Mittuniversitetet
MID SWEDEN UNIVERSITY

Thesis for the degree of Doctor of Technology, Sundsvall 2010

# ON THE WOOD CHIPPING PROCESS – A STUDY ON BASIC MECHANISMS IN ORDER TO OPTIMIZE CHIP PROPERTIES FOR PULPING

**Lisbeth Hellström**

Supervisors:
Professor Torbjörn Carlberg
Professor Per Engstrand

FSCN - Fibre Science and Communication Network
Department of Natural Sciences, Engineering and Mathematics
Mid Sweden University, SE-851 70 Sundsvall, Sweden

ISSN 1652-893X,
Mid Sweden University Doctoral Thesis 83
ISBN 978-91-86073-72-5

FSCN

*Fibre Science and Communication Network*
ett skogsindustriellt forskningscentrum vid Mittuniversitetet

*Investing in your future*

EUROPEAN UNION
European Regional Development Fund

Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig granskning för avläggande av teknologie doktorsexamen i teknisk fysik fredagen den 21:a maj, 2010, klockan 10.15 i sal O 102, Mittuniversitetet Sundsvall.
Seminariet kommer att hållas på svenska.

**ON THE WOOD CHIPPING PROCESS – A STUDY ON BASIC MECHANISMS IN ORDER TO OPTIMIZE CHIP PROPERTIES FOR PULPING**

**Lisbeth Hellström**



FSCN - Fibre Science and Communication Network
Department of Natural Sciences, Engineering and Mathematics
Mid Sweden University, SE-851 70 Sundsvall
Sweden

Telephone: +46 (0)771-975 000

Printed by Kopieringen Mittuniversitetet, Sundsvall, Sweden, 2010

## ON THE WOOD CHIPPING PROCESS – A STUDY ON BASIC MECHANISMS IN ORDER TO OPTIMIZE CHIP PROPERTIES FOR PULPING

**Lisbeth Hellström**

FSCN - Fibre Science and Communication Network, Department of Natural Sciences, Engineering and Mathematics, Mid Sweden University, SE-851 70 Sundsvall, Sweden
ISSN 1652-893X, Mid Sweden University Doctoral Thesis 83;
ISBN 978-91-86073-72-5

## ABSTRACT

In both the chemical and mechanical pulping process, the logs are cut into wood chips by a disc chipper before fibre separation. To make the wood chipping process more efficient, one have to investigate in detail the coupling between process parameters and the quality of the chips. One objective of this thesis was to obtain an understanding of the fundamental mechanisms behind the creation of wood chips. Another objective with the thesis was to investigate whether it was possible to, in a way tailor the chipping process so as to reduce the energy consumption in a following mechanical refining process.

Both experimental and analytical/numerical approaches have been taken in this work. The first part of the experimental investigations, were performed with an in-house developed chipping device and a digital speckle photography equipment.

The results from the experimental investigation showed that the friction between the log and chipping tool is probably one crucial factor for the chip formation. Further more it was found that the indentation process is approximately self-similar, and that the stress field over the entire crack-plane is critical for chip creation.

The developed analytical model predicts the normal and shear strain distribution and to be more specific, the model can predict the compressive stresses parallel to the fibre direction for an assumed linear elastic and orthotropic material. The analytical distributions were found to be in reasonable agreement with the corresponding distributions obtained from a finite element analysis.

To be able to study the chipping process under realistic conditions, which for example means to use chipping rates representative for a real wood chipper, a laboratory chipper was developed. Details regarding the chipper and how to evaluate the force measurements are given together with an example of how the force on the cutting tool (the knife) varies with time during cutting.

To investigate the influence of a certain chipping process parameter, the chips were after production in the laboratory chipper, refined in a pilot refiner during conditions optimized for TMP (thermomechanical pulp) and CTMP (chemithermomechanical pulp) processes. It was concluded that the details concerning the chip process had a large impact on e.g. the energy consumption in both first stage and second stage refining. Results showing this are given in this thesis.

**Keywords**: Wood chipping, Chip formation, Digital Speckle Photography, Friction, Fracture Processes, Analytical model, Laboratory Wood Chipper, Force Measurement, Vibration Synthesis, Energy Efficiency, Chip Damage,
TMP , CTMP

## SAMMANFATTNING

För både kemisk och mekanisk pappersmassa så tillverkas flis av trädstockar med hjälp av en skivhugg innan fibrerna separeras. För att göra flisningsprocessen mer effektiv, måste kopplingen mellan processparametrar och fliskvalitet studeras. Ett mål med denna avhandling är att ge fundamental kunskap om mekanismerna bakom bildandet av träflis.

Både experimentella och analytiska/numeriska metoder har använts i detta arbete. De experimentella undersökningarna har gjorts med hjälp av egen utvecklad utrustning och.

Resultaten från den experimentella undersökningen visar att friktionen mellan stammen och flisningsverktyget har betydelse vid flisning. Vidare observerades det att inträngnings processen är approximativt självlik (self similar) och att det är spänningsfältet över hela sprickplanet som är kritiskt för bildandet av en flis.

Den utvecklade analytiska modellen förutsäger normal- och skjuvspänningsfördelningen över sprickplanet och kan mer specifikt förutsäga den kompressiva belastning som verkar parallellt fiberriktningen i ett linjärt elastiskt och ortotropt material (trä). De analytiskt bestämda fördelningarna stämmer relativt väl överens med motsvarande fördelningar beräknad med finit element analys.

För att kunna studera flisningsprocessen under realistiska förhållanden, vilket bl.a. betyder att skärhastigheter som är representativa för en verklig process skall användas, så utvecklades inom ramen för avhandlingsarbetet, en laboratoriesflishugg. Detaljer rörande flishuggen samt hur uppmätta lastsignaler skall utvärderas ges tillsammans med ett exmpel på hur kraften på skärverktyget (kniven) varierar under ett skärförlopp.

Inverkan av en viss flisningsprocessparameter undersöktes genom att flis tillverkades i laboratorieflishuggen varefter de raffinerades i en pilotraffinör under förhållanden som var optimerade för TMP (termomekanisk massa) och CTMP (kemitermomekanisk massa) processerna. Det konstaterades att detaljer i flisningsprocessen hade stor inverkan på t.ex. energiåtgången i både första stegs – och andrastegsraffinering. Resultat som verifierar detta ges i avhandlingen.

## TABLE OF CONTENTS

## LIST OF PAPERS

This thesis is mainly based on the following five papers, herein referred to by their Roman numerals:

Paper I **A Method for Experimental Investigation of the Wood Chipping Process**
Hellström L.M., Gradin P.A. and Carlberg T.
Nordic Pulp and Paper Research Journal , 23:3, pp 339-342 (2008)

Paper II **An Analytical and Numerical Study of some aspects of the Wood Chipping Process**
Hellström L.M., Isaksson P., Gradin P.A., Eriksson K.
Nordic Pulp and Paper Research Journal, 24: 2, pp 225-230, (2009)

Paper III **A Laboratory Wood Chipper for Chipping Under Realistic Conditions**
Hellström L. M., Gulliksson M., Carlberg T. To be submitted to Experimental Mechanics

Paper IV **The Influence of the Wood Chipping Process on the Energy Efficiency During Mechanical Pulping**
Hellström L. M., Engstrand P., Gregersen Ø. To be submitted to Holzforschung

Paper V **Energy Efficiency Improvement Potential in TMP and CTMP by Axial Precompression of Wood During Chipping**
Hellström L. M., Engstrand P. To be submitted to J. of Pulp an Paper Sciense

## CONTRIBUTION REPORT

The authors contribution to the papers presented in this thesis are as follows:

| | |
|---|---|
| Paper I. | Performing all the experimental work and writing the article. Interpretation of the results in co-operation with Per Gradin and Torbjörn Carlberg. |
| Paper II. | Discussing details with Per Gradin and Kjell Eriksson. Doing all the numerical work and writing the article. The finite element analysis was performed by Per Isaksson. |
| Paper III. | Performing strength analyses of the chipper during its development. Carrying out all the theoretical work and writing the article together with Torbjörn Carlberg. The implementation of the theoretical model and numerical analysis was performed by Mårten Gulliksson. |
| Paper IV. | Developing an idea regarding the chip pretratment together with Øyvind Gregersen. Performing all the experimental work (except the refining) and writing the article. Discussing details with Per Engstrand. |
| Paper V. | Performing the experimental work (except the refining). Writing the article. Interpretation of the results in co-operation with Per Engstrand. |

# 1. INTRODUCTION

The total worldwide production of virgin wood pulp amounts to about 180 million tons a year. This includes both chemical and mechanical pulp. Common for both of these types of pulp is that the raw material (the logs) has to be cut into small parts i.e. chips before the fibres can be separated. If it is assumed that 70% of the weight of chips becomes pulp (in the chemical pulping process for example, some of the material is dissolved during the chemical treatment) then it can be concluded that at least 260 million tons of chips are produced annually. From this it follows that the chipping process is an important part of the pulping process.

A common demand from the pulp and paper industry is the smallest possible variation of certain chip population parameters, in particular the chip thickness distribution. A narrow distribution promotes uniform product properties, e.g. in chemical impregnation processes, and is generally recognized as a characteristic of a high-quality product by consumers. For the mechanical refining process, one important parameter is the bulk density of the chips since it determines the degree of packing in the feeding screw.

This means in practice that it might be more important to produce chips with a narrow thickness distribution rather than a specific thickness, so that it is more important, that the chipping tool retains its characteristics over time rather than it retains a given sharpness. In order to predict the influence of for example tool wear on the chip thickness, it is necessary to understand the underlying mechanisms of chip formation in detail.

Traditionally, the chipping has been performed in such a way so as to minimize the compressive damage induced on the chips by the high compressive stresses that might occur for a certain choice of chipping process parameters. This is a demand from the producers of chemical pulp and it has been assumed that this should be beneficial also for chips intended for the production of mechanical pulp.

Refining wood chips to produce mechanical pulp is very energy-intensive process. One of the main aims in the development of the mechanical pulping process is to achieve the desired degree of refining with a minimum of energy expenditure. Reducing energy consumption is of utmost importance to producers of mechanical pulp, because of both increasing electricity prices and the importance of environmental issues. The interest of mechanical chip pretreatment has arisen due to an expected high potential to achieve energy reduction in refining. One of the aims with this thesis has therefore been to investigate the possibilities to perform mechanical pretreatment of chips intended for mechanical pulping, already during the chipping process.

