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SOME EFFECTS OF WOOD CHARACTERISTICS AND THE PULPING PROCESS ON MECHANICAL PULP FIBRES

by

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ABSTRACT

The thesis comprises three parts: Existing methods for characterisation of fibre cross-sections have been improved, and new methods have been developed. These methods have then been applied to study the effects of wood characteristics and the pulping process on mechanical pulp fibres. Links have been established between fibre structure and paper properties such as surface smoothness and light scattering coefficient.

New methods, based on SEM-images and image analysis, are described for providing cross-sectional fibre dimensions for large fibre populations, for wood tracheids (app. 60 000 tracheids in a wood trunk) and for processed pulp fibres (app. 1000 fibres per sample). The methods are suited e.g. for evaluation of changes in the fibre cross-sections from wood to the finished paper, or for mapping of fibre parameters within and between growth rings in a wood trunk. The treatment of data is discussed, showing how one may examine the changes in different groups of fibres (earlywood fibres, latewood fibres, split fibres) throughout a process.

It is known from the literature that groundwood-based paper is superior to TMP-based paper with respect to printability. Fibres from SGW and PGW-pulp were found to be much more split in the longitudinal direction than TMP-fibres at comparable freeness. Intact groundwood fibres had thicker walls than intact TMP-fibres, but nevertheless super calendered hand sheets made from groundwood fibres were less roughened by moistening than were TMP-based sheets. Both for groundwood pulps and for TMP-pulps, it was shown that reduced fibre wall thickness and increased fibre splitting was beneficial for improved surface smoothness and opacity.

Latewood defibrate easier than earlywood during refining. In the case of grinding, there was no particular preference for earlywood or latewood to be defibrated. Reject refining of groundwood reject was, however, found to be very important for defibration of latewood-containing shives. Pulps made from a raw material with more compact fibres (high wall area to lumen area ratio) were found to defibrate easier, and contain less shives. It was found that refining tends to reduce wall thickness most on thickwalled parts of the fibre, thus causing a reduction of the wall thickness variation around the perimeter.

Earlywood fibres were found to be preferentially split during refining. Most fibre splitting occurs during the primary stage, while the fibres are firmly attached to chips or fibre bundles. Latewood fibre wall thickness decreases considerably more than earlywood fibre wall thickness during refining. It seems that choosing an appropriate raw material is more effective than using excessive energy on reducing the wall thickness of thickwalled fibres. Earlywood fibres became more flattened during refining compared to latewood fibres, possibly due to repeated compressions and relaxations in the refiner.

The energy consumption to a given freeness was found to be considerably larger for Scots Pine than for Norway Spruce. However, the fibre transverse dimensions did not differ much between Norway Spruce and Scots Pine. Pine pulps were far less developed than spruce pulps at similar energy level. A possible explanation for the large energy consumption may be that redistribution of extractives at the fibre surface could reduce friction in the refiner. This hypothesis should be further explored.

The results in this study improve the knowledge of which fibre parameters that matter for surface smoothness and opacity of wood-containing publication paper. Further, this study elucidates how important fibre parameters such as wall thickness and fibre splitting are altered during a refining process. The results may be utilized to identify possible ways of modifying the TMP-process in order to produce paper with improved surface smoothness and opacity.

PREFACE

This thesis is submitted in partial fulfilment of the *doktor ingeniør* degree at the Norwegian University of Science and Technology. The work has been carried out at PFI-Norwegian Pulp and Paper Research Institute and Department of Chemical Engineering at the Norwegian University of Science and Technology from 1996 to 1999, with Professor Torbjørn Helle as supervisor.

Wood-containing publication paper is a very important product for the Norwegian pulp and paper industry. Mechanical pulp, and especially thermomechanical pulp (TMP) is a major component of such paper. Detailed knowledge of process mechanisms is crucial in order to maintain superior quality at low production costs. The objectives of the study were to: a) develop and improve methods for fibre characterisation, and to b) develop new knowledge regarding the mechanisms in TMP-refining and the relationships between fibre properties and the surface roughness and opacity of the paper.

The work in this study is a part of the project "New knowledge base for reducing the energy consumption during TMP production with unchanged or improved product quality". The doctoral study was funded by Norske Skog ASA and the Norwegian Research Council.

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LIST OF PAPERS

This thesis includes the following papers as journal articles referred to as **Paper I-VII** in the text:

I. Reme, P.A., Johnsen, P.O., Helle, T., "Assessment of Fibre Transverse Dimensions using SEM and Image Analysis", Submitted for publication in Journal of Pulp and Paper Science

II. Reme, P.A., Helle, T., "Accurate assessment of transverse dimensions of wood tracheids using SEM and image analysis", Submitted for publication in Holz als Roh- und Werkstoff

III. Reme, P.A., Johnsen, P.O., Helle, T., "Fibre characteristics of some mechanical pulp grades", Nordic Pulp and Paper Research Journal, 13(4):263 - 268 (1998)

IV. Reme, P.A., Johnsen, P.O., Helle, T., "Changes induced in early- and latewood fibres by mechanical pulp refining", Nordic Pulp and Paper Research Journal, 14(3):260 - 266 (1999)

V. Reme, P.A., Helle, T., "The fibre characteristics of shives initiating web rupture", Submitted for publication in Nordic Pulp and Paper Research Journal

VI. Reme, P.A., Helle, T., "Quantitative assessment of mechanical fibre dimensions during defibration and fibre development", Annual Meeting, Technical Section, CPPA, Montreal (2000)

VII. Reme, P.A., Helle, T., "On the difference in response to refining between Norway Spruce and Scots Pine", Submitted for publication in Paperi ja Puu

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CHAPTER 1

INTRODUCTION

1.1 Background

The demands on print quality of publication papers are increasing. Producers of printing papers do not only face competition from other suppliers but also from electronic media. Print quality is affected by paper properties such as formation, surface smoothness, gloss and opacity. Paper strength requirements should match runability demands in high speed printing presses. However, the objective should be to produce a superior printing surface within the constraints set by runability.

The paper surface will to a large extent reflect the properties of the mechanical pulp fibres. Mechanical pulp fibres will not collapse spontaneously. However, they can be forced to collapse in the calendering. In converting processes exposing the paper to moisture, such as pigment coating or offset printing, the fibres will partly recover their original shape. The consequence is a roughening of the paper surface. This fibre decollapsing behaviour is especially pronounced for coarse latewood fibres [1]. Between 20 and 50% of the tracheids in Norway Spruce (*Picea Abies* L. Karst.) are latewood fibres. By decreasing the wall thickness, or by other means increasing the flexibility and bonding ability of the latewood fibres, the surface smoothness can be improved. A fibre with longitudinal cracks in the wall will have a less circular cross-section than an intact fibre. The extent of fibre cracks and splitting may therefore be significant for the surface roughness. Further work is needed to examine the effect on surface smoothness by fibre splitting.

In the production of Thermomechanical Pulp (TMP), wood chips are exposed to mechanical action at high temperature and pressure, and are progressively broken down to individual fibres and fibre fragments. The refining is a two-stage operation; a defibration stage followed by fibre development. In the development stage, smaller particles and fibres are further treated to improve papermaking properties. Despite the inhomogeneity of the wood raw material, earlywood and latewood are refined together today. In the future, when fractionation techniques have improved, it might be possible to refine earlywood and latewood fibres separately.

The basic mechanisms of fibre development in refining have been studied [2]. Although several studies have shown a reduction in coarseness by refining, it is not clear whether this reduction in fibre wall thickness occurs preferably for latewood fibres, or if fibres with different cross-sectional dimensions are equally affected. A wider understanding of the refining mechanisms is needed, especially how earlywood and latewood fibres respond to refining.

