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FRACTURE PROCESSES IN WOOD CHIPPING

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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 the process parameters and the quality of the chips. The objective of this thesis is to obtain an understanding of the fundamental mechanisms behind the creation of wood chips.

Both experimental and analytical/numerical approaches have been taken in this work. The experimental investigations were performed with an in-house developed equipment 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. The analytical distributions are in reasonable agreement with the corresponding distributions obtained from a finite element analysis.

Keywords: Wood chipping, Chip formation, Digital Speckle Photography, Friction, Fracture Processes, Analytical model

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. Målet 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 gjordes med hjälp av en i egen utvecklad utrustning och digital speckle fotografering.

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. De analytiskt bestämda fördelningarna stämmer relativt väl överens med motsvarande fördelningar beräknad med finit element analys.

TABLE OF CONTENTS

LIST OF PAPERS

This thesis is mainly based on the following two 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 & Paper Research Journal , 23:3. 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.
To be submitted for publication in Nordic Pulp & Paper Research Journal

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 is for example in the chemical pulping process, where 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 demand from the pulp and paper industry is that the chip quality should be as uniform as possible. It seems to be a consensus that the primary quality requirement of the chips is that they should have an as narrow as possible a thickness distribution. This view on quality comes from e.g. that in order to produce chemical pulp, the chips have to be impregnated with chemicals, and with a very narrow thickness distribution all chips are uniformly impregnated. If so, the quality of the pulp will presumably also become very uniform.

The important thing is not primarily to produce chips with a given thickness but that the thickness of the chips does not vary over time. This means that it is not necessarily so that the chipping tool should be as sharp as possible but rather that the chipping tools retain their characteristics for a long time. To be able to predict the impact of for example tool wear on the chip thickness, one has to have a detailed understanding of the underlying mechanisms of chip formation.

To be able to formulate criteria's 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. To determine the deformation fields, a Digital Speckle Photography (DSP) equipment is used, which together with image processing software makes it possible to determine the strain field on the surface of the wood specimen.

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

Further on, to get a qualitative picture regarding the influence of different parameters on the stress and strain fields in the chip, a simple analytical model is developed. The relevance of the model is checked against a more general Finite Element (FE) model.

To conclude, this thesis is an attempt to develop both experimental and analytical tools for the study of the wood chipping process.

2.   WOOD CHIPPING

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. After that, the concept of wood chip quality will be discussed.

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.

In most pulp mills, the logs are run through a process line specially constructed for producing chips. The chipping is normally performed in a by a disc chipper, where the basic design (the Wigger chipper) was invented 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. The action of a disc chipper is shown schematically in Figure 1.
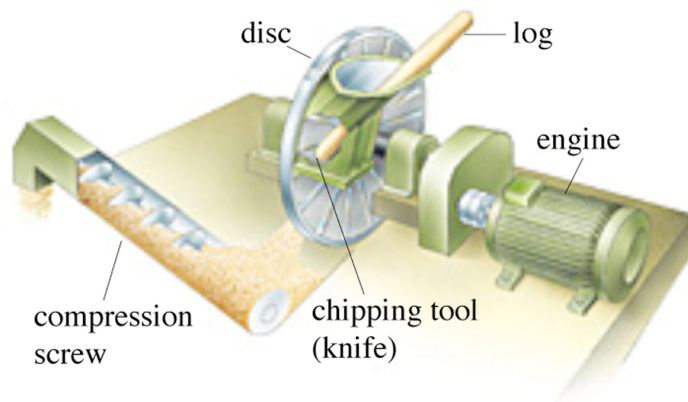

Figure 1. Wood chipping by a disc chipper [2]