To be able to formulate criteria for determining the onset of creation of a wood chip one should be able to study the deformation fields in the vicinity of the edge of the chipping tool. Another aim with this thesis was thus to study the deformation fields by utilising a Digital Speckle Photography (DSP) equipment, which together with image processing software makes it possible to determine the strain field on the surface of the wood specimen during the cutting of chips.

The results from the DSP investigations give quantitative information about the fracture processes and deformation fields in a wood specimen during chipping.

On the other hand, to get a qualitative picture regarding the influence of different parameters on the stress and strain fields in the chip, it should be of value to have access to a simple analytical model. As another aim with this thesis, such a model was developed, the relevance of which was checked against a more general Finite Element (FE) model. One outcome of the model was that it predicted high compressive stresses in the fibre direction due to the wedging action of the chipping tool (the knife). This opens up the possibility to choose chipping process parameters to actually maximize the compressive damage induced to a chip during chipping. This should in the sequel be referred to as "directed chipping"

To evaluate the pulping response on directed chipping, an in house developed laboratory wood chipper located at FSCN (Fibre Science and Communication Network) at Mid Sweden University was used to produce wood chips under some different chipping conditions. The development of this equipment was yet another aim with the work, and the equipment is described in detail in this thesis. To cover all possible chipping conditions, the laboratory wood chipper was designed so as to admit the variation of cutting angles in two orthogonal planes. Further on, the cutting rate can be varied in the interval 0 to 50 m/s which is well in the interval found for commercial wood chippers. Also, the design admits an easy change of chipping tool and the tool holder is equipped with force sensors such that the forces in three orthogonal directions can be measured. Due to inertia effects, the force that is measured and the force acting on the knife is not the same so that a two degrees of freedom model has to be utilized in order to extract the real cutting force versus time during cutting.

To summarise, this work is an attempt to develop both experimental and analytical tools for the study of the wood chipping process and its implications on the wood refining process.

# 2. AN INTRODUCTION TO WOOD CHIPPING AND RELATED ITEMS

The following section is intended to make the reader more acquainted with the topics dealt with in this thesis. The section starts with a short description of the disc chipping process, followed by a short presentation of relevant wood chipping parameters and a discussion of wood chip quality. Mechanical pretreatment of wood chips will be the topic of the final part of this section

## 2.1. Disc chipping process

In both the chemical and mechanical pulping processes, the logs are cut into smaller parts i.e. wood chips by for example a disc chipper before fibre separation.

The chipping is normally performed in a disc chipper, where the basic design (the Wigger chipper) was developed in 1889 [1]. The disc chippers of today are improvements from this Wigger chipper. There are other techniques to produce wood chips, but only disc chippers will be considered in this thesis. How a disc chipper works is shown schematically in Figure 1.

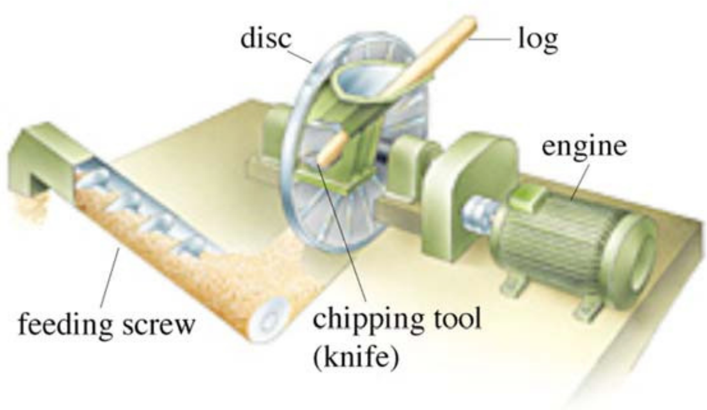


**Figure 1**. Wood chipping by a disc chipper [2]

In a disc chipper, the chip length can be controlled by the $T$-dimension (Figure 2), i.e. the distance between the knife tip and the disc wear plate together with the spout angle $\varepsilon$ (Figure 3). The feeding through the chipper can be controlled by the clearance angle (Figure 3), $\alpha$ [3].

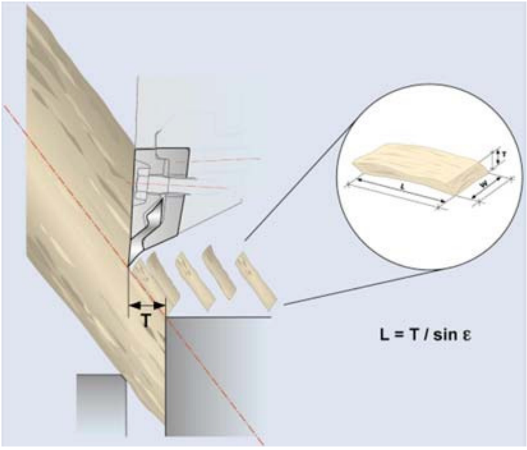


**Figure 2**. The *T*-dimension (with the permission of Iggesund Tools AB)

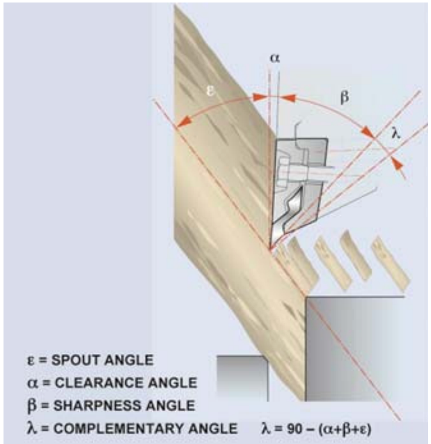


**Figure 3**. The angles (with the permission of Iggesund Tools AB)

The edge angle (Figure 3), $\beta$, is often combined with a larger angle (the bevel angle, $\beta'$) at the edge to give the knife higher strength and durability.

The knifes are mounted in radial directions on the chipper disc, very much like spokes on a bicycle wheel. The commonly used cutting speeds are 20-40 m/s (varying in the radial direction). The chip length, $L$, is normally set to be about 20-25 mm (in the grain direction). In a disc chipper this will give an average chip thickness, $t$, of about 3-5 mm.

## 2.2. Wood chipping parameters

Depending on what type of chipper that is used and the wood quality, one will get a distribution of chip thicknesses, which may be more ore less narrow. One should keep in mind that the wood and fibre properties vary not only between trees but also within a tree.

### 2.2.1. Wood properties

The Latin word for timber is "materia". Wood is often referred to as a material but sometimes also to as a structure. On a macroscopic scale it is logical to call wood a material but on a microscopic scale, wood has a pronounced structure. This can be seen in Figure 4, where different regions referred to as early wood, latewood and transitionwood can be identified.

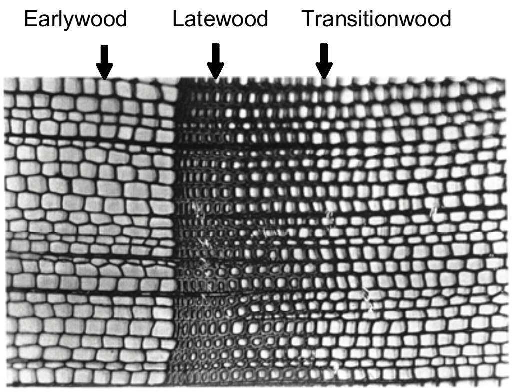


**Figure 4**. Cross-section of spruce wood (approximately one annual growth ring) as observed in a light microscope [4]

In Norway spruce, the earlywood cell wall thickness is approximately 1-3 μm while latewood cells have a wall thickness of 2-7 μm [5]. The densities of the earlywood, latewood and transitionwood are approximately in average 300, 900 and 450 kg/m$^3$ respectively [6].

Wood is an anisotropic material exhibiting unique and varying mechanical properties in different directions. To be more specific, wood is cylindrically orthotropic with reference to a system of axes aligned with the radial, tangential and axial directions as shown in Figure 5.

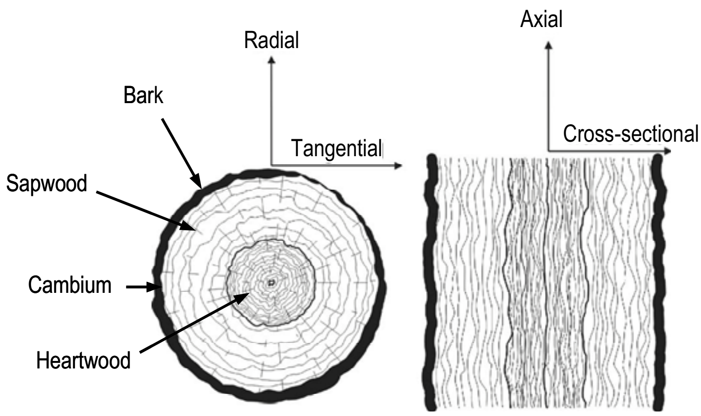


**Figure 5**. The principal anisotropy axes in a tree stem [7]

Wood exhibits both viscoelastic and plastic behaviour that is highly dependent on both moisture and temperature. The formation of small-size chips will show variations because; due to seasonal changes the logs will have varying temperatures and moistures content. At low temperatures more slender chips are formed (so called pin chips). Pin chips and sawdust are produced in larger quantities particularly when chipping frozen and very dry wood [8].

As for the influence of moisture it has been observed that the input of mechanical work decreases and the chip thickness increases with increasing moisture content to a fairly steady value when the saturation moisture content is reached [9].

It has been observed that cutting in radial direction of the annual growth ring gave a more (more regular in shape) uniform chip thickness than cutting in the tangential direction [10]. Twaddle showed that the there is a relation between annual growth ring orientation and chip thickness [11]. The chips are thicker when cut in the direction where the ring orientation is 0° to the knife-edge than for the situation where this orientation is 90° to the knife-edge. The chip thicknesses versus chip length are shown in Figure 6 for Loblolly pine. The average chip thickness increases almost linearly with increasing chip length.