1.2 Objectives of the study

Improvement of old methods and development of new methods for fibre characterization has been one of the objectives of this study.

The main objective of this study has been to examine the alteration of fibres in a refining process, all the way from wood tracheids to finished TMP-fibres. Both defibration mechanisms, as well as fibre development mechanisms have been analysed. The study has particularly focused on differences between earlywood and latewood fibres. Differences in cross-sectional fibre dimensions between different wood species have also been studied.

A further objective has been to examine the effect of fibre structure such as cross-sectional dimensions and longitudinal splitting on paper properties such as surface smoothness, light scattering coefficient and apparent density. Possible ways of modifying TMP-fibres in order to produce paper with smoother surfaces have been identified.

Most of the work has been done using Norway Spruce wood (*Picea Abies* L. Karst.). Although it is believed that most of the conclusions reached here may have general validity, one should be aware of this limitation.

1.3 Outline of the thesis

This thesis comprises results from papers that have been published or submitted for publication in journals (referred to as **Paper I - VII** in the text, see pp. 9). The presentation order of the results has been rearranged somewhat in the thesis to ease the reading, and to set the results into a larger context.

Chapter 2 is a review of relevant literature covering the following topics:

- Characteristics of TMP-pulps and SGW-pulps.
- The alteration of wood fibres in mechanical pulping.
- The effect of fibre dimensions and structure on paper properties, especially with respect to properties important to printability.
- Techniques for assessment of transverse dimensions of tracheids and fibres.

Chapter 3 gives an overview of the experimental methods applied in Chapter 4 - 6. The methods that have been developed for characterization of fibre and tracheid cross-sections are described in detail. These methods are also described in **Paper I and II**.

Chapter 4 establishes connections between fibre parameters such as fibre wall thickness and fibre splitting and paper parameters such as surface smoothness and light scattering coefficient. First, important fibre parameters are identified, by a comparison of various mechanical pulp grades (**Paper III**). Secondly their effects on paper properties are quantified (**Paper III and VI**).

Chapter 5 deals with defibration mechanisms and fibre development in mechanical pulping. Successive stages in TMP and GW-processes are studied. Defibration is studied indirectly through the development of undefibrated shives particles in the pulp (**Paper V**). The development of wood fibres in Thermomechanical pulping is discussed. Special attention is given to the different behaviour of latewood and earlywood fibres in a refining process (**Paper IV and VI)**.

Chapter 6 describes differences between Norway Spruce and Scots Pine as raw material in the TMP process. Differences in dimensions of wood tracheids are discussed. Through pilot scale trials, the different behaviour of Scots Pine and Norway Spruce in TMP refining is shown. Possible reasons for the different behaviour of these wood species are discussed.

Chapter 7 gives an overall discussion of the main findings in this work. Both implications of fundamental interest, as well as practical industrial implications of the findings are discussed. Suggestions for further work are given.

Chapter 8 presents the overall conclusions of this work.

CHAPTER 2

OVERVIEW OF RELATED WORK

2.1 Thermomechanical pulping and wood grinding

2.1.1 The wood grinding process

There are two distinctly different commercial processes for production of mechanical pulp, the grinding process and the refining process. The grinding process is one of the oldest wood processing techniques. The first commercial wood grinder was introduced in Germany in 1855 [3]. In conventional wood grinding logs are pressed against a grinding stone. As the logs are ground, water is sprayed onto the stone for two reasons; to transport pulp and to absorb excess heat caused by friction. The temperature in the grinding zone may exceed 150 °C [3]. Groundwood can also be produced at pressurized conditions in the grinding chamber (Pressure Groundwood, PGW). Pressure raises the boiling point of water, and the temperature is raised in the grinding zone. At pressures of some 4.5 bar in the grinding chamber, the process is termed Super Pressure Groundwood (PGW-S).

2.1.2 Thermomechanical pulping

Refiner mechanical pulp (RMP) is made by refining wood chips in disc refiners. The origin of the refining process was simple groundwood reject refiners, constructed by J.M. Voith in 1859. A successor of this equipment was the Nacke's refiner that was developed in 1893 [4]. Stone discs were replaced with metal discs at the end of the 19th century, giving what is considered to be the first refiners. Wood was first defiberized thermomechanically (refining at high temperature and pressure) for production of wallboard by Defibrator in 1932 [5]. However, RMP was not used for newsprint paper until the 1950's. Eberhardt [6] reported some of the first attempts with RMP for newsprint production in 1956. Bauer, Sprout Waldron and Defibrator came all up with different refining process designs [4]. The first commercial RMP-installation was at Gould Paper in 1956 [7]. The Thermomechanical Pulp process (TMP) was developed in the 1960's, and involves disc refining at elevated pressure and temperature. The first TMP-installation was supplied by Defibrator in 1968 [4].

Today the TMP-process is the dominating process for production of pulp for wood-containing paper. Thermomechanical pulp (TMP) may be produced from a variety of softwoods, and is used as the sole raw material for newsprint paper without addition of reinforcement pulp [8,9]. Compared to groundwood and refiner mechanical pulps, TMP-pulps have excellent strength properties, and the TMP process offers a series of other advantages. It is not limited to logs as raw material, and may also utilise saw mill chips. The process allows energy recovery, which is a significant economical advantage. A range of process parameters may be varied, such as specific energy consumption, temperature, concentration, plate gap, production, rotational disc speed, segment-patterns and alloy, refiner type (e.g. single disc/double disc), energy splits between refiners etc. All these choices make the TMP-process a flexible process, allowing tailor-made high-quality pulps for specific end purposes.

It has however been an experience that paper from groundwood may yield a smoother surface than TMP-based paper. The reason for this has not been quite clear, and the reasons for this difference are parts of the background for the present study.

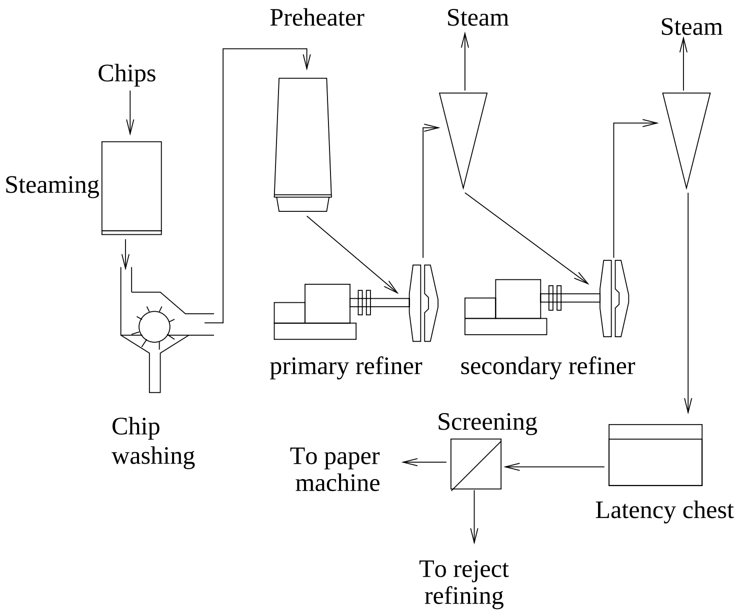


Figure 2.1 Typical Production line for TMP-production.