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, and the spout angle (cutting angle) (Figure 3), ε. The feeding through the chipper can be controlled by the clearance angle (pulling angle) (Figure 3), α [3].
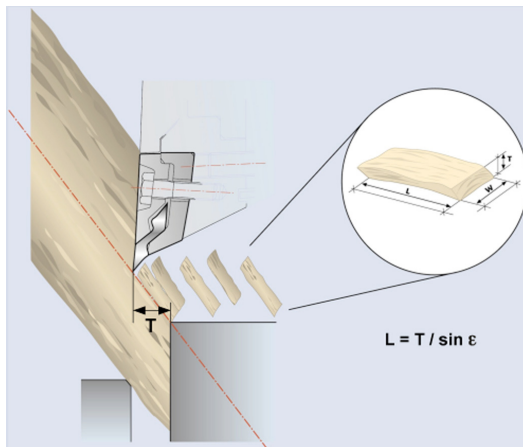
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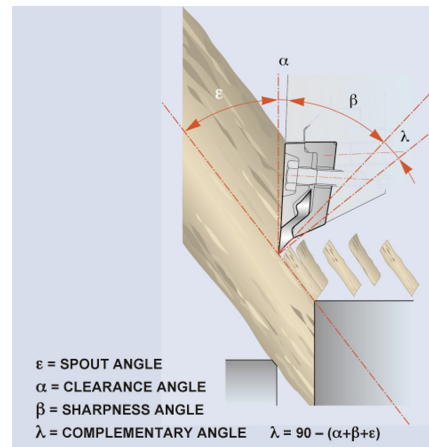**Figure 2**. The *T*-dimension (with the permission of Iggesund Tools AB)

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

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

The knifes are mounted in radial directions on the chipper disc. 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 range 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.
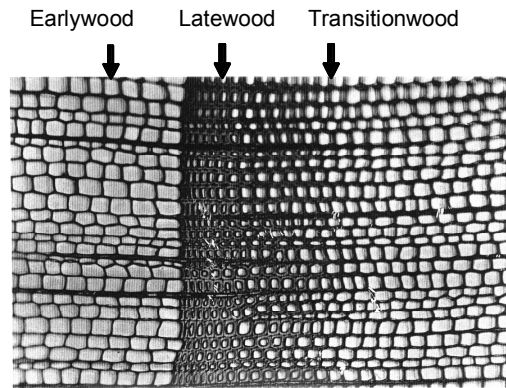
Figure 4. Cross-section of spruce wood (approximately one annual growth ring) as observed in a light microscope [4]

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, 450 and 900 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 orthotropic in a system of axes aligned with the radial, tangential and axial directions defined in Figure 5.
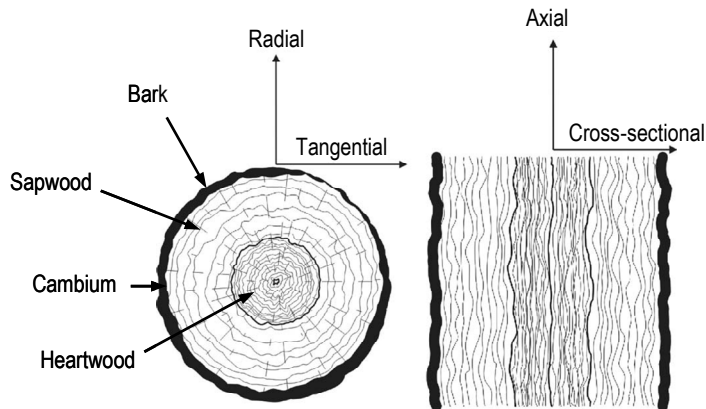

Figure 5. The principal anisotropy axes in a tree stem [7]

Wood exhibits both viscoelastic and plastic behaviour that is highly dependent on both moisture and temperature. The formation of small-size chips will show seasonal variations due to temperature and moisture content changes. At low temperatures more slender chips are formed (so called pin chips). Pin chips and

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saw dust 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 at about the saturation moisture content [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 distribution of chip thickness broadens with increasing chip length.
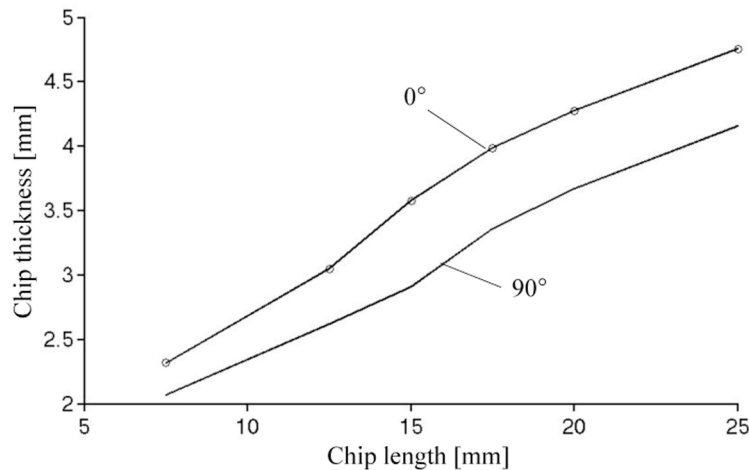
Figure 6. The distribution of chip thickness