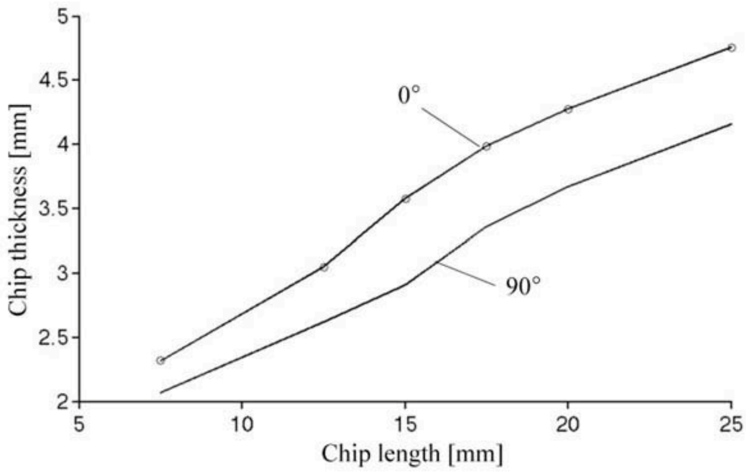


**Figure 6**. The average chip thickness vs. chip length when cut in different ring orientations

### 2.2.2. Operating parameters

Operating parameters such as different angles affect the chip thickness. The clearance angle, $\alpha$, controls the pulling of the logs towards the chipper plate [12], and therefore the chip size distribution. The clearance angle also affects the resulting cutting force [13].

The edge angle used, $\beta$, is normally between 30° and 37° [14]. Kivimaa and Murto [10] and Buchanan and Duchnicki [9] showed that a decrease in the knife angle from 40° to 30° reduces the chip thickness, the cutting force and chip damage. Buchanan and Duchnicki [9] also identified at least two chip formation processes i.e. an opening mode and a forward shear mode. The 20° and 30° knife angle produced chips by opening. The 40° knife angle formed chips by forward shearing in a small percentage of cases and the 50° knife angle formed chips by forward shearing in most instances.

At short chip lengths, an increase in bevel angle, $\beta'$, gives rise to a thinner chip, but the effect is opposite for longer chips (see Figure 8) [13].

With an increase in the spout angle, $\varepsilon$, the chips become thicker at the same length [15], [16]. It is believed that it is the complementary angle, $\lambda$ equal to $\lambda = 90 - (\alpha + \beta + \varepsilon)$, that controls the chip thickness rather than the spout angle $\varepsilon$ [15].

Pin chips are formed in larger quantities particularly when the cutting speed of the disc-chipper is very high [8].

## 2.3. Wood chip quality

In most pulping processes, a narrow chip thickness distribution is normally desired. In order to improve chip quality in terms of chip geometry, the mechanisms of chip formation must be better understood. In the following sections the importance of chip geometry are discussed.

### 2.3.1. Chip geometry

The importance of chip geometry has been a source for discussion since one first started making pulp out of chips. Chips produced by a disc chipper have a typical parallelepipedical shape, and the three dimensions; length, *L*, thickness, *t*, and width, *w* as defined in Figure 7. What is considered to be the optimal chip geometry differs between mills.

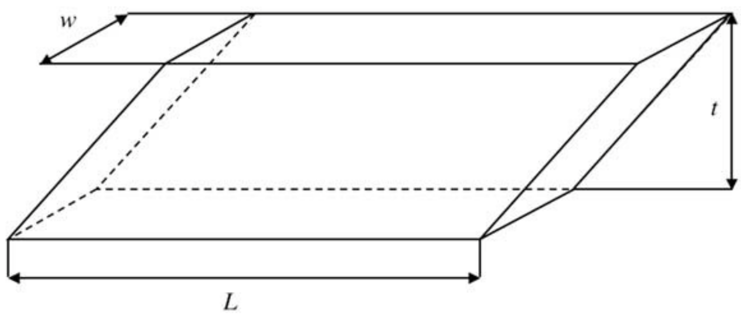


**Figure 7.** Chip geometry; length, *L*, thickness, *t* and with, *w*

It has been reported in the literature (c.f. [3], [10], [11] and [13]) that for the same process parameters and geometry of the chipping tool, the ratio between length and thickness of the chip is (in some average sense) constant. The matter is also discussed in [17] where an attempt to give an explanation to this observation is made.

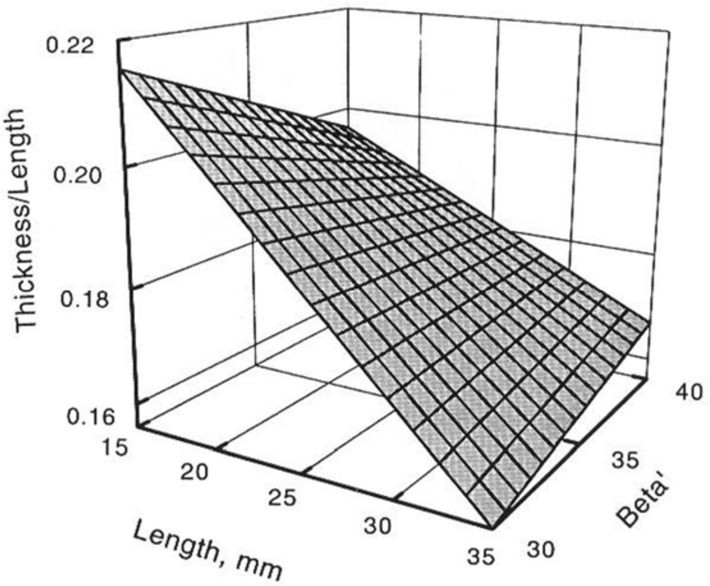


**Figure 8**. The relative chip length vs. chip length and bevel angle, $\beta'$ [13]

One requirement from the pulp and paper industries is that the variation in chip size distribution should be as small as possible because it affects (among other things) for example the packing degree in the compression screws used to transport the chips. It is generally accepted that the chip quality affects the whole pulp production and thereby the properties of the pulp.

In the case of chemical pulping, the wood is impregnated with chemicals. Small sized chips will be overcooked (i.e. the lignin-dissolving chemicals would have started to attack the cellulose and weaken the fibres). The penetration rate of acid sulphite liquors in the grain direction is 50 to 100 times faster than in the cross-grain directions. Other pulping liquors penetrate with nearly equal rates in all directions [18].

Oversized chips will be undercooked (i.e. will still be a chunk of unseparated fibres). Pieces of wood that are too small (e.g. 'shoe pegs' and sawdust) tend to agglomerate and create plugs in some types of chemical pulping equipment [18].

In the case of mechanical pulping, the refiner will only accept a piece of wood small enough to enter between the refiner discs [18].

## 2.4. Precompression

One of the main aims in the development of the mechanical pulping process is to achieve the desired degree of refining with minimum of energy expenditure. Reducing energy consumption is of utmost importance to producers of mechanical pulp, because of both increasing electricity prices and the importance of environmental issues. The interest of mechanical pretreatment has arisen due to the possibility to achieve energy reduction in refining.

To induce damage in wood chip, axial precompression has shown to be the most efficient method [19]. It was also shown that it was possible to achieve a reduction in refining energy of axially precompressed blocks of western hemlock by 9% for TMP (thermomechanical pulp) and 40% for CTMP (chemithermomechanical pulp).

Precompression of wood chips opens up the wood structure, which increases the specific surface [19], [20] and facilitates the penetration and uptake of chemicals and water. Dinewoodie [21], [22] observed that small dislocations of microfibrils in the cell wall progressed to grow to microscopic creases. The small creases grow successively to larger creases up to failure, with increasing load when compressing wood parallel to the grain.

There are a number of devices on the market, which can be claimed to give a compressive mechanical pretreatment. The most well known equipments are: Impressafiner [23], [24], Plug screw feeder [25], PREX impregnator [26] and Bi-Vis Extruder [27]. The drawback with those equipments is that; the pretreatment is not only in the axial direction of the wood fibre, also it have to be space in the mill in order to install this extra equipment and in many cases it will become a bottleneck.

A new possibility to achieve precompression in wood chips by adjusting the wood chipping process, is presented in [16], [28]. During chipping, large compressive stresses in the fibre direction of the chips, might occur in certain situations. In [17] is shown that one process parameter that determines the size of this compressive stress is the spout angle. This investigation is limited to an elastic, orthotropic material. However, in [29] is shown that the irreversible deformations are large when plasticity effects are allowed, indicating that the compressive damage (irreversible deformations) can be made large by choosing appropriate e.g. spout angles.

In both [16] and [28] this effect has been utilised to accomplish a more directed way of inducing compressive damage to the wood chips. Directed in this context means that different from the devices referred to above, the large compressive stresses that occurs during chipping (for certain process parameters) will act in the most beneficial direction i.e. parallel to the fibres.

# 3. METHODS

In the following section both experimental and analytical/numerical techniques are described. The methods are presented in the context of a review of each of the papers I, II, III, IV and V.

## 3.1. Review of paper I

The general aim with paper I was to develop a device and an experimental method by which it was possible to determine the strain field and to observe the fracture processes in wood during chipping.

### 3.1.1. Background

To be able to formulate criteria's for determining the onset of the creation of a wood chip; it is desirable to be able to study the deformation fields in a vicinity of the edge of the chipping tool. To that end, an experimental setup; WC05 has been developed where it was possible to control the cutting rate and to measure the force on the tool. The setup also admitted that the angle of the wood specimen with respect to the cutting plane could be varied in both a horizontal and a vertical plane.

To determine the deformations, a Digital Speckle Photography (DSP) equipment was used, which together with image processing software made it possible to study the local deformation fields i.e. the strain distributions on the surface of the wood specimen in a vicinity of the chipping tool i.e. the knife-edge.

DSP has found large applicability in a number of interesting applications. The method has been used among other things e.g. for estimating hygro-expansion of paper [30], visco-plastic properties of metals [31] and elastic properties of wood fibre walls [32]. Using this technique to study local parameters in connection with the wood chipping process is a novel approach.

### 3.1.2. Experimental Setup

To be able to perform the chipping in a well-defined way, a special fixture was designed. A photo of the experimental setup is shown in Figure 9. The ARAMIS measuring system [33] was used for the deformation analysis of the specimen surface. A hydraulic testing machine (MTS) was used to load the chipping tool. To fix the wood sample, a specimen holder was used (Figure 9). The whole chipping device is shown in Figure 10.