Fig. 2.1 shows a typical production line for TMP-production. The wood chips are steamed atmospherically at 100 °C and then washed in hot water. This treatment provides a thermal softening of the wood structure and removes air from the chips. The chips are then preheated at a pressure of approximately 1.5 - 2 bar for a few minutes. The primary refining takes place at high pressure (3-5 bar) and temperature (140-160 °C) at a consistency of approximately 30-40%. After steam separation, the pulp is blown to the second-stage refiner. This refiner may be operated pressurized or atmospherically. In some cases refining is done in three stages. After all refining stages, the pulp is diluted with water and subjected to gentle agitation in an atmospheric latency vessel. This latency treatment releases tensions in the fibres allowing them to straighten. After the latency treatment, the pulp is screened. The screen reject may either be treated in a separate reject refiner, or the reject may be returned to the second stage refiner. The latter is a cheaper, but also a less flexible system in terms of later process modifications. Several kinds of refiners exist, including single disc (one rotor) and double disc refiners (two rotors). Further information on refiner types may be found in the many good textbooks on the subject [e.g. 4].

2.1.3 Characteristics of TMP and groundwood pulps

The TMP-pulp fibres are generally longer and stronger than SGW-pulp fibres [10,11,12,13]. However, when increasing the pressure and temperature in the grinder (PGW, PGW-S) the fibre length increases towards the levels of TMP-pulps [10,14,15,16,17]. The amount of fines is reported to increase from TMP to SGW, while PGW-pulps here are closer to TMP-pulps [10,11,15,16,17].

The TMP-pulps are superior with respect to strength properties. Both tensile and tear strength tend to improve when TMP-pulp replaces SGW [10,11,14,15,18,19]. PGW-pulp strength properties come close to those of TMP-pulp. The main reasons for the differences in strength properties are the differences in average fibre length and bonding ability. Lindholm [20] compared SGW, TMP and PGW at a given fibre length, and found no significant differences in tensile strength between the PGW and TMP-pulps. However, the tensile strength of the SGW-pulp was lower. Consequently, there must be some additional factor causing the low strength level of SGW. The SGW-fibres are more damaged than the TMP-fibres [20]. It is likely that they will not contribute to the tensile strength to the same degree as the less damaged TMP and PGW-fibres.

Optical properties like opacity, brightness and light scattering coefficient are generally clearly better for SGW-pulps than for refiner pulps [10,11,14,15,18,21]. PGW-pulps have optical properties close to those of SGW. A high light scattering coefficient is obtained when the specific surface area in the sheet is high. The specific surface area can be increased with larger amounts of fines or with a higher degree of fibrillation. Hence, the superior light scattering coefficient and opacity for groundwood pulps can partly be explained by the large fines fractions.

Studies on mechanical pulps have revealed that the fines fraction differs considerably from one kind of pulp to another. Mohlin [22] and Lindholm [11] characterized TMP-fines as slime stuff, and GW fines as flour. The turbidity of a dispersion of fines is a measure of the specific surface area of the fines particles. Dispersions of refiner fines have higher turbidity compared to SGW-fines [10,23]. Although no unique relation has been found between turbidity and scattering coefficient, there is good correlation between the light scattering coefficient and fines content [10,19]. Hence, the higher light scattering coefficient of groundwood pulp seems to be more a function of the quantity rather than the quality of the fines.

The structural organizations of the fibre walls and fibre surfaces for SGW-fibres differ from those of RMP- and TMP-fibres [13]. Fibres from refiner pulps have relatively clean and homogeneous surfaces. SGW-fibres have damaged fibre walls, and are highly fibrillated [10,13,14]. PGW-fibres have been reported to be even more fibrillated than SGW-fibres [10,14]. The light scattering coefficient has been reported to be higher for PGW and SGW than for refiner pulps on sheets made from the long fibre fraction [10,11]. In a recent study, Braaten [24] argued that these differences were more dependent on the extent of outer fibrillation than on splits in the fibre walls. Hence, in addition to the fines content, the degree of fibrillation on the fibres also affects scattering abilities.

Compared to refiner pulp grades, SGW and especially PGW tend to have superior property profiles with respect to print quality. Low porosity, low oil absorbtion and high opacity result in low print through and a low ink requirement [10,15,18]. Compared at the same freeness, surface roughening and linting propensity have been found to be lower for groundwood grades than for refiner pulp grades [10,15,21]. Lint particles originate from loosely bonded material on the paper surface. The high degree of fibrillation of groundwood fibres indicates that they conform and bond well. These properties are important with respect to surface roughening and linting [10,21].

2.2 Wood structure

2.2.1 Norway Spruce (*Picea Abies* (L.) Karst.) as TMP raw material

In Norway Spruce (*Picea Abies* L. Karst) 90-95 vol% of the wood are tracheids [25]. The tracheids serve as transport channels for water and minerals, and as mechanical support for the wood trunk. Figure 2.2 shows schematically the composition of a wood fibre. The tracheids are bonded together in the wood by a lignin-rich matrix termed the middle lamellae (M). Inside the middle lamellae we find the primary wall (P) and the secondary

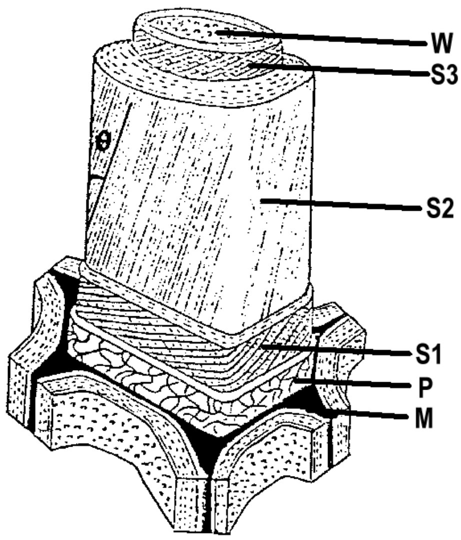


Figure 2.2 Sketch showing the composition of a wood fibre [4].

wall (S). The secondary wall is divided into three layers (S1, S2, S3). S2 constitutes some 70% of the cell wall. The fraction of cellulose and hemicellulose increases with debth into the inner fibre layers, while the lignin fraction decreases. In the S2-layer cellulose microfibrils are arranged as a helix around the fibre, embedded in amorphous hemicellulose. In the S1 and S3-layers the fibrils are randomly directed left and right around the tracheid axis with larger angles to the axes than in the S2-layer. It has been shown that decreasing angle between the fibril orientation in the S2-layer and tracheid direction (θ) raises fibre breaking load [26].

Wood is a heterogeneous material. Both between and within trees, there are large variations in structure. Within trees, the tracheid dimensions vary both with time of growth (earlywood/latewood) and with the tree age. Between trees, the tracheid dimensions vary depending on factors such as growth conditions and age. Other factors influencing the wood structure are degree of compression wood and knot wood. In the first 5-20 years of tree growth (Scandinavian conditions, juvenile wood [27]), transport of water and minerals is particularly important. Hence, the tracheids that are formed in this period have large lumen and small wall thickness. In the later stages of wood growth (mature wood) the support function of the tracheids is very important. In mature wood, the cell wall thickness is relatively large, and the tracheids are longer. Also the fibril angle in the S2-layer is smaller in mature wood than in juvenile wood [28].

The main function of earlywood tracheids is transport of nutrition. Hence, earlywood tracheids have low wall thickness and large lumen. Latewood tracheids serve more as mechanical support, and these tracheids have thicker cell walls, less lumen, longer length [29,30,31] and smaller fibril angle in the S2-layer than do earlywood tracheids [32,28]. In Norway Spruce, the average content of latewood has been reported to be 20-25% on volume basis [33].

