, showing that the assumptions made for the simulations are feasible.

Two sawblades, E and F, were tensioned from 175 mm (0.5 \(R_y\)) and outwards with evenly spaced grooves with distances between them of 7 and 14 mm, respectively. The results showed a negligible difference in the magnitude of change in natural frequencies (≤ 2 Hz for ND = 2) compared to sawblade D, which had a distance of 10 mm between grooves.

Sawblade G was tensioned using grooves from 233 mm (0.67 \(R_y\)) to 273 mm (0.78 \(R_y\)), which were the outermost positions used in these experiments. The distance between grooves was 10 mm. Figure 11 shows the frequency ratio for ND = 2 to 7 with NC = 0 and how it varies with increasing number of grooves. Lines for illustration purposes only connect the values of natural frequency ratios; the lines do not mean anything else, as the number of grooves is a discrete number. The results illustrate the existence of a limit between increasing (tensioning) and reducing (detensioning) the natural frequencies of the sawblade. In this work, this limit was called the critical tensioning radius (\(R_{tc}\)). \(R_{tc}\) is different for different modes and here it was determined for ND = 2 and ND = 3.

Fig. 11. Critical tensioning position for NC = 0 for blade G.
The critical value of $R_t$ for the tested sawblades was 253mm (0.72 $R_y$). Tensioning the sawblade G to the critical radius ($Gr = 3$) resulted in a 33.5% rise in the frequency for $ND = 2$.

From the graphs presented above and knowledge of the operational rotation speed, the proper amount of tensioning force, number of grooves, and tensioning radius to use can be decided. Thus, a good cutting performance can be achieved. The results presented are for a specific geometry of sawblade and roller. Future work will be carried out to examine the effect of tensioning different geometries of circular sawblades.

CONCLUSIONS

1. The highest rise in natural frequencies when tensioning was found for $ND = 2$ and 3 for $NC = 0$. Frequencies for $NC = 1$ were lowered slightly by the tensioning procedure except in the case of $ND = 0$, for which they were lowered considerably.
2. Natural frequencies obtained with FEM using the temperature method were in good agreement with the experimental natural frequencies.
3. The most effective roller load among those tested was 19.5kN.
4. The critical tensioning radius was found to be 253 mm (0.72 $R_y$).
5. The effect of tensioning using many grooves was highest for the first two to three grooves and lower for the fourth and fifth grooves.
6. The distance between grooves showed a negligible influence on the variation in natural frequencies when the sawblade was tensioned in the range from 175 mm (0.5 $R_y$) to 231 mm (0.66 $R_y$).

ACKNOWLEDGMENTS

The authors express their gratitude to the European Regional Development Fund, Objective 2, Northern Sweden via Tillväxtverket (the Swedish Agency for Economic and Regional Growth), and Vinnova (the Swedish Agency for Innovation Systems) for financial support.

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Article submitted: December 8, 2011; Peer review completed: March 15, 2012; Revised version received: March 22, 2012; Accepted: March 24, 2012; Published: March 27, 2012.