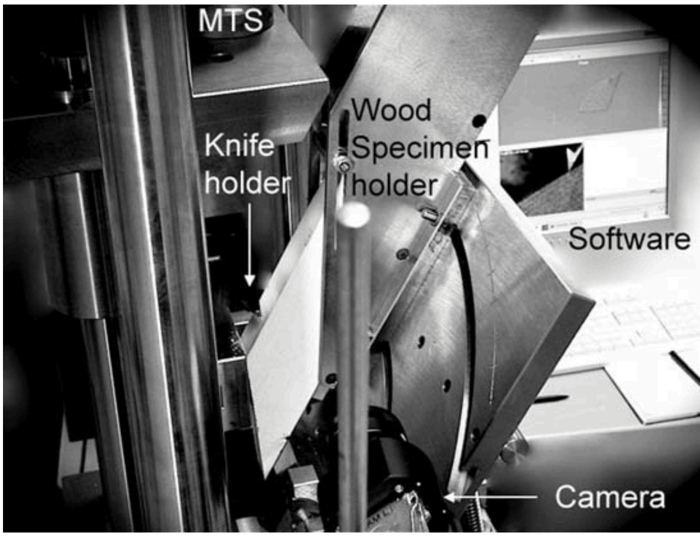


**Figure 9**. The experimental setup

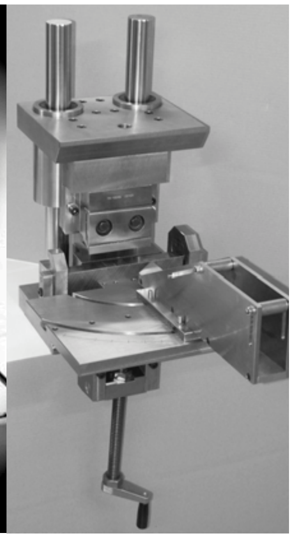

**Figure 10**. The chipping device; WC05

The loading of the chipping tool was accomplished by mounting the whole fixture in a servo hydraulic testing machine (MTS), and a 50 kN load cell was used to measure the applied force. In this way, the cutting rate can be controlled accurately.

In Figure 9 is also shown the camera belonging to the DSP equipment. A necessary condition for application of the technique is however, that the surface has a clearly identifiable structure. To that end, the surface of the wood specimen was first painted white and then sprayed with black colour to get a random pattern of black dots. The technique relies on that the motion of this pattern can be detected between frames; therefore the quality of the pattern is crucial.

As soon as at least two images of the test surface are captured, the relative displacement between them can be calculated. The software included in the equipment calculates the displacement field and after that, the strain field is obtained by numerical differentiation of the displacement field. For best results, the sample has to be perpendicular to the camera. For this study, fresh Norway Spruce (*Picea Abies*) in form of planks with cross section 35 X 82 $mm^2$ was used.

## 3.2. Review of paper II

The general aim with paper II was to investigate some aspects of the wood chipping process. To perform that, a simple analytical model was developed. To get some idea of the accuracy of the analytical model, a Finite Element (FE) analysis was also performed.

### 3.2.1. Analytical-modelling of the wood chipping process

To judge the influence of different parameters on the wood chipping process, a simple analytical model was developed. It might seem a strange thing to do since much more reliable results can be obtained by using the Finite Element (FE) method. This is true, however, an analytical model is much more transparent when it comes to judging the influence of specific parameters. The most severe limitations with both the analytical and the FE model are that the material is assumed to be linear elastic. On the other hand it is felt that existing models for anisotropic plasticity in metals lacks so much of physical relevance to be applied to wood with some confidence.

### 3.2.2. Analytical-model

The model assumes sliding friction and is based on an assumed displacement field together with the theorem of minimum potential energy. Small deformations, a plane strain situation, and a linear elastic orthotropic material, are assumed.

In Figure 11 is shown a single wood chip, assumed to be clamped at the lower boundary. The cutting-plane is at an angle $\beta$ to the horizontal plane and the knife tip is occupying an angle $\alpha$. The length and thickness of the chip is $L$ and $t$ respectively.

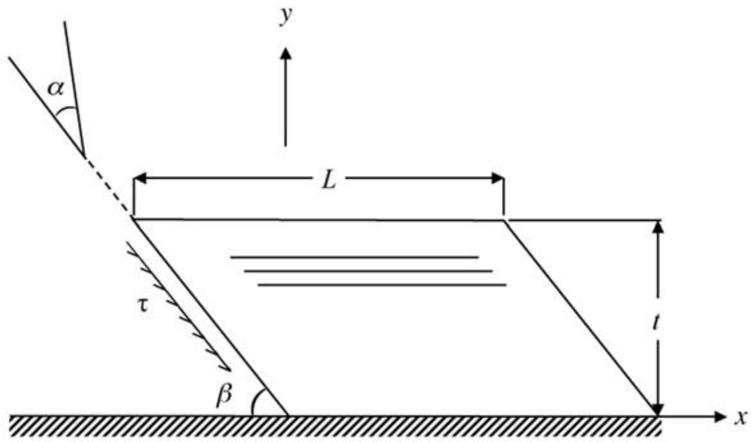


**Figure 11**. An idealised situation

On the left boundary, a shear load $\tau$ is assumed to be acting. Consistent with the assumption of small deformations is that $\alpha$, is a small angle. To simplify matters, coordinates $\xi$ and $\eta$ are used as shown in Figure 12:

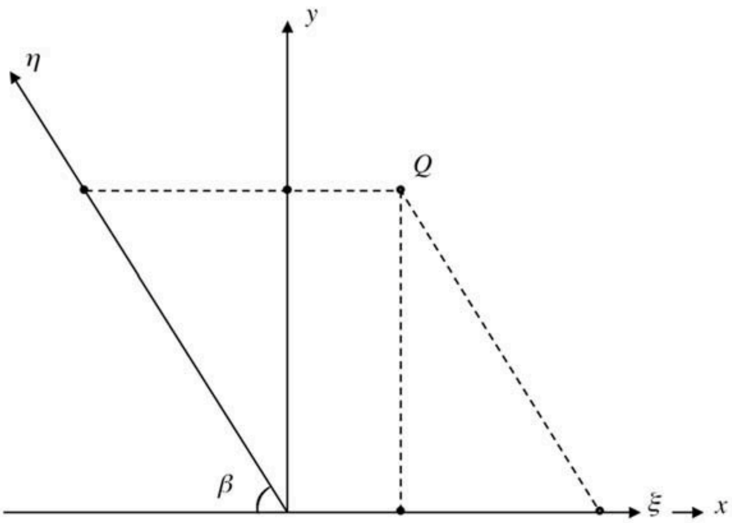


**Figure 12**. Coordinate transformation

It is assumed for $u_x(\xi, \eta)$ and $u_y(\xi, \eta)$ that:

$$u_x(\xi,\eta) = \eta f(\xi) \text{ and } u_y(\xi,\eta) = \eta g(\xi) \tag{1}$$

where $f$ and $g$ are functions to be determined. Note that the displacements given in 1 satisfies the requirement that the boundary $\eta = 0$ is clamped.

The boundary conditions that have to be satisfied is that the displacements in the $x$- and $y$- directions i.e. the displacements $u_x$ and $u_y$ equals zero on the boundary $\eta = 0$, and that points on the cutting plane $\xi = 0$, are confined to move on a plane making the angle $\alpha + \beta$ with the $x$-axis (Figure 13).

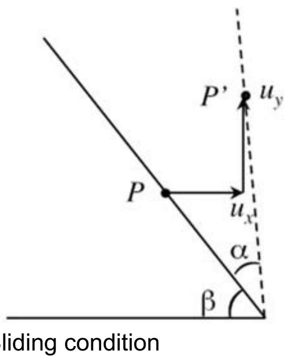


**Figure 13**. Sliding condition

Since the only external load is the shear load $\tau(\eta)$ on the boundary $\xi = 0$, the potential energy $U$ is given by:

$$U = \int_S \frac{1}{2}(\sigma_x \varepsilon_x + \sigma_y \varepsilon_y + \tau_{xy}\gamma_{xy})\mathrm{d}S - \int_\Gamma \tau\left(cu_x - su_y\right)\mathrm{d}\Gamma \tag{2}$$

where $\sigma_x$, $\sigma_y$ and $\tau_{xy}$ are the normal and shear stresses respectively and $S$ is the domain in the $x$- $y$- plane, occupied by the chip and $\Gamma$ denotes the boundary $\xi = 0$. For brevity, cos $\beta = c$ and sin $\beta = s$ has been used.

The stresses are obtained from the strains (derived from (1)) through the constitutive relations relevant for an orthotropic material. The differential equations for $f$ and $g$ and natural boundary conditions are obtained from $\delta U = 0$ i.e. from the requirement that the first variation of the potential energy equals zero.

Since the ambition is to include sliding friction in a consistent way and the stresses and hence the contact pressure on the boundary $\xi = 0$ will be linear in $\eta$, it is assumed for $\tau(\eta)$:

$$\tau(\eta) = k_\tau \eta + m_\tau \tag{3}$$

where $k_\tau$ and $m_\tau$ are constants to be determined. With $\tau(\eta)$ given by (3) the line integral in (2) can be evaluated to read:

$$-\int_\Gamma \tau(c\delta u_x - s\delta u_y)\mathrm{d}\Gamma = K_1 \delta g(0) - K_2 \delta f(0) \tag{4}$$

where $K_1$ and $K_2$ both depends linearly on $k_\tau$ and $m_\tau$

Having obtained $f$ and $g$, these are inserted into (2) to obtain the strains, which together with elastic constants will give the stresses and in particular, the contact pressure $p$ on the boundary $\xi = 0$ which is given in terms of the stresses on this boundary by:

$$p = -(\sigma_y c^2 + \sigma_x s^2 + 2\tau_{xy} cs) \tag{5}$$

Assuming Coulomb sliding friction one will have:

$$\tau = \mu p \tag{6}$$

where $\mu \geq 0$ is the coefficient of friction.

Since linear conditions are assumed, the contact pressure must depend in a linear way on the loading parameters $\alpha$, $k_\tau$ and $m_\tau$ so that $k_\tau$ and $m_\tau$ (for a given $\alpha$) can be determined such that $\tau = \mu p$ is satisfied. With $k_\tau$ and $m_\tau$ an approximate solution for $g$ and $f$ for a case of sliding friction can be obtained.

#### 3.2.3 FE- model

A FE analysis was also performed where sliding friction is assumed. The same assumptions as for the analytical model are made for the FE analysis i.e. small deformations, a plane strain situation and a linear elastic orthotropic material.

The problem was analyzed using the finite element method, implemented in the Matlab [34] code. Conventional four-node isoparametric elements with two degrees of freedom i.e., translation in the $x$-, and $y$-directions have been utilized. A thorough description of the element and its implementation procedure can be found in Bathe [35].

### 3.3. Review of paper III

The general aim with paper III was to develop a laboratory wood chipper by which it was possible to produce chips under realistic conditions.

#### 3.3.1. Background

In order to be able to study the damage mechanisms and in general the mechanisms active when a wood chip is created during the wood chipping process, it is crucial to have an experimental equipment in which chips can be produced under realistic conditions.