The character of the wood affects the character of the wood pulp [34], and also its refining behaviour. The dimensions of the fibres will change during refining, but still the pulp quality will be finger-printed by the character of the wood raw material. In recent years the quality of the raw material has gained more attention, as modern forestry techniques provide possibilities of sorting and genetic engineering. Several attempts have been made to correlate wood properties to pulp properties [e.g. 9,35,36,37,38,39,40,41]. Due to its simple assessment, basic density is a wood parameter that has been extensively reported. Since the density of the cell wall is approximately constant (ca. 1500 kg/m^3 [42]), variation in basic density can be explained by volume variations in fraction of cell wall in the wood. Even though an increased basic density often correlates with the latewood content [e.g 43], it will not reflect the true morphology of the wood. The basic density is influenced both by changes in cell wall thickness as well as changes in cell wall perimeter, both of which may vary independently. Another complicating factor is the extractive content, since extractives may fill voids in the wood, increasing the basic density. It seems that there is no clear relationship between basic density and specific energy consumption or pulp properties [e.g. 35,37,40]. With respect to the former discussion, this cannot be very surprising. However, in several studies juvenile wood has been found to give pulps with superior light scattering coefficient but inferior strength properties compared to mature wood. Juvenile wood has also been reported to require more energy to reach a given freeness compared to mature wood [36,39,44]. In a theoretical consideration, Miles [45] proposed that the energy consumption to a certain freeness was depending on initial fibre length and initial coarseness. A low energy consumption should accordingly be favoured by large initial fibre length and low initial coarseness. This theory was based on the following assumptions:

- Freeness is depending on fines content and the fibre flexibility
- The fines content is fixed at a given specific energy consumption
- Larger fibre length implies more flexible fibres
- High initial coarseness implies high final coarseness
- Fibre length is preserved during refining

Cell characteristics such as tracheid length, tracheid wall thickness and tracheid width (radial and tangential) change systematically from the pith to the cambium of a wood trunk. During the first 20 years, there is a large increase in each of these parameters (Scandinavian conditions), after which the characteristics tend to even out with increasing growth ring number in the radial direction [28,29,31,46].

2.2.2 Scots Pine (*Pinus Silvestris*) as TMP raw material

Today Norway spruce (*Picea Abies* L. Karst.) is by far the major raw material for TMP-pulp in Scandinavia. The tracheids are long, the extractives content is low, and the brightness is high [40,47]. Scots Pine (*Pinus Silvestris*) contains much resin, both reducing strength properties [48,49,50,51] as well as causing problems with deposits on refiners, in screening systems and on the paper machine. Compared to Norway Spruce about 30% more energy is needed in refining of pine to a given freeness level [49]. The much higher energy consumption for pine pulps has often been blamed on the higher density of pine wood. Even compared at the same freeness level, the strength properties of pine pulps are inferior to those of spruce pulps. It has been shown that it is possible to produce pine TMP with characteristics more or less equal to those obtained for spruce, by increasing the energy consumption and refine to lower freeness [50]. The pine pulps got equal strength, but inferior drainage rate due to lower freeness. It has been shown that acetone extraction of pine pulp significantly increased the strength properties [48,52]. This increase in strength properties was attributed to the removal of extractives from the fibre surface, increasing the degree of bonding in the paper. If the resin content could be lowered, either mechanically [49] or by addition of chemicals [e.g. 53,54], Scots Pine might become an attractive raw material for TMP-pulp due to lower wood costs.

Larger basic densities are reported for Scots Pine than for Norway Spruce [43]. However, Hakkila [43] also found extracted pine wood to have the same basic density as unextracted wood from Norway Spruce. Hence, the increased density of pine wood does not necessarily implicate increased fibre wall thickness. The increased density can simply be due to the larger amount of extractives.

The actual resin content in Scots Pine is found to be some 2.2% [55] compared to some 0.8% [55] for Norway Spruce. The extractives are located as canal resin and in parenchyma cells. In Scots Pine, some 30% of the resin is located inside the parenchyma cells [55]. Cisneros and Drummond [56] investigated the fate of parenchyma cells during chip compression and refining of *Pinus Contorta*. It was found that more than 70% of the parenchyma cells remained intact after chip compression, while more than 90% of the parenchyma cells were damaged after 1st stage refining. Hence, both canal extractives and practically all parenchyma resins are liberated after the primary refining stage. It seems logical that the extractives will tend to redistribute on free surfaces, including fines and fibre surfaces. Back [57] showed that paper-to-paper and paper-to-metal friction dropped because of such "self-seizing". This can be explained by a surface being covered by long aliphatic chains such as those from fatty acids. Resin acids, however, would raise the friction. Hence, a redistribution of extractives on the surface, in particular fatty acids, may decrease the fibre-to-fibre friction in the refiner.

2.3 The alteration of wood fibres in mechanical pulping

In both refining and grinding processes the temperature is high. The defibration mechanisms are based on two components:

- Softening of the lignin in the middle lamellae
- Mechanical stresses and relaxations in the wood structure

2.3.1 Alteration of fibres in wood grinding

The fibre release process may be divided into three stages [58,59]:

1. Heating and softening of the middle lamellae due to periodic compressions and relaxations in the wood structure.
2. Release of the fibres due to shear forces.
3. Removal of fibres from the grinding zone and re-grinding of the fibres.

In the grinding zone, the wood is subjected to oscillating stresses and relaxations. The stresses cause a temperature raise in the grinding zone, and the upper layers of the wood matrix are softened. When the fibres in the wood surface have been sufficiently softened and weakened by the mechanical action, one end of the fibre will initially be released. This release occurs when the local friction forces exceed the strength of the bonds between the fibres. The fibres are peeled in sequences and in the same direction. Since the logs are lying parallel to the grind stone's axis, the defibration forces will attack perpendicularly to the fibre length direction. Fibres may also be cut by sharp-edged grits and released as pieces of fibres. The fibres still attached to the wood matrix are further treated by the passing grits (regrinding) until they are completely released and removed from the grinding zone. Atack [60] attributed the shorter fibre length of groundwood compared to refiner pulp to the regrinding process. Small pieces of fibres that are created in the grinding process will enter the middle and fines fractions of the pulps. Stationwala et al. [23] reported higher fibre coarseness values for SGW-fibres than for TMP-fibres compared at the same freeness. Based on their findings, they suggested that fines in groundwood pulps were created from broken ends of fibres. Kibblewhite [13] performed investigations of the fines material in groundwood pulp grades that support these findings. He observed that SGW fines were more homogeneous in appearance, with finer "fibre-like" components, compared to fines in TMP-pulps.

Salmén and coworkers [61,62,63] have done several studies on mechanical compression of wood. They concluded that the release of fibres was caused by fatigue due to the mechanical pulses in the grinding zone. A certain number of mechanical deformations is required to cause breaks between the fibres. Accordingly, the number of pulses required is lower if the amplitude of the deformations is large. A few high amplitude pulses are more efficient than many low ones [61,62,63].

Salmén et al. [61,63] found that the destruction of wood was promoted by higher temperatures. As discussed earlier in this chapter, a temperature increase in the GW-process (PGW, PGW-S) raises the fibre lengths. When the pressure in the grinding zone is raised, the boiling point of the shower water increases, thus permitting a higher temperature in the grinding zone. The heating time of the wood fibres is reduced, and the temperature in the grinding zone stays high for a longer time. As a consequence, the fibres are more softened, and fibre shortening does not occur to the same extent as in conventional grinding. Kärnä [16] showed through microscopy evaluations that there are more middle lamellae fragments and more exposed S2-layers in PGW-fibres than in SGW-fibres.

2.3.2 Mechanisms of TMP-refining - Overview

When the chips are fed into the refiner eye they have zero velocity relative to the plate. In the next moment they collide with the breaker bars, and accelerate to approximately 100 m/s within milliseconds. In 1963, Atack and May [65] proposed that the reduction of chips to single fibres was due to chip fragments being subjected to compression and rolling in the refiner zone. Later, Atack et al. [66] used high-speed photography to show that chips were broken down into coarse pulp between the eye of the refiner and the breaker bars. They concluded that the fibres were stapled on the refiner bars causing shearing and compression to take place through several layers of fibres. Repeated stresses and relaxations then caused fractures between fibres in the chips.