2.2.2. Operating parameters

Operating parameters such as different angles affect the chip thickness. The clearance angle, α, 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 knife angle used, β, 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 that there are 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, β', 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, ε, the chips become thicker at the same length [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 relatively thin chip, with a minimum of compression induced fibre damage, as well as a narrow chip thickness distribution is normally desired. In order to improve chip quality in terms of chip geometry and fibre damage, the mechanisms of chip formation must be better understood. In the following sections the importance of chip geometry and fibre damage 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- are defined in Figure 7. What is considered to be the optimal chip geometry differs from pulp mill to pulp mill.
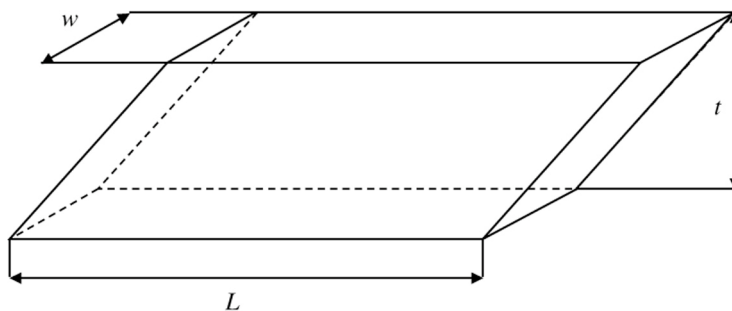

Figure 7. Chip geometry

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.
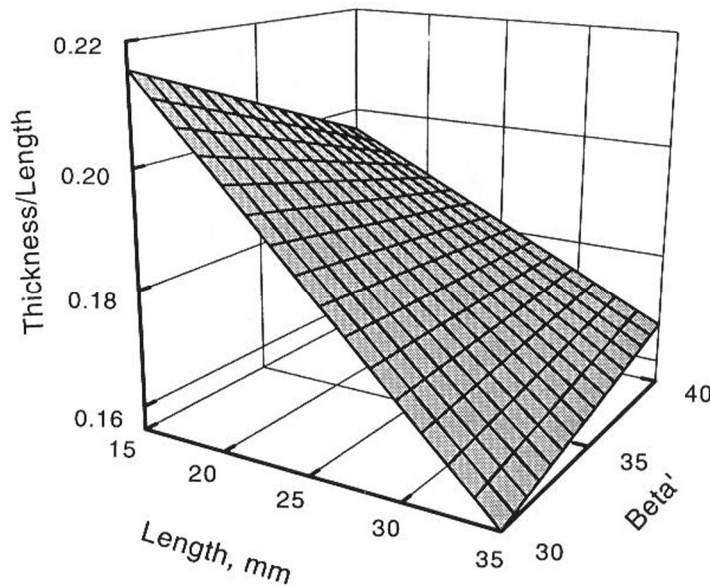

Figure 8. The relative chip length vs. chip length and bevel angle, β' [13]

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 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 impregnates 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 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 [16].

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 [16].

In the case of mechanical pulping, the refiner discs will only accept a piece of wood small enough to enter between them [16].

2.3.2. Damages

When wood is loaded in compression above some critical stress, irreversible structural changes take place, which are denoted as compression damage. Locally the fibre walls become misaligned or kinked [8].

Mechanical damage to the wood in the chipping process may result in degradation of pulp quality. The extent of chip damage is more or less constant regardless of chip length so that, the percentage of chip damage and its deteriorating effect on pulp quality decreases with increasing chip length [8] [10].

3. METHODS

The following section is divided into one experimental and one analytical/numerical part. The methods are presented as a review of each paper, (I and II).

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

Investigations carried out previously have concentrated on e.g. measuring forces on the chipping tool (at low velocities) [9] and [13]; measuring chip thicknesses when varying different process parameters etc [9], [10], [12], [15] and [17]. 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 has been developed in which the chipping can be performed under very well defined conditions. In this setup it is possible to control the rate of indentation of the chipping tool and also to measure the force on the tool. The setup admits also that the angle of the wood specimen with respect to the cutting plane can be varied in both a horizontal and a vertical plane.