Previous studies c.f. [9], [36], [10], [11] and [13] have been restricted to low cutting rates if force on the cutting tool were measured. In cases where realistic cutting rates were considered, no forces were measured [15].

#### 3.3.2. Experimental Setup

The wood chipper; WC05/HSS consists in principle of an electrically powered motor, a circular disc and a shaft connecting them. The circular disc is equipped with a chipping tool i.e. a knife and an instrumented holder.

The wood specimen holder admits a variation of the cutting angle (spout angle and side angel) i.e. the angles in two planes. Also, the wood chipper is equipped with a window where the cutting process can be recorded through high speed filming. An overview of the wood chipper is shown in Figure 14.

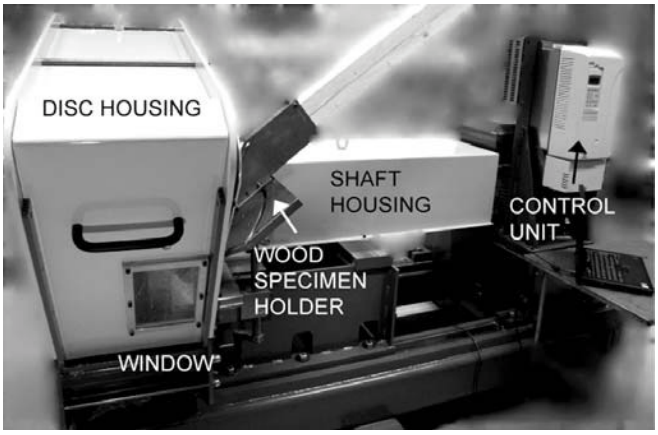

**Figure 14.** An overview of the wood chipper; WC05/HSS

#### 3.3.3. Force Measurements

By measuring the resulting force on the wood chipping knife in different situations one can obtain valuable information regarding the chipping process and the knife holder is to that end instrumented by force sensors (see Figure 15).

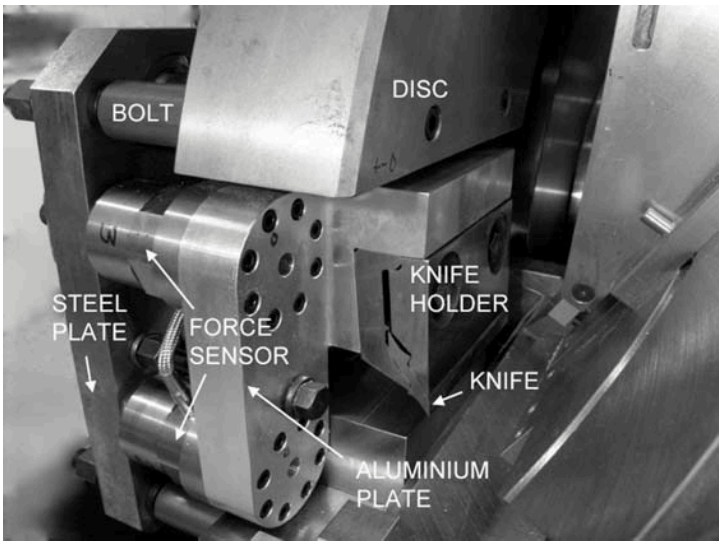

**Figure 15.** Here is a part of the disc housing removed in order to show a pert of the front side of the disc.

## 3.4. Review of paper IV

The general aim with paper IV was to investigate whether it was possible to modify the wood chipping process so as to induce cracking in the chips, which would be beneficial for the chip pretreatment and refining process in terms of energy consumption.

### 3.4.1. Background

Refining wood chips to produce mechanical pulp is a very energy-intensive unit operation. Previous investigations have shown that it is by means of mechanical pretreatment of wood chips, is possible to quite substantially reduce the electrical energy consumption in the subsequent refining c.f. [19]-[27].

### 3.4.2. Refining trial

Wood chips from spruce were produced under well-controlled conditions in a laboratory wood chipper at three different spout angles (30°, 40° and 50°) and at constant chip length. The chips were refined in a TMP (thermomechanical pulp) pilot refiner plant, and the pulp properties freeness and shives content were determined and evaluated as a function of specific energy consumption.

### 3.4.3. Energy consumption during chipping

To motivate the benefit of using a spout angle of 50° when producing chips for mechanical refining, it must be made clear that the increase in energy consumption when chipping at the spout angle 50° is extremely small compared to what is gained in the refining process. To that end, two tests regarding the energy consumption during chipping were performed.

### 3.4.4. Water adsorption test

In order to quantify the degree of cracking induced during chipping, an experiment was performed. Wood chips from each spout angle i.e. 30°, 40° and 50° were collected and immersed in water, and the weight as a function of time was recorded.

## 3.5. Review of paper V

The general aim with paper V was to investigate whether it was possible to achieve an improvement of some of the properties which are used to define the quality of printing grades, i.e. tensile index and specific light scattering coefficient by combining refining of chips produced using a spout angle of 50° with the addition of bisulphite to the dilution water during refining.

### 3.5.1. Background

It has recently been shown (see previous paper IV) that it was possible to improve the energy efficiency during first stage TMP refining by performing the wood chipping so as to increase the compressive damage in the chips and hence breaking up the wood structure. The parameter that was varied was the spout angle, i.e. the angle between the fibre direction of the wood specimen and the cutting plane. It have been shown earlier that by utilizing somewhat acidic conditions in CTMP production it is possible to improve the strength properties at the same energy consumption without loosing the for printing paper so important light scattering coefficient [37].

### 3.5.2. Refining trial

This study describes whether it is possible to achieve an improvement of some of the main properties used to define the quality of printing grades, i.e. tensile index and specific light scattering coefficient by combining refining of chips produced using spout angle of 50° (more prone to induce directed cracks) with the addition of bisulphite solution ($NaHSO_3$) to the dilution water during chip refining.

## 4. RESULTS AND DISCUSSIONS

In the following section results from an experimental investigation of the deformation field in a wood specimen during chipping, and from an analytical/numerical model of the chipping process are presented. Further on, a laboratory chipper and the results from two refining trials are presented.

### 4.1. Results from the experimental investigation (Paper I)

In paper I the loading of the chipping tool was accomplished by mounting the whole fixture in a servo hydraulic testing machine (MTS), and a 50 kN load cell was used to measure the applied force. Displacement-controlled testing was performed with a crosshead speed of 1.0 mm/s and the force on the chipping tool was measured.

The charge-coupled-device (CCD) camera focused on the part of the specimen closest to the knife-edge and the software was programmed to take 12 photographs per second for a 2D analysis. The material used in the chipping test was Norway spruce (Picea abies) with a moisture content corresponding to green wood. For the test, a specimen with cross section dimensions of 35 x 82 $mm^2$ was used. The following cutting angles were chosen: sharpness angle $\beta = 34°$, clearance angle $\alpha = 3°$, spout angle $\varepsilon = 30°$ (Figure 14).

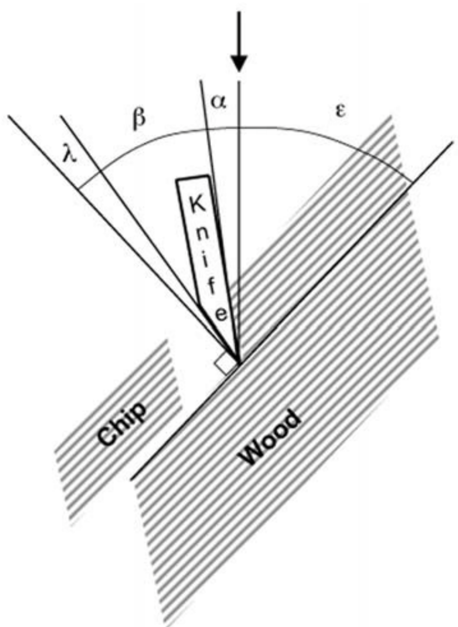


**Figure 16.** The cutting angles $\alpha$, $\beta$ and $\varepsilon$, and the arrow indicates the cutting direction

Due to limitations of the camera in the DSP system, the cutting rate had to be kept as low as 1 mm/s, which is far below the rate used in the chipping process. However, even though it is well known that wood in general shows a rate dependency, it is believed that studies of this kind will shed some light over the basic mechanisms involved in creating a wood chip.

An example of the output from a DSP study can be seen in Figure 17, where the normal strain in the radial (*R*) direction is shown.

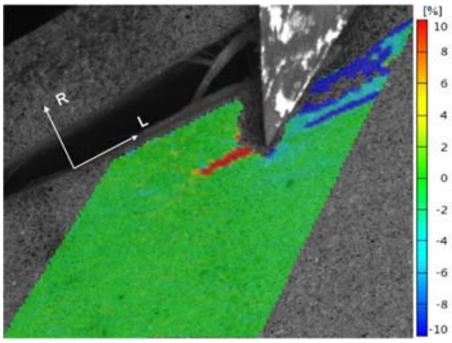


**Figure 17**. Normal strain distribution in the R-direction

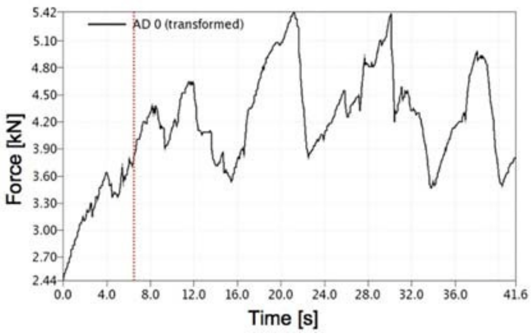


**Figure 18**. Force vs. time

In Figure 17, the read colour indicates a thin region with high normal strains just prior to chip formation. In Figure 18, the force vs. time (in essence the knife edge position, since the cutting rate is constant) is shown. The red, dotted vertical line refers to the instant for which Figure 17 is relevant. It can be observed that the force curve is composed of large amplitude variations on which smaller variations are superimposed. The large variations correspond to chip formation while the smaller ones correspond to the initiation of smaller sub-critical cracks.

During the experiments mainly three different types of chip formation processes have been identified i.e. an opening-modus (Figure 19), a forward shear modus (Figure 20) and a mode according to Figure 21 which in lack of better might be referred to as a remote opening mode.