In the innermost part of the refining zone steam and pulp cycle back and forward, with a net flow towards the outer perimeter of the disc [67]. It can be seen, if a refiner is stopped and opened, that most of the fibres are oriented with their longest axis perpendicularly to the refiner bars [66,68,69]. This direction is the direction of least resistance in the refiner [68].

The disc refining process proceeds in two stages [2,35]:

1. Fibre separation
2. Fibre development

In the separation stage the chips are reduced to smaller particles. The second stage develops the papermaking properties of the fibres. Fibre separation is most pronounced in the first part of a refining process, while fibre development is most pronounced towards the end. The two stages overlap to some extent. The amount of particles increases exponentially with the distance from the refiner eye to the outer disc perimeter [70]. Only a small amount of the energy consumed in the refining process is used for defibration. Most of the energy applied in the process is consumed to develop the flexibility and bonding potential of the fibres [2,8,9,70,71,72,73,74,75,76,77,78]. Corson found that the energy consumption for defibration was almost the same for different wood raw materials [79]. This result was found in spite of differences in tracheid dimensions, and differences in energy consumption to low freeness.

2.3.3 Defibration mechanisms in the TMP-process

Wood is a viscoelastical material, and both temperature, moisture content and time under load will affect its response to mechanical treatment. The three main polymers in wood; cellulose, hemicellulose and lignin, soften at different temperatures. At refining conditions, both the hemicelluloses and the amorphous cellulose soften at temperatures far beyond the softening temperature of lignin [80]. The lignin softening is therefore the limiting factor of wood softening. The nature of the defibration process is very much dependent on the temperature. If the primary stage is done atmospherically, the wood is subjected to a brittle failure through the fibre wall. The defibration then occurs mainly along the S1-layer, and the brittle fracture causes fibre shortening [58,81]. If the temperature is increased, the defibration will shift towards the middle lamellae. If the temperature is increased to 170 °C, as in the Asplund wallboard process [5], the fibre separation will be mainly in the middle lamellae. The fibres will then tend to be covered by a dark lignin robe, and the pulp will both get poor bonding and poor optical properties [82].

At typical TMP-conditions (130 °C), the defibration will mainly occur near the primary wall. The fibre separation rupture does not take place through the middle lamellae itself, but somewhere at the middle lamellae/fibre wall interface. However, it is not clear where the fracture occurs most frequently. Kibblewhite [13] found that about 30% of the fibres separated within the S1-layer, and about 60% within the S2-layer. In the separation the middle lamellae will either be separated from both fibres, or it will attach to one of the fibres. Maximum middle lamellae coverage on the fibres is thus 50%. Johnsen et al. [83] found a middle lamellae coverage of 13% after first stage, supporting the theory that middle lamellae can be separated from both fibres. They further concluded that the interfibre rupture occurred mainly through the S1, the interface S1/S2 or through the S2-layer.

The shear and compression forces in the refining process are used for elastic, viscoelastic and plastic straining. Plastic straining will break internal bonds in the fibre wall and give irreversible changes to the fibre structure. Elastic and also viscoelastical straining will convert the energy to heat. Obviously, an energy efficient process is favoured by maximizing the amount of plastic straining. Thiruwengadaswamy and Ouellet subjected wood to cyclic compression [84]. The wood samples were either restrained or unrestrained. In compression, unrestrained samples experience both shear and compression forces, while restrained samples experience only compression forces. The restrained samples revealed no sign of destruction, while the unrestrained samples got a structural destruction. Hence, it seems that shear forces are of largest importance in the defibration of wood. According to Hattula [85], the shear forces are most important in the inner part of the refiner. In the outer zone the plate clearance decreases, and compression becomes more important.

As wood is a heterogeneous material, the earlywood and latewood will respond differently to mechanical treatment. Compared to the dense latewood, earlywood of low density will compress readily by the refining forces. As a consequence, earlywood will be less able to transfer the required rupture forces to the interfibre bonding. Latewood is approximately 3 times stiffer than earlywood [86]. Earlywood has been reported to require 40% more energy for defibration compared to latewood [87]. Salmén et al. subjected wood to cyclic compression [88]. At a certain specific stress level, earlywood fibres were compressed by 50%, while the latewood fibres experienced only 5% deformation. Similar results were found by Hickey and Rudie [89]. They also found a preferential energy absorption by earlywood in loblolly pine subjected to cyclic compressions. Thiruwengadaswamy and Ouellet [84] found that cracks tended to propagate between fibres in the latewood regions when wood was subjected to cyclic compressions at high straining rate. At low straining rate earlywood fibres were distorted. The latewood sections were little damaged, but the fibres were well separated. Similar results were reported by Lai and Iwamida [87].

2.3.4 Fibre development mechanisms in the TMP-process

In the fibre development stage, undefibrated shives and long fibres are further treated. Since the fibres tend to be tangentially oriented in the refiner [66,68,90], the forces from the bars are directed along the fibre length. Material is peeled off from the P and S1-layers, exposing the S2-layer [2]. Even parts of the S2-layer may be removed by hard refining. Figure 2.3 shows an example of what Giertz termed the sleeve-rolling effect, where the S1-layer is stripped off the fibre, exposing the S2-layer [91].The peeling-mechanism will preserve the fibre length. The fibre walls will become slimmer, and the fibres more flexible.

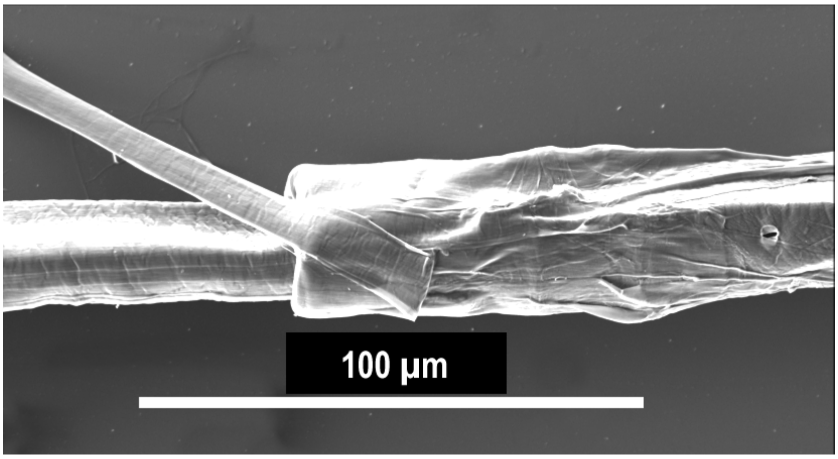


Figure 2.3 Example of the sleeve-rolling effect.

It has been shown that the fibre wall thickness is reduced through progressive refining [83,92,93,94]. Corson and Ekstam [95] refined radiata pine mechanical pulp in 5 stages, and applied a total specific energy of 6300 kWh/t. The fibre length was reduced in the first stages, but remained approximately constant in the later stages. However, the long fibre fraction was reduced from 64% in the original pulp to 34% after 5th refining stage. The drop in long fibre fraction was balanced by a corresponding increase in the fines fractions. As the refining energy increased, the fibres became more collapsed, and narrower and thinner in their cross-sectional dimensions.