To determine the deformations, a Digital Speckle Photography (DSP) equipment is used, which together with image processing software makes 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 [18], visco-plastic properties of metals [19] and elastic properties of wood fibre walls [20]. Thuvander *et* al. [21] used it to study crack tip strain field in wood at the scale of annual growth rings. Jernkvist and Thuvander [22] studied stiffness variation across annual growth rings in spruce (Picea Abies). Ljungdahl *et* al. [23] studied transverse anisotropy of compressive failure in European oak and Dumail *et* al. [24] analyzed rolling shear of spruce wood. Using this technique to study local parameters in connection with the wood chipping process is (to our knowledge) 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 [25] 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 specimen holder admitted a variation of the cutting-angles in both a horizontal and a vertical plane. The whole chipping device is shown in Figure 10.
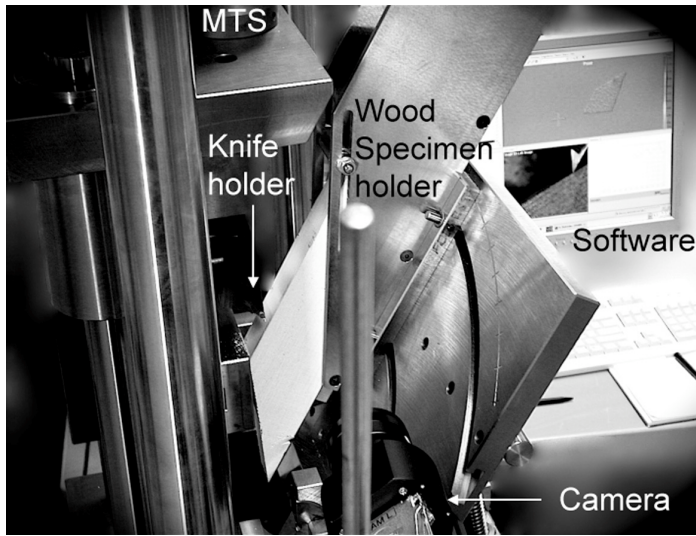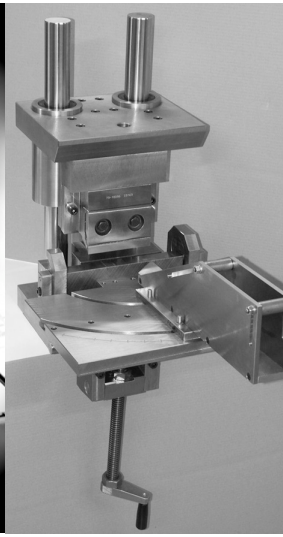

Figure 9. The experimental setup   **Figure 10**. The chipping device

The loading of the chipping tool is 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 and the force on the chipping tool can be measured.

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.

Wood sample selection

Five trees of Norwegian spruce (Picea abies) were selected from a stand in Länna, just outside Uppsala in Sweden. The tree stems were selected to be as free as possible from reaction wood [26] and cut into 1.5 m long pieces and each log where cut into 4 cm thick planks. The planks from each 1,5 m part was put together and wrapt in airtight plastic to prevent moisture loss and transported directly to Sundsvall by car and placed in a freezer.

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 is 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 is developed. It might seem strange to use a simple analytical model to study this 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. In particular, the influence of sliding friction between the wood chipping tool and the log is considered. To get some idea of the accuracy of the analytical model, a FE analysis is also performed. 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