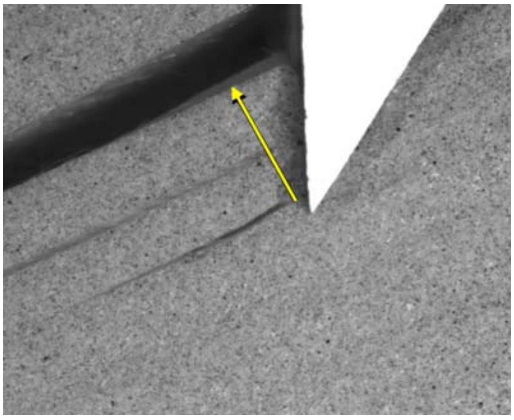

**Figure 19**. Opening mode

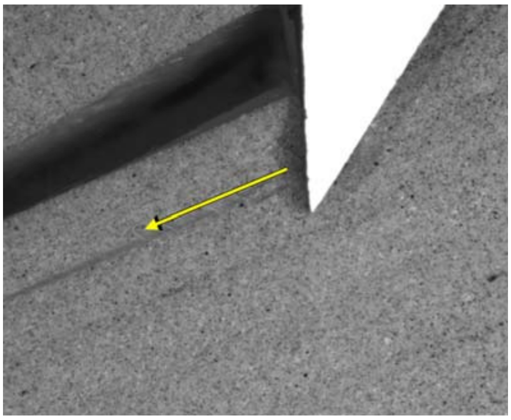

**Figure 20**. Forward shear mode

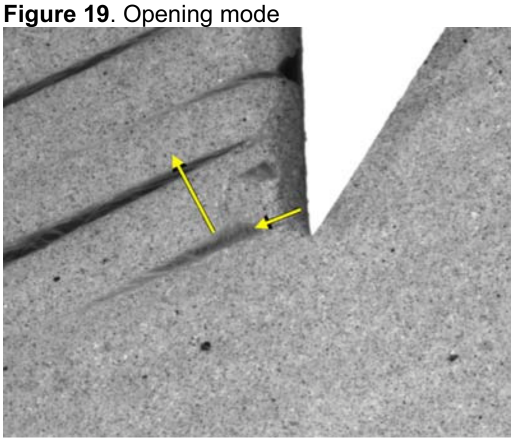

**Figure 21**. Remote opening mode

Which one of the processes that will be the most frequent, is largely dependent on the friction between the wood material and the chipping tool. Figures 19, 20 and 21 show the influence of friction ranging from low friction in Figure 19 to high friction in Figure 21. To get an as narrow as possible chip thickness distribution, a god start would be to ascertain that only one fracture process is active and this means that the surface of the chipping tool should be such that the friction is as low as possible.

Apart from e.g. the friction, the process of chip formation is also greatly influenced by the mechanical properties of the wood and it is obvious that it is impossible to get a smaller variation in the chip thickness than what is dictated by the inherent variations in the wood material.

Another interesting observation made, is that before a chip or a small sub critical crack has formed, the force vs. time relation is always almost linear despite the fact that the material behaviour of wood is highly non-linear. Considering a hypothetical situation with a homogenous semi-infinite structure with no intrinsic length scale, it can be shown that irrespective of the material behaviour, the load vs. penetration depth is always a linear relation (self similarity) provided that the chipping tool has straight edges.

In wood, the assumption regarding the intrinsic length scale is obviously not true since one length scale is determined by the annual growth ring structure. Also, the assumption regarding the semi-infinite nature of the problem does not hold in a real situation.

In Figures 22 and 23 is shown the force vs. displacement (penetration depth) for two different values of the distance, *d*, from the cutting plane to the free end. In each figure is shown the result from two tests.

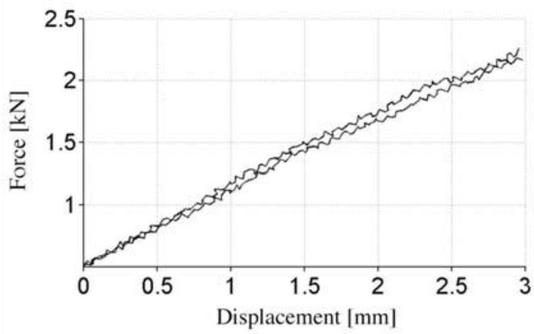


**Figure 22**. Force vs. displacement for *d*=10 mm

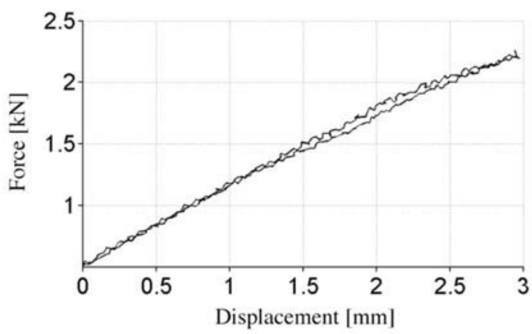


**Figure 23.** Force vs. displacement for *d*=20 mm

It can be observed that even though the assumptions regarding homogeneity and semi-infinity are violated, the cutting process is approximately self-similar.

## 4.2 Results from the Analytical and Numerical Study (Paper II)

In paper II elastic data for wet spruce [29] were used in the calculations i.e. with:

**Table 1**. Material properties

| $E_L$ [MPa] | $E_R$ [MPa] | $G_{LR}$ [MPa] | $\nu_{LR}$ | $\nu_{RL}$ |
|---|---|---|---|---|
| 10000 | 820 | 660 | 0,4 | 0,033 |

In Table 1, *E*, *G* and *ν* are the Young's modulus, the shear modulus and the Poisson's ratio respectively. The subscripts *L*, *R* denote the principal material directions, namely the longitudinal and radial directions relative the original log.

With elastic data taken from Table 1, the stresses $\sigma_y$ and $\tau_{xy}$ along the crack-plane are calculated for $\alpha = 10°$, $L$ =25 mm, $t$ = 5 mm, $\mu = 0{,}2$, $\beta = 60°$. The calculated stresses and are shown in Figure 24 versus $\xi/t$ and normalized with respect to $E_R$.

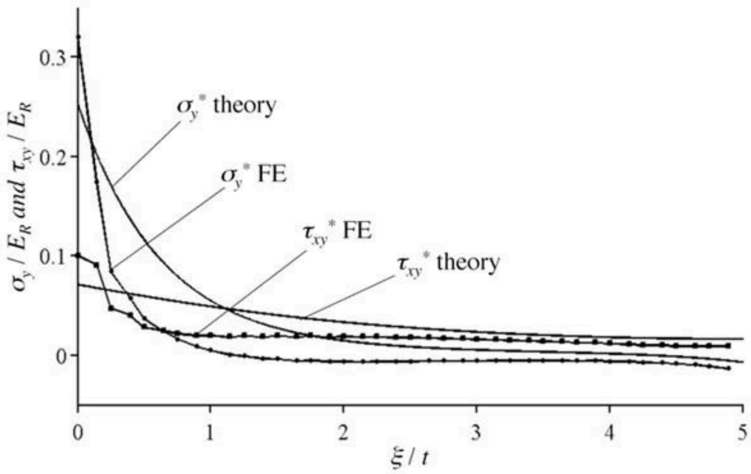


**Figure 24**. Normalized stresses $\sigma_y$ and $\tau_{xy}$ along the crack-plane for the case $\beta = 60°$ and $\mu = 0{,}2$

It was observed that the model indicates a large influence of $\beta$ on the magnitude of $\tau_{xy}$ i.e. a small value of $\beta$ will give a more pronounced opening mode compared to a large value of $\beta$.

In Figure 25 are shown the contact stress distributions for the cases considered in Figure 24, and for the case $\beta = 30°$.

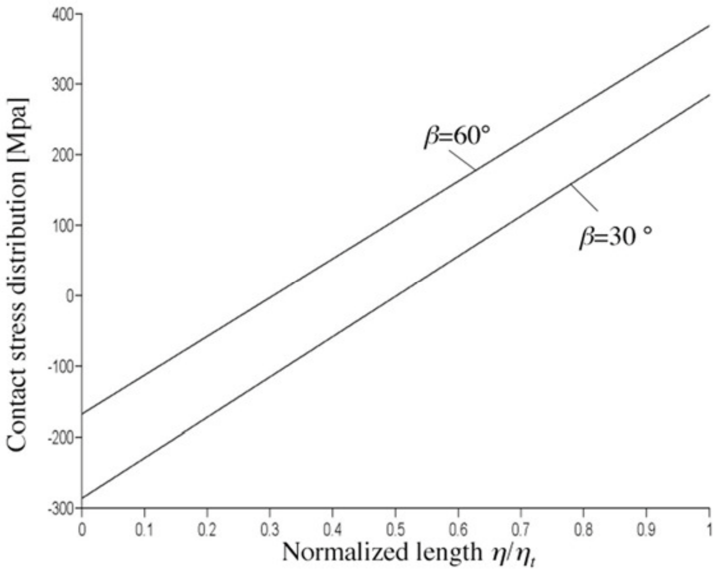


**Figure 25**. The contact stress distribution on the chip for $\beta$ = 60° and $\beta$ = 30° along the chip-end

It was also observed that the model indicates contact stresses being tensile in a region close to the tip of the chipping tool. This is due to that the assumed displacements are too simple. However and in spite of this, the model predicts a decreasing contact pressure with a decreasing $\beta$.

## Comparison of results

Results from the analytical model were compared with results from FE analysis (Figure 24). The theoretical calculated stresses $\sigma_y$ and $\tau_{xy}$ along the crack-plane agree reasonably well with the FE calculated stresses for $\beta = 60^\circ$. For smaller values of $\beta$, the assumption made regarding the displacement field becomes insufficient.