Høydahl et al. [96] found equal fibre length distributions in all stages in an industrial TMP-process, while the coarseness was reduced. Thus, the fibres are stripped, so that fibrillar fines material is produced at the same time as the fibres become more flexible. Similar results were found in pilot-scale studies by Karnis [2] and Mohlin [92]. However, in a mill study, Mohlin [92] found a reduction in fibre length with decreasing long-fibre fraction. The fibre shortening occurred preferentially for thin-walled earlywood fibres. Thus, some fibre shortening may occur. The controlled conditions of a pilot plant are seldom present in a mill. The fibre length in a TMP-process depends on the refiner conditions, especially those in the first refining stage. It seems that one may attach a fingerprint to the pulp by choosing right conditions in the primary stage [2,34,79,96,97,98,99].

Heikkurinen and Hattula [100] investigated the fines produced in a TMP-process. They found an increase in average length of the fines particles with increasing energy input in the process. Chemical analyses of the fines material revealed that the cellulose content increased and lignin content decreased with increasing energy input. The results were explained by a fines production due to gradual fibrillation and stripping of fines. After the first refining stages the lignin content of the fines material was formed mainly from the outer layers of the fibre wall, and later mainly from the S2-wall. Chang et al. [101] found an enrichment of lignin, arabinose and galactose in the fines from a primary stage pulp, and a deficiency of other carbohydrates compared with whole pulp. After the second refining stage an increase of glucose content in the fines, as well as a drop in lignin content was found. Lignin, arabinose and galactose are concentrated in the middle lamellae and the primary wall. The secondary wall contains much glucose. These results are consistent with those of Heikkurinen and Hattula [100], and imply a gradual stripping of the fibre wall surface.

The cross-sectional dimensions of softwood fibres vary during the growth seasons. Earlywood fibres tend to have large outer perimeters and thin walls, while latewood fibres tend to have smaller perimeters and thicker walls. Norway spruce (*Picea Abies* L. Karst.) has a gradual transition from earlywood to latewood [28]. Other wood species, such as loblolly pine, has an abrubt transition from earlywood to latewood [64]. Due to the large structural differences, earlywood and latewood fibres behave differently in the refining process.

As discussed above, many studies have shown a reduction in coarseness by refining. However, it is not clear whether this reduction in fibre wall thickness occurs preferentially for latewood fibres, or if fibres of different cross-sections are equally affected. Mork [31] defined a latewood fibre as a fibre where the double wall thickness was larger than the lumen diameter, measured in the log's radial direction. Mork's rule was meant to be applied on solid wood, and not on separate fibres. Applied on pulp fibres, the classification is strongly influenced by the cross-sectional shape of the fibre. Mork's rule implies a sharp transition from earlywood to latewood, while a gradual transition is more common. A better parameter to distinguish between earlywood and latewood fibres in pulp was suggested by Mohlin [92]. She used the ratio between fibre perimeter and lumen perimeter (F/L) as an indicator of the amount of latewood fibres. A larger ratio indicates more latewood fibres in the pulp sample.

Corson and Ekstam [95] found a reduction in the amount of latewood fibres in succeeding refining stages. Earlywood fibres were characterized as fibres with thin walls and large perimeters. They could not show whether the cause was decreasing fibre wall thickness or breaks in the less flexible latewood fibres. Koljonen and Heikkurinen found a decrease in the number of latewood fibres in the long fibre fraction of a mechanical pulp at increased levels of refining [102]. Mork's rule was used to distinguish between earlywood fibres and latewood fibres. No shortening of fibres was observed. However, it was not clear whether Mork's rule was unable to identify the latewood fibres or if fines were created faster from latewood fibres than from earlywood fibres. Johnsen et al. [83] found the changes in wall thickness to be uniformly distributed within the wall thickness groups. In a recent study, Corson [103] found that the larger diameter fibres got a preferential reduction in wall thickness, and that the latewood fibres appeared to retain their original wall thickness. On the other hand, Mohlin [92] found a decrease in coarseness primarily for latewood fibres. Kure [93] also reported results indicating a more extensive stripping of thickwalled fibres. Clearly, there are split opinions in the literature regarding the response of latewood- and earlywood fibres to refining. The issue discussed here is important, since long thinwalled fibres are a goal in TMP-refining. Further investigations are necessary on this point.

Mohlin [92] and Jones [104] found that fibre shortening occurred mainly for earlywood fibres. Laamanen [105] found that the fraction of thickwalled fibres increased among the fibres as the amount of long fibres decreased. He explained this observation by a specific rupture of the thinwalled fibres. Conversely, Corson and Ekstam [95] reported results indicating that the less flexible latewood fibres were easier broken during refining than the more flexible earlywood fibres. According to Pearson [68] latewood fibres are more shortened during refining than earlywood fibres. He proposed that if the cell wall is very thick, it will be very difficult to compress, and the fibre will then break more easily when captured between the refiner bars.

In addition to reducing the fibre wall thickness, refining may cause other structural changes in the fibres, such as fibre splitting, fibrillation or delamination. Simon's stain may be used to examine changes in the fibre wall structure [102,106]. Refining has been found to increase the fraction of fibres with structural damages. Pulps rich in earlywood fibres have been reported to contain more fibres with mechanical damages than latewood rich pulps. Earlywood fibres tend to get more structural damages than latewood fibres during refining [93,105].

Lammi and Heikkurinen found that pulps rich on latewood fibres got a faster freeness reduction during refining than pulps rich on earlywood fibres [106]. The refining caused much more outer fibrillation on latewood fibres than on earlywood fibres. They also found that fibre stiffness was reduced considerably more during refining for latewood rich pulps than for earlywood rich pulps. Karnis examined the fibre flexibility of TMP and RMP fibres for various energy levels [2]. At the same specific energy consumption, TMP-fibres were more flexible than RMP-fibres. Initially, the fibre flexibility increased at increasing energy levels, and then evened out at energy levels higher than 5 GJ/t. Jang et al. [94,107] investigated the collapse behaviour of mechanical pulps. They found that an increased degree of refining caused flatter fibres. The fibre flattening may be caused either by the reduction of the fibre wall thickness, or by a loosening of the fibre wall structure.

During fibre development, the fibres are repeatedly compressed and relaxed. At a given compression, a certain amount of earlywood tracheids collapse. When the wood is compressed again in the next cycle, the formerly collapsed earlywood cells will need much less force for deformation than the other cells [88]. Salmén et al. [88] concluded that formerly deformed fibres very often will be the ones that again are deformed by the next bar passing. The fibres that are most easily deformed are the earlywood fibres, while the latewood fibres to a less extent will be subjected to these compressions and relaxations. Continuous compressions and relaxations will, according to Salmén et al. [88], consume energy without contributing much to fibre development. However, Höglund et al. [71] are of the opinion that the energy that is converted to heat represents useful energy, in the sense that the fibres are made more flexible due to breaking of internal bonds.

2.3.5 Some aspects on energy consumption in mechanical pulping

Both grinding and refining are very energy-intensive processes. To produce a newsprint pulp of 100 ml CSF, the grinding process typically requires 1500 kWh/t, the pressure groundwood process somewhat more, while the TMP process typically requires 2200 kWh/t. Campbell [73] estimated the theoretical efficiency of grinding to be 0.012%, suggesting that 90-99% of the energy is lost. In mechanical pulping, particles with highly specific physical characteristics should be produced, being one of the reasons for the high energy consumption. Atack [90] described refining as a form of longitudinal grinding, which has been shown to consume considerably more energy than conventional grinding. The energy consumption in refining is closely related to the refining mechanisms. As mentioned earlier, it is known that large amplitudes and low frequency is favourable to accomplish fatigue in wood during cyclic compression. [61,62,63]. Uhmeier and Salmén [108] pointed out that to have an energy-efficient fatigue situation, the fibres should preferably recover to the shape prior to compression, before next compression takes place. Similarly, in refining, energy consumption alone is not deciding the final properties of the pulp, but even the intensity at which the refining is done [109]. It has been shown that increased refining intensity gives a reduction in energy consumption to a given freeness [110,111,112,113]. Increased refining intensity can be achieved for instance through increasing disc speed [110,111], changing from single disc refining to double disc refining [111], using more aggressive refiner plates [110], increasing production [112], reducing refining consistency [113] or increasing disc diameter. Raised intensity may lead to fibre shortening, and the process parameters thus should be optimized in each specific case. A recent PhD-thesis discusses this topic in more detail [28].