To obtain at least qualitative results regarding the influence of different parameters and the friction in particular, a simple analytical model is considered. 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 β to the horizontal plane and the knife tip is occupying an angle α. The length and thickness of the chip is L and t respectively.
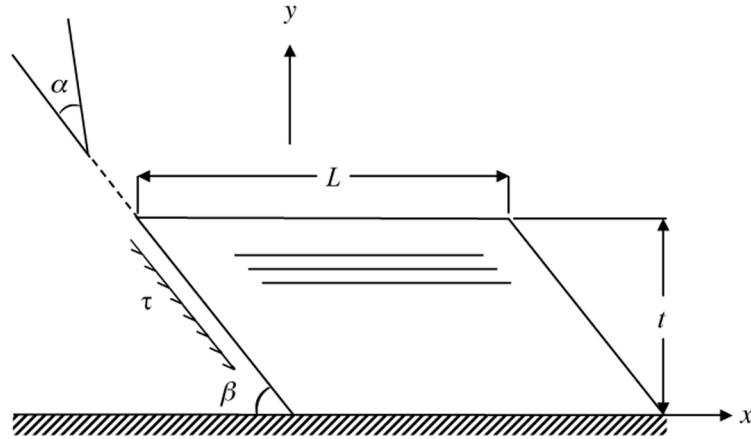

Figure 11. An idealised situation

On the left boundary, a shear load τ is assumed to be acting.

Consistent with the assumption of small deformations is that α, is a small angle.

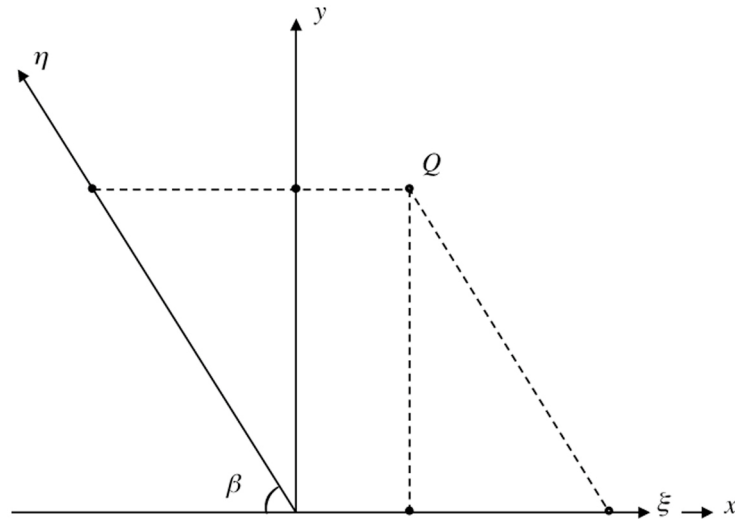To simplify matters, coordinates ξ and η are used as shown in Figure 12:

Figure 12. Coordinate transformation

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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).
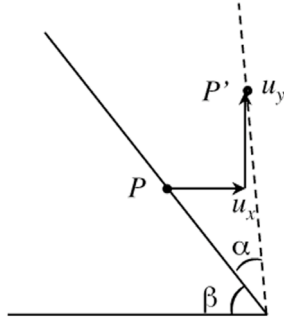

Figure 13. Sliding condition

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

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

where σ_x, σ_y and τ_{xy} are the normal and shear stresses respectively and S is the domain in the x- y- plane, occupied by the chip and Γ 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 η, it is assumed for $\tau(\eta)$:

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

where k_τ and m_τ 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_τ and m_τ

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 α, k_τ and m_τ so that k_τ and m_τ (for a given α) can be determined such that $\tau = \mu p$ is satisfied. With k_τ and m_τ an approximate solution for g and f for a case of sliding friction can be obtained.

3.2.3   FE- model

To get some idea of the accuracy of the analytical 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 [27] code.

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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 [28].

An iterative technique has been employed to solve the equilibrium equations. The equilibrium equations are iterated until that $\tau = \mu p$ is satisfied. The crack surfaces contact algorithm employed uses constraint functions to enforce all contact conditions of the Coulomb-friction contact at the contact nodes (cf. [29]). The results obtained after each iteration then correspond to estimates of the incremental displacements from which the current stress is computed.

4.   RESULTS AND DISCUSSIONS

In the following section are results from investigation of the deformation field, and the analytical- and the numerical model 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).
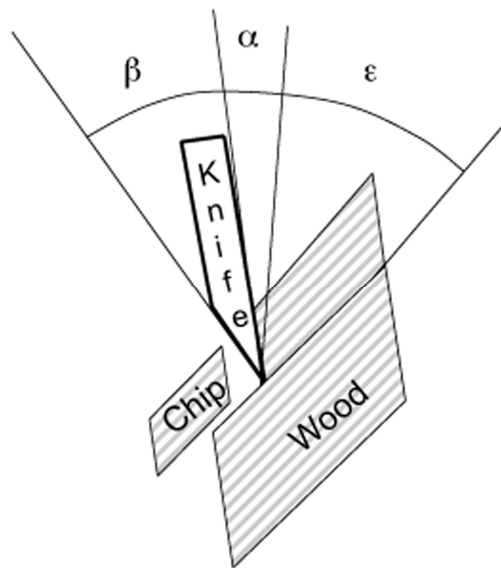