## Constant length-to-thickness ratio

It has been reported in the literature (c.f. [3], [10], [11] and [13]) that for the same process parameters and geometry of the chipping tool, the ratio between length and thickness of the chip is (in some average sense) constant. Some consequences of this observation will now be discussed. Consider Figure 26 below:

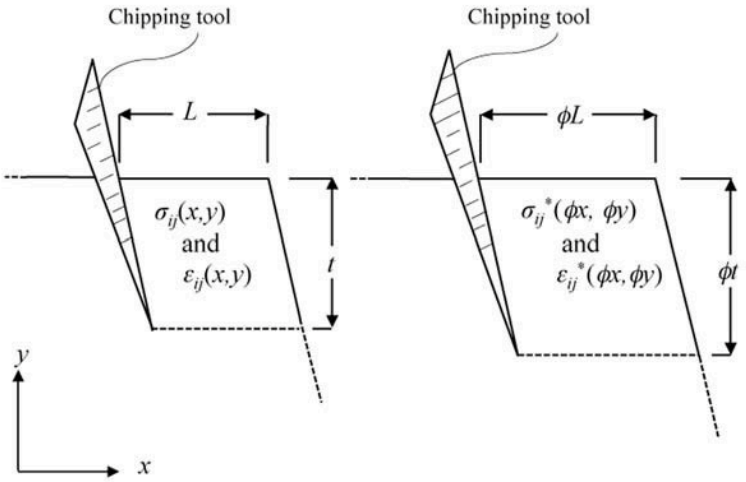


**Figure 26**. Quarter infinite geometries

If it is assumed that there are no intrinsic length scales associated with the material, then the stress and strain fields in the left geometry i.e. $\sigma_{ij}(x, y)$ and $\varepsilon_{ij}(x, y)$ will be related to the same fields in the scaled geometry according to:

$$\sigma_{ij}(x,y) = \sigma_{ij}^*(\phi x, \phi y) \text{ and } \varepsilon_{\mathrm{ij}}(x,y) = \varepsilon_{ij}^*(\phi x, \phi y) \quad (7)$$

This is often referred to as self-similarity. Obviously, the assumption that there are no intrinsic length scales associated with wood is not true, since wood have a structure. On one length scale an annual ring structure can be identified and on a smaller length scale, a fibre structure can be seen etc. However, in spite of this, it is shown in [36] that the wood chipping process is approximately (at least for the cases considered) self-similar.

Assuming that self-similarity holds, then the stresses along the horizontal plane indicated in Figure 26, will be identical in the normalised $x$- coordinate $\psi = x/(\phi L)$, for all values of $\phi$. In the same way, the stresses along the left inclined plane will be the same in the normalised coordinates $\nu = y/(\phi t)$. From experiments, it can be observed that short cracks appear when the chipping tool penetrates the wood piece to be chipped. However, it is not until the tool has penetrated a critical distance, that such a small crack becomes critical and a chip is formed.

The conclusion is that it is not the stress field close to the tip of the tool that determines the creation of a chip, but it is the stress field over the entire crack-plane that is critical.

This is very much unlike for instance what is seen in e.g. fracture mechanics where the crack-length has an influence on the strength. Another example is the strength of an infinite plate with a circular hole where the diameter of the hole influences the strength.

## 4.3 Results from the Laboratory chipper development (Paper III)

In paper III a laboratory chipper was developed that admit chipping at rates that can be varied in a large interval, i.e. at rates ranging from zero to 50 m/s. The wood specimen holder admits a variation of the cutting angles (spout angle and side angle).

The knife used to cut the chips is mounted in a knife holder, which is instrumented in such a way that forces in three orthogonal directions can be measured. Since the actual force and measured force differ due to inertia effects, a simple mathematical model is developed and used to evaluate the forces acting on the knife. In Figure 27 a typical result from a single cut, performed at the spout angle $\varepsilon$ = 30° and the cutting rate $v_c$ = 15 m/s. On the vertical axis is shown the cutting force $P_y$ as an electrical voltage and on the horizontal axis is shown the time.

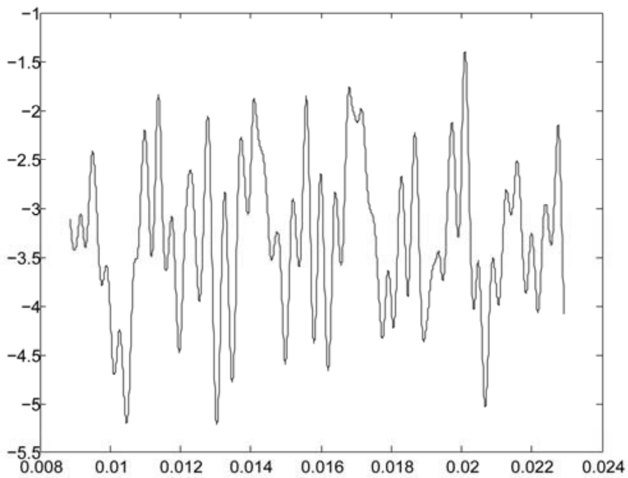


**Figure 27.** $P_y$ (V) vs. Time (s)

## 4.4 Results from the TMP study (Paper IV)

In paper IV a TMP trial was carried out to evaluate if the wood chipping process can be used as a possible mechanical chip pretreatment method.

In Figure 28 is shown the outcome of the refining trails. The circles and the squares denote chips produced at spout angle 30° and 40° respectively. The unfilled and filled triangles denote the chips produced at spout angle 50° but they represent two production rates such that the unfilled triangles are the outcome from a higher production rate while the filled triangles are the outcome from a lower production rate.

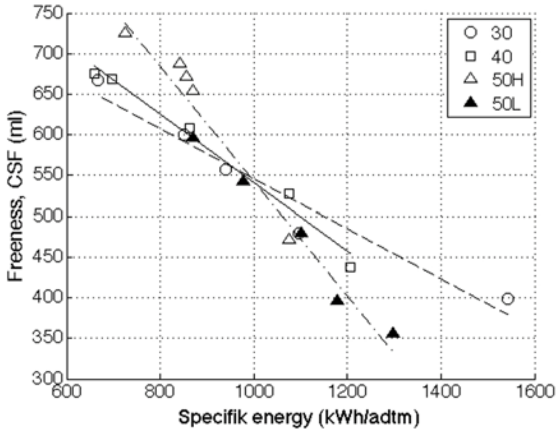


**Figure 28.** Freeness vs. Specific energy

For a specific energy below about 1000 kWh/ton the curve for the pulp from chips cut at the spout angle 50° is above the other curves. One explanation might be that since chipping at a spout angle of 50° resulted in a large amount of clusters of chips, i.e. chips which were not entirely disintegrated, much energy might be consumed at an early stage just to brake up the clusters. For specific energies above 1000 kWh/ton, the process can benefit from the larger compressive damage induced by using the spout angle 50°. By extrapolating the 30° spout angle curve to CSF 350 ml it can be seen that the difference in energy compared to the spout angle 50° is approximately 20%.

### Energy consumption during chipping

Two simple experiments shows, omitting possible effects of that the cutting energy might be rate dependent, that the increase in energy consumption per ton dry chips during chipping between spout angles 30° and 50° is only marginal, compared to the specific energy consumption during first stage refining (see Figure 28) which is in the order of 1000 kWh per ton dry pulp.

Water adsorption test

The results from the water adsorption test are shown in Figure 29. On the vertical axis is the specific water adsorption i.e. the difference between current weights minus the dry weight divided by the dry weight. On the horizontal axis is the logarithmic time. The results indicate that for chips produced at a spout angle of 50° the specific water adsorption is clearly higher, which implies a larger specific surface than for chips with the spout angles 30° and 40°.

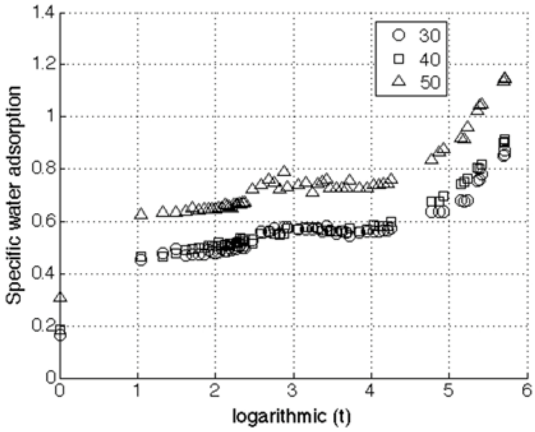


**Figure 29.** Specific water adsorption vs. logarithmic time

## 4.5 Results from the CTMP study (Paper V)

In paper V it was investigated how the refining of chips produced at two spout angles, i.e. 30° and 50°, influenced on the properties of CTMP (chemimechanical pulp).

In Figures 30-32 is shown the outcome of the refining trials. The circles denote chips produced at spout angle 30° and triangles 50° (directed chipping). The unfilled markers denote TMP pulp production and filled markers denote CTMP pulp production.

It was found that the specific energy input for a certain CSF (Canadian Standard Freeness) showed a reduction in refining energy in the order of 15% for pulp from refining of chips by directed chipping. It was also found that the addition of the chemical $NaHSO_3$ to the dilution water had no influence on the specific energy value for a given CSF value (see Figure 30).

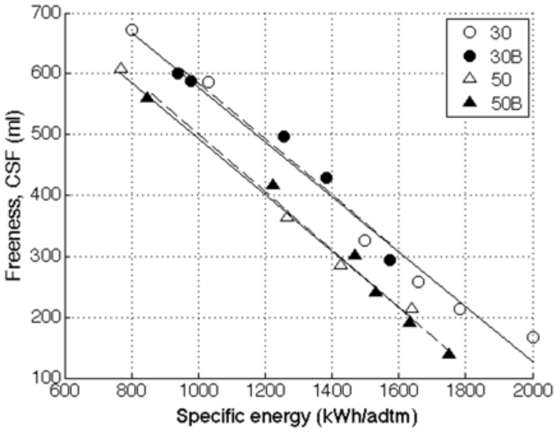


**Figure 30.** Freeness vs. Specific energy

For printing grades, the tensile index and specific light scattering coefficient are important parameters. From the Figures 31-32 one can see that for the same energy consumption there is a substantial improvement for both tensile index and light scattering coefficient for pulp made from chips produced through directed chipping and with bisulphite added to the dilution water as compared to conventional TMP.

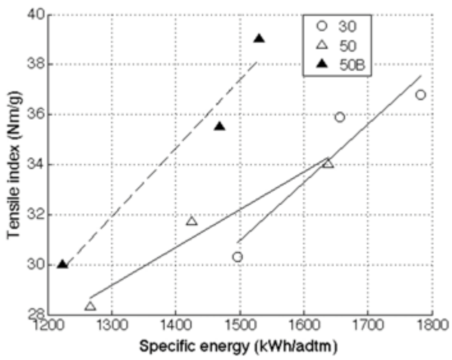


**Figure 31.** Tensile index vs. specific energy

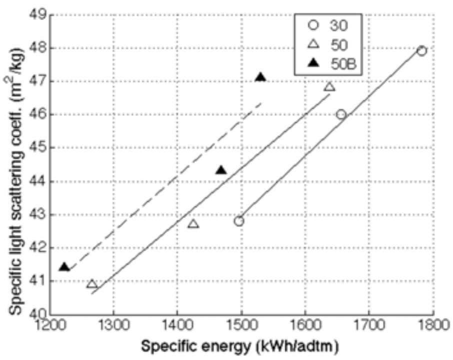


**Figure 32.** Specific light scattering coefficient vs. specific energy

# 5. CONCLUSIONS

To study details regarding the chipping process, an experimental method was developed and was found to be a versatile tool in particular when it comes to studying the local strain fields in the vicinity of the cutting edge of the chipping tool.