2.4 The influence of cross-sectional fibre dimensions on sheet properties

The focus in this section will be on the properties of wood-containing printing paper, such as newsprint paper and magazine paper (including SC-paper and LWC-paper). For such grades, print quality and runability are primary quality parameters. Print quality is affected by properties like surface smoothness, formation, gloss and opacity. Paper strength requirements should match runability demands in production and high speed printing. However, the objective should be to produce a superior printing surface within the constraints set by runability. Traditionally, mechanical pulp quality has been assessed by pulp parameters such as Canadian Standard Freeness and fibre length. Although freeness correlates with other pulp properties such as fines content, shives content and drainage resistance, this parameter gives limited information on fibre properties and paper quality. In a study of 18 different TMP-pulps, 97% of the variation in surface smoothness was caused by variation in fines content, long fibre fraction and fibre wall thickness [114]. An increase in fines content will strongly improve surface smoothness and light scattering [110,115]. However, restrictions set by runability will in practice limit the amount of fines in the pulp. Hence, at realistic fines content, fibre properties will govern important paper properties like surface smoothness and opacity.

The intrinsic fibre properties influencing pulp quality are fibre length, fibre coarseness, fibre width, wet fibre flexibility, fibre wall thickness and degree of collapse [116]. The fibre coarseness is defined by the mass of fibre per fibre length. This parameter is relatively easy to assess, and has been frequently used as an indication of the fibre morphology. Since the coarseness may change both with changing fibre perimeter and/or changing fibre wall thickness, it is obvious that two fibres with equal coarseness may have very different morphology. Hence, in order to provide a more precise description of the fibre morphology, the coarseness should be supplied with values of fibre wall thickness and fibre perimeter.

2.4.1 Paper surface and printing characteristics

The most common printing methods applied for wood-containing printing paper are offset (newsprint, magazines) and gravure printing (magazines). The latest years water-based flexography has been used to print some newsprint. A smooth paper surface is crucial for a good printing result [117,118,119,120]. During printing, the paper is compressed. Peaks in the surface of offset-printed paper have been found to have poor coverage of printing ink [121]. The local pressure between blanket and fibres appears to be so high on the peaks that the ink is squeezed down to lower areas. Only areas in direct contact with the offset blanket appear to carry ink. Hence, ink-free parts of printed paper are either peaks or local deep voids. Coarse fibres protruding from the paper surface will produce a peak and a nearby void, both of which will not be covered by ink. Gravure printing is especially sensitive to the paper surface [120], and a low quality paper causes missing dots, local gloss variation and poor print quality. Missing dots often occur on paper areas with particularly low grammage [122]. Antoine et al. found 77% of the missing dots in gravure printing to be caused by surface pores due to one or several large fibres [117]. Uneven offset printing is due to variation in surface roughness and ink penetration. High roughness reduces the contact area ink/paper and causes a poor ink transfer. The ink penetration determines how much transferred ink will remain on the paper surface, and hence the print density [123].

An uneven paper surface as well as porosity variations may be caused by local grammage variations. Poor formation may cause variations both in gloss and opacity, and cause poor ink transfer. Areas with very high local sheet density (flocks) may cause calender blackening. The sheet formation is set in the forming, and is highly correlated with fibre length and forming conditions [124,125].

Coarse mechanical pulp fibres represent special problems for paper smoothness. Such fibres tend not to collapse spontaneously, and if forced to collapse by calendering etc., they decollapse upon moistening [1,115,126], causing a roughening of the paper surface [1,115,126,127,128,129,130]. This roughening leads to loss of gloss and poorer print quality [131,132]. Moisture may be added for instance as dampening water in offset printing, during coating or by using water-based inks. More use of water-based gravure inks in the future may increase the roughening problem [133]. Skowronski et al. [128,129] concluded that the main mechanism of moisture-induced surface roughening is the recovery of calendered, collapsed fibres to their original shape. As can be seen in Fig. 2.4, the diameter of uncollapsed mechanical pulp fibres may be almost half the sheet thickness in an SC magazine paper [28]. Fig. 2.5 shows ESEM (Environmental Scanning

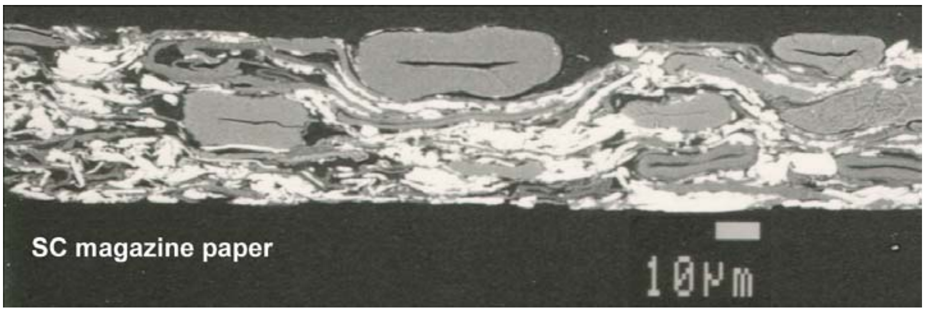


Figure 2.4 Cross-section of a super calendered magazine paper [28].

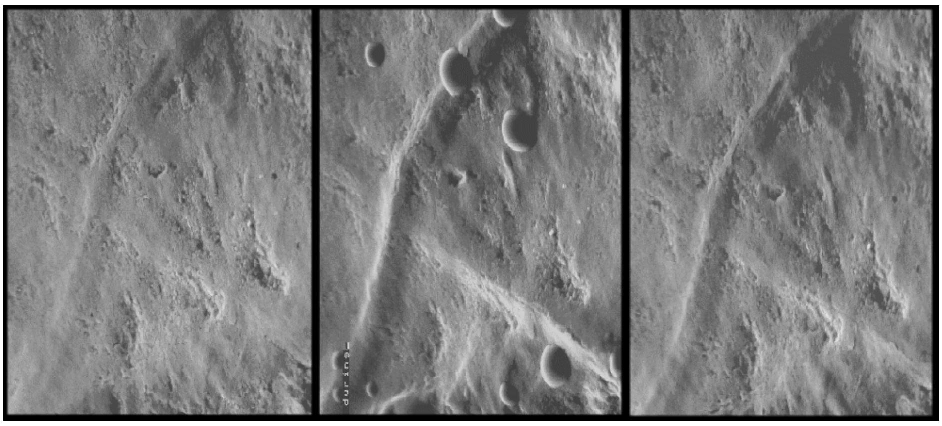


Figure 2.5 ESEM images of a coated super calendered paper before (left), during (middle) and after (right) moistening [134].

Electron Microscope) images of a coated supercalendered paper surface before, during and after wetting [134]. It is clearly seen that some of the structural changes during moistening are irreversible. Surface roughening is controlled by the quantity and coarseness of long fibres in the mechanical pulp [115,135,136,137].