Figure 14. The cutting angles

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 15, where the normal strain in the radial (*R*) direction is shown.
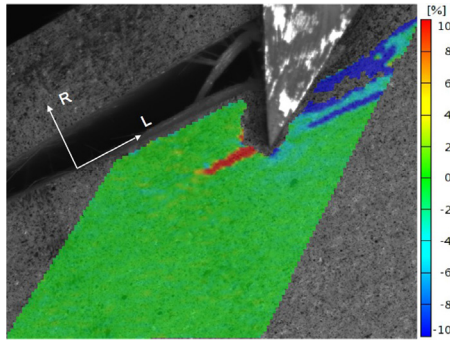

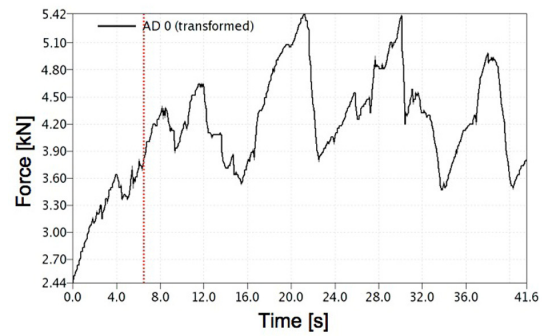**Figure 15**. Normal strain distribution in the R-direction

Figure 16. Force vs. time

In Figure 15, the read colour indicates a thin region with high normal strains just prior to chip formation. In Figure 16, 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 15 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 17), a forward shear modus (Figure 18) and a mode according to Figure 19 which in lack of better might be referred to as a remote opening mode.
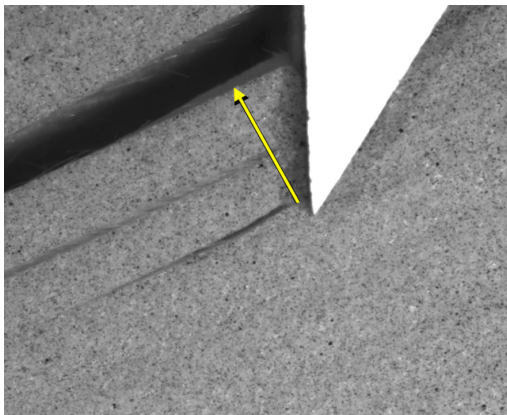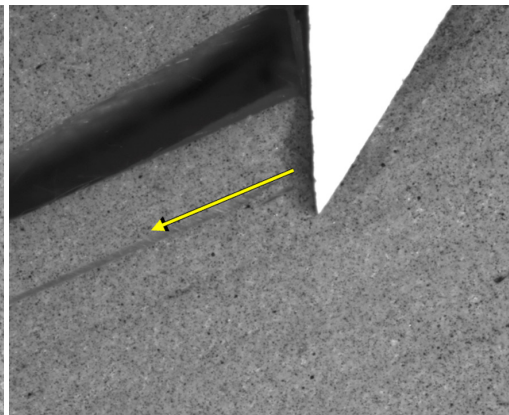

Figure 17. Opening mode
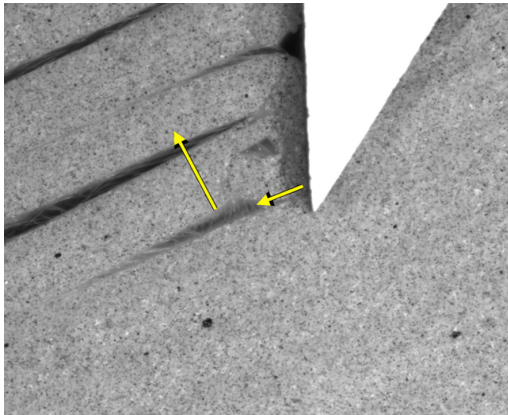
Figure 18. Forward shear mode

Figure 19. Remote opening mode

Which of the processes that will be the most frequent, is largely dependent on the friction between the wood material and the chipping tool. Figures 17, 18 and 19 show the influence of friction ranging from low friction in Figure 17 to high friction in Figure 19. 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 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.