One outcome from studies using this experimental method is that it is observed that there exist different types of fracture processes, each giving different chip thicknesses. It is concluded that the friction between the wood and the chipping tool is probably one crucial factor for the chip formation process.

Another outcome from the above experiment is that the indentation process is approximately self-similar.

Also it is concluded that just prior to the formation of a chip, there is a concentration of strains in a narrow zone in a thin region starting from the edge of the tool and directed parallel to the grain.

Finally it is suggested that the stress field over the entire crack-plane, i.e. not only the stress field close to the tip of the chipping tool, is critical for chip creation rather than just the latter.

In order to get a more qualitative understanding of the chipping process an analytical model was developed. The model predicts among other things the normal and shear strain distribution in the crack-plane prior to crack initiation and the analytical distributions were found to be in reasonable agreement with the corresponding distributions obtained from a FE analysis.

One drawback with the experimental method discussed above is that the cutting rate is very low compared to a real situation. Hence a laboratory chipper was developed and found to be a versatile tool in the process of increasing the understanding of the wood chipping process, i.e. in particular when it comes to studying the influence of cutting angles, cutting rate, knife wear and modifications of the geometry of the knife.

Combining the use of the laboratory chipper with refining trials it was concluded that modifying the wood chipping process, i.e. increasing the spout angle, was beneficial regarding the energy consumption during refining.

It was observed that the specific water adsorption was larger for chips produced at the spout angle 50°, as compared to chips produced at spout angles 30° and 40°, which implies that chipping at spout angle 50° will give a larger specific surface area than does chipping at lower spout angles.

It was also concluded that combining refining of wood chips produced at a spout angle of 50° and adding bisulphite to the dilution water during chip refining improved the tensile index and light scattering coefficient at the same energy consumption.

## 6. ACKNOWLEDGMENTS

I want to thank people working at Fibre Science and Communication Network (FSCN) at Mid Sweden University and the Department of Natural Sciences, engineering and mathematics for contributing to the progressive and inspiring working atmosphere.

The Swedish KK-Foundation and the European Regional Development Fund are acknowledged for financial support.

Iggesund Tools AB, Holmen Paper AB and Saint-Gobain Abrasives are greatly acknowledged for supporting, in different ways, the project.

Iggesund Tools AB, GRW PRODUKTER AB, and Staffan Nyström at the Mid Sweden University are greatly acknowledged for their support in developing of the experimental equipments.

Thanks to all persons at SCA R&D centre that have helped me.

I would like to thank my supervisors Prof. Torbjörn Carlberg and Prof. Per Engstrand for being ever-helpful and supportive. I would also like to thank Prof. Per Gradin for valuable comments on the thesis.

All my colleagues and friends at the Mid Sweden University are also acknowledged.

Anna Haeggström is acknowledged for here outstanding work taking care of administrational tasks and being ever-helpful.

Many thanks to IMT, and all the people that comes every now and then for coffee at "Torken".

Last, but not least, thanks to my family, my children Sandra, Erika, Mattias and Emil. Also thanks to my extra children and my friends for supporting me in this.

## 7. REFERENCES


[1] Keays J.L. (1979); *History of wood chipping*; Chip Quality Monograph, Hatton J.V. (Editor), Pulp and Paper Technology Series No 5 (TAPPI)

[2] Original picture from Metso Paper.com

[3] Hartler N (1986); *Chipper design and operation for optimum chip quality*; Tappi J. Vol. 69, No. 10: 62-66

[4] Svensson B.A. (2007); *Frictional Studies and High Strain Rate Testing of Wood under Refining Conditions*; Doctoral thesis, Mid Sweden University, Department of Natural science, Sundsvall

[5] Fengel D., and Stoll M. (1973); *Variation in cell cross-sectional area, cell-wall thickness and wall layer of spruce tracheids within an annual ring*; Holzforschung 27: 1-7

[6] Persson Kent (1997); *Modelling of Wood Properties by a Micromechanical Approach*; Licentiate of technology thesis, Lund University: ISSN 0281-6679

[7] Zmitrowicz A. (2006); *Models of kinematics dependent anisotropic and heterogeneous friction*; International Journal of Solids and Structures, Vol. 43, Issues 14-15: 4407-4451

[8] Hartler N. and Stade Y. (1979); *Chip specifications for various pulping processes*; Chip Quality Monograph, Hatton, J.V. (Editor), Pulp and Paper Technology Series No. 5 (TAPPI)

[9] Buchanan J.G. and Duchnicki T.S. (1963); *Some Experiments in Low-Speed Chipping*; Pulp and Paper Magazine Can. May 1963: T235-T245

[10] Kivimaa E. and Murto J.O. (1949); *Investigations on factors affecting chipping of pulp wood*; Statens Tekniska Forskningsanstalt, Finland Publ.9

[11] Twaddle A. (1997); *The influence of species, chip length, and ring orientation on chip thickness*; Tappi J Vol. 80, No. 6: 123-131

[12] Hartler N. (1962 c); *Studies on the Suction Feeding of Chippers*; Svensk Papperstidning Vol. 65, No 12: 475-487

[13] Uhmeier A. (1995); *Some fundamental aspects of wood chipping*; Tappi J Vol. 78, No. 10: 79-86

[14] McLauchlan T.A. and Lapionte J.A. (1979); *Production of chips by disc chippers*; Chip Quality Monograph, Hatton, J.V. (Editor), Pulp and Paper Technology Series No 5 (TAPPI)

[15] Hartler N. (1962a); *The Effect of Spout Angle as Studied in an Experimental Chipper*; Svensk Papperstidning Vol. 65, No. 9: 351-362

[16] Paper IV in "On the Wood Chipping Process – A study on basic mechanisms in order to optimize chip properties for pulping", Hellström L.M., Dissertation, Mid Sweden University 2010

[17] Hellström L.M., Isaksson, P. Gradin P.A. and Eriksson K. (2009); *An Analytical and Numerical Study of some Aspects of the Wood Chipping Process*; Nord. Pulp Paper Res. J., Vol. 24, No. 2: 225-230

[18] Fuller W.S. (1983); *Chipping, Screening and cleaning*; Pulp and Paper Manufacture Vol. 1 Properties of Fibrous Raw Materials their Preparation for Pulping, M.J Kockrek and C.F.B. Sterens, Tappi; ISBN: 0-919893-07-4

[19] Frazier W.C. and Williams G.J. (1982); *Reduction of specific energy in mechanical pulping by axial precompression of wood*; Pulp and Paper Canada: Vol. 83, No. 6: T162-T167

[20] Berg J-E. and Gradin P.A. (2000); *Effect of Temperature on Fracture of Spruce in Compression, Investigated by Use of Acoustic Emission Monitoring*; Journal of Pulp and Paper Science: Vol. 26, No. 8: 294-299

[21] Dinwoodie J.M. (1968); *Failure in Timber. Part 1. Microscopic Changes in Cell Wall Structure Associated with Compression Failure*; J. Intl. Wood Sci.: Vol. 21, 37-53

[22] Dinwoodie J.M. (1974); *Failure in Timber Part 2: The Angle of Shear Through the Cell Wall During Longitudinal Compression Stressing*; Wood Sci. Technol.: Vol. 8, 56-67

[23] Sabourin M.J. (2000); *Evaluation of a Compressive Pretreatment Process on TMP Properties and Energy Requirements*; Pulp and Paper Canada: Vol. 101, T54-T60

[24] Hill J., Sabourin M., Johansson L. and Aichinger J. (2009); *Enhancing Fibre Development at Reduced Energy Consumption Using TMP Sub-Processes and Targeted Chemical Application and Commercial Scale Results*; Proceedings International Mechanical Pulping Conference 2009

[25] Law K.-N. and Lanouette R. (2000); *Effect of Mechanical Conditioning of Chips on the Quality of Softwood TMP*; Pulp and Paper Canada: Vol. 101, No. 7, T189-T193

[26] Peng F. and Granfeldt T. (1996); *Changes in the Microstructure of Spruce Wood Chips After Screw Press Treatment*; Journal of Pulp and Paper Science: Vol. 22, No. 4, J140-J144

[27] De Choudens C., Lombardo G., Michalowicz G. and Robert A. (1985); *Destructuration of Wood Chips in a Cylinder Press*; Paperi ja Puu: No. 3, 108-116

[28] Paper V in "On the Wood Chipping Process – A study on basic mechanisms in order to optimize chip properties for pulping", Hellström L.M., Dissertation, Mid Sweden University 2010

[29] Uhmeier A. and Persson K. (1997); *Numerical Analysis of Wood Chipping*; Holzforschung Vol. 51, No. 1: 83-90

[30] Lif J.O., Fellers C., Söremark C. and Sjödahl, M. (1995); *Characterizing the In-Plane Hygroexpansivity of Paper by Electronic Speckle Photography*; Journal of Pulp and Paper Science: Vol. 21, No. 9: J302-J309

[31] Kajberg J. and Wikman B. (2007); *Viscoplastic parameter estimation by high strain-rate experiments and inverse modelling – Speckle measurements and high-speed photography*; International Journal of Solids and Structures 44: 145-164

[32] Bergander A. and Salmén L. (2000); *The Transverse Elastic Modulus of the Native Wood Fibre Wall*; Journal of Pulp and Paper Science: vol.26, No. 6: 234-238

[33] GOM mbH (20040820); ARAMIS user manual, en Rev; Germany

[34] Matlab (2007); Version 7.4. The MathWorks Inc., Natick, MA USA

[35] Bathe K.J. (1982); *Finite element procedure in engineering analysis*; Prentice-Hall, USA

[36] Hellström L.M., Gradin P.A. and Carlberg T. (2008); *A method for Experimental Investigation of the Wood Chipping Process*; Nord. Pulp Paper Res. J., Vol. 23, No. 3: 339-342

[37] Svensson E., Engstrand P., Htun M. and Svensson B. (1994); *A Better Balance Between Shives Content and Light-Scatter Properties of TMP/CTMP by Sulphur dioxide Gas-Phase Impregnation Prior to Defibration*; Nord. Pulp Paper Res. J., Vol. 9, No. 3: 167-171