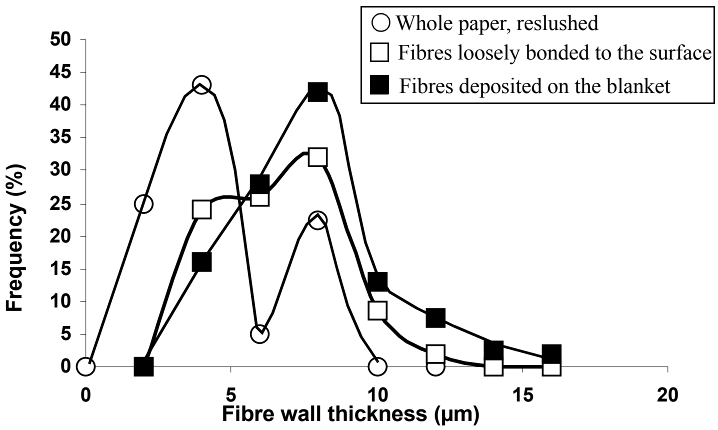


Figure 2.6 Wall thickness distribution for fibres from: 1) reslushed paper, 2) fibres loosening from the paper in a fibre rising test and 3) fibres deposited on the offset blanket [138].

The degree of fibre decollapse during moistening has been found to increase with increasing wall thickness [115]. Mohlin [138] examined fibres deposited on the blanket in a four-colour offset printing press, fibres coming loose from the surface in a fibre rising test, and the fibres in the reslushed paper (Fig 2.6). Fibres that loosened from the surface during printing were predominantly thick-walled fibres.

Fibre flattening will reduce the moment of inertia of the fibre cross-section, and hence increase fibre flexibility. Chagaev et al. [139] flattened TMP-fibres experimentally by pressing hand sheets from the long fibre fraction at temperatures above the glass transition temperature. TMP-pulp containing such flattened long fibres produced sheets with increased apparent basic density, as well as reduced moisture-induced surface roughening.

2.4.2 Optical properties

The light scattering coefficient of a pulp is linearly dependent on the area of fibre-air interfaces. Light scattering coefficient and fibre coarseness are correlated [140]. Geometrical calculation has shown that the total surface area of smooth fibres is governed by the wall thickness (*WT*) as in Equation 2.1 [24,141]. The fibre was considered a tube, and the quality of the fibre surface neglected:

$$\text{Specific surface area} = \frac{2}{WT \cdot 0.00153} \tag{2.1}$$

A reduction in wall thickness consequently raises the light scattering coefficient. Good correlations have been reported between fibre wall thickness and the pulp's light scattering coefficient [114,142]. Fractionation trials have shown that fibre fractions rich in earlywood have light scattering coefficients superior to latewood rich fractions [102,106]. Corson et al. [143] found that TMP from low density Radiata Pine (375 kg/m^3) had larger light scattering coefficient than TMP from higher density wood (425 kg/m^3). Low density wood contains more earlywood fibres with thin walls and large specific surface area. Well fibrillated fibres will raise the light scattering coefficient [142].

2.4.3 Paper strength

Several papers discuss the relationship between fibre morphology and paper strength for chemical pulps [e.g. 144,145]. However, few studies have been published on this relationship for mechanical pulps. It is generally accepted that fibre length is a key property for tear strength. According to Mohlin, strength properties of wood-containing paper are to a large extent determined by fibre length and fibre bonding ability [138]. At a fines content of 20-25%, fibre length is of prime importance for tear strength and the fibre bonding ability is critical for tensile strength. The fibre bonding index is defined as the tensile index of standard handsheets from the BMcNett 16-30 mesh fraction. Hence, this index is governed by factors such as fibre flexibility, surface area available for bonding, degree of collapse and degree of fibrillation. Earlywood fibres are less stiff than latewood fibres, improving their ability to form fibre-to-fibre bonds. Koljonen and Heikkurinen fractionated a TMP-pulp into fractions with varying latewood contents [102]. Earlywood rich fractions had lower fibre stiffness and more mechanical fibre damage (as measured by Simon's Stain) than had latewood rich fractions. At equal fibre length, earlywood rich fractions had tensile strength superior to fractions rich in latewood fibres. For chemical pulps, Paavilainen [144] found good relationship between fibre coarseness and tensile strength. Decreasing coarseness improved tensile strength. When paper from mechanical pulp is fractured, the main mechanism is fibre pull-out, and not fibre breaks [146]. Hence, the fibre strength is less important for mechanical pulps than for chemical pulps. Kärenlampi [147] used the model of Shallhorn and Karnis [146] together with suitable literature data to predict the tensile and tear strengths for sheets made from earlywood and latewood fibres. In this theoretical consideration, he found that at identical fibre length, a sheet made from purely earlywood fibres would have 50% higher tear and tensile strength than a sheet made from latewood fibres. The earlywood fibres' lengths could be reduced down to 70% of the latewood fibre length before the sheets from early- and latewood fibres had equal tensile strength.

2.4.4 Summary

To sum up, the fibres in mechanical pulps should have as thin walls as possible. The fibre length should be sufficient to meet the demands set by runability in paper production and in printing presses. Thickwalled fibres, in particular latewood fibres, are detrimental to surface smoothness. One way of reducing the problem is to lower the fibre content. This is not very attractive, as it obviously will reduce paper strength. Wood sorting may be one important strategy to raise paper quality. The right fibres should be picked for the right quality. When the quality of the raw material is set, further quality improval could be done by refining at optimal process conditions. During refining, the fibre wall thickness is reduced. However, as discussed in Chapter 2.3.4, it is important to know the mechanisms of how latewood and earlywood fibres are altered during a refining process.

2.5 Techniques for assessment of transverse tracheid dimensions.

2.5.1 Tracheid dimensions in wood

Cross-sectional dimensions of tracheids in wood trunks have long been measured by optical microscopy [e.g. 28,46,148]. Such measurements have been limited to cell wall thickness and radial and tangential cell width. The procedure is very time-consuming. Also, since the fibre wall thickness is commonly measured only at one point of the cross-section, variation of the wall thickness around the cross-section will not be accounted for. Evans [149] used an automated scanning x-ray microdensitometer combined with image analysis to provide transverse tracheid dimensions. The procedure is very rapid, and it is a very good tool to discriminate between different trees. However, the resolution is rather low. Evans [149] stated: "This instrument is a tool for the rapid screening of plantation-grown *P.radiata* pulpwood. It is not intended to replace detailed traditional microscopy".

2.5.2 Fibre dimensions

An indirect method for measuring fibre wall thickness was proposed by Jordan [150]. He analysed the void fraction in a thin fibre network. From grammage and fibre wall density, the fibre wall thickness could be calculated.

Kibblewhite and Bailey [151] dehydrated fibres using a solvent exchange procedure. The dried fibres were then aligned and embedded in resin before microtome preparates were made. Based on optical micrographs, cross-sectional dimensions were assessed. Optical microscopy has a resolution limited to half the wavelength of light, and the depth of field is also limited. Different refractive indexes on interfaces between fibre wall and resin in a microtome preparate may cause halos and artefacts in the micrograph. Koljonen and Heikkurinen [102] measured the fibre wall thickness on single fibres using light microscope on fibres viewed from above. The wall thickness was assessed as half the difference between fibre width and lumen width. Mohlin [92] embedded aligned fibres in epoxy. Thin sections were cut using a microtome. Images of cross-sections were provided by a light microscope. Transverse dimensions were assessed using image analysis on the images.

Jang et al. [152,153,154] used a confocal laser scanning microscope (CLSM) to provide cross-sectional micrographs of wood pulp fibres. The CLSM has several advantages over conventional light microscopy. The preparation time is short. One may get a clear image of a focal plane, undisturbed by layers above or underneath. Since the fibres are not embedded in a hard material, it is possible to perform other analyses on the same fibre besides the cross-sectional dimensions. This also means that one may study the changes in the fibre shape during drying of wet fibres. Although being an effective technique