18

In Figures 20 and 21 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.
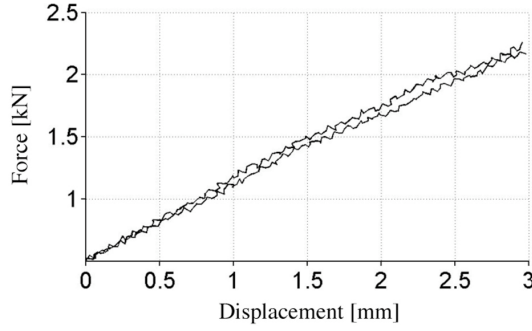

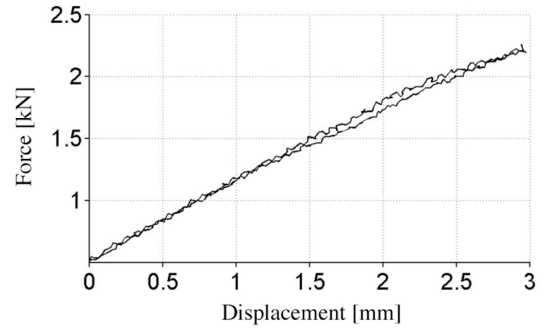**Figure 20**. Force vs. displacement for *d*=10 mm

Figure 21. 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 [30] were used in the calculations i.e. with:

Table 1. Material properties

E_L	E_R	G_{LR}	v_{LR}	v_{RL}
[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
10000	820	660	0,4	0,033

Where *E*, *G* and *v* 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 σ_y and τ_{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 22 versus ξ/t and normalized with respect to E_R.
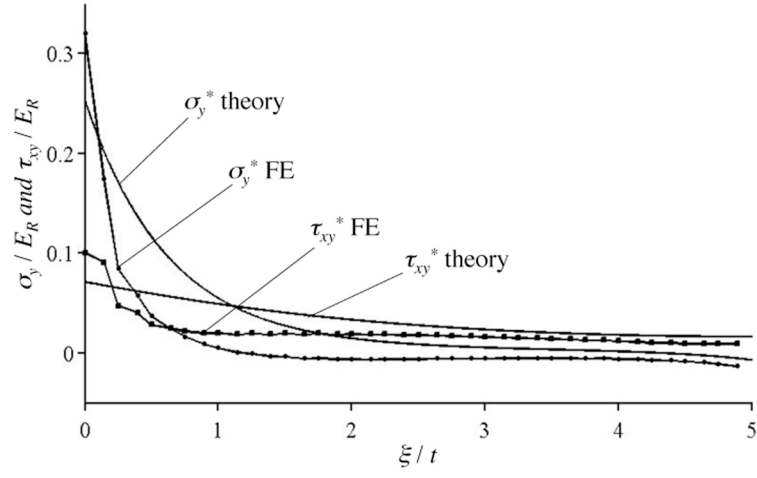
Figure 22. Normalized stresses σ_y and τ_{xy} along the crack-plane for the case $\beta = 60°$ and $\mu = 0,2$

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

In Figure 23 are shown the contact stress distributions for the cases considered in Figure 22, and for the case $\beta = 30°$.
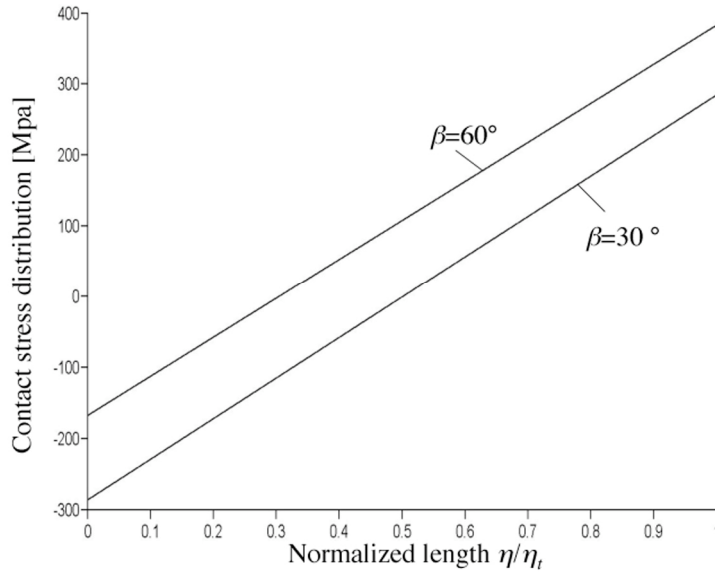

Figure 23. The contact stress distribution on the chip for $\beta = 60°$ and $\beta = 30°$ along the chip-end

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 β.

Comparison of results

Results from the analytical model were compared with results from FE analysis (Figure 22). The theoretical calculated stresses σ_y and τ_{xy} along the crack-plane agree reasonably well with the FE calculated stresses for $\beta = 60°$. For smaller values of β, the assumption made regarding the displacement 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 24 below:
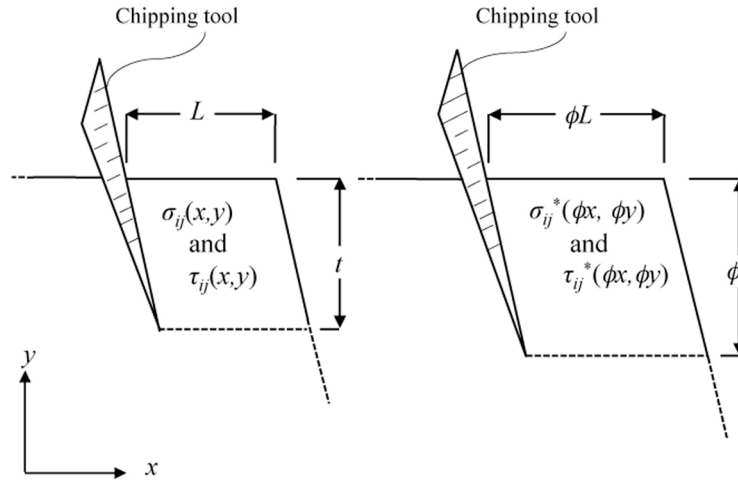

Figure 24. Quarter infinite geometries

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:

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

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 [31] 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 24, will be identical in the normalised x- coordinate $\psi = x/(\phi L)$, for all values of ϕ. 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.

5.   CONCLUSIONS

In the present thesis both an experimental method and an analytical model were developed.

The experimental method developed is a versatile tool when it comes to studying the chipping process and in particular the local strain fields in the vicinity of the cutting edge of the chipping tool.

The analytical model developed predicts among other things the normal and shear strain distribution in the crack-plane prior to crack initiation. The analytical distributions are in reasonable agreement with the corresponding distributions obtained from a FE analysis.

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.

It is observed that the indentation process is approximately self-similar.

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.

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.

6. ACKNOWLEDGMENTS

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, 43(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 chipper*; 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] 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

[17] Hartler, N. (1962 b); *The Effect of Sharpness Angle as Studied in an Experimental Chipper*; Svensk Papperstidning Vol. 65, No. 10: 397-402

[18] 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

[19] 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

[20] 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

[21] Thuvander, F., Sjödahl, M. and Berglund, L.A. (2000); *Measurement of crack tip strain field in wood at scale of growth rings*; Journal of Materials Science 35: 6267-6275

[22] Jernkvist, L.O. and Thuvander, F. (2001); *Experimental Determination of Stiffness Variation Across Growth Rings in Picea abies*; Holzforschung Vol. 55, No. 3: 309-317

[23] Ljungdahl, J., Berglund, L.A. and Burman, M. (2006); *Transverse anisotropy of compressive failure in European oak – a digital speckle photography study*; Holzforschung Vol. 60: 190-195

[24] Dumail, J.-F., Olofsson, K. and Salmén, L. (2000); *An Analysis of Rolling Shear of Spruce Wood by the Iosipescu Method*; Holzforschung Vol. 54, No. 4: 420-426

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

[26] Parham, R.A. (1983); *Wood Variability*; 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

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

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

[29] ADINA R&D Inc. (1995); *Theory and Modelling Guide*; Watertown MA, USA

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

[31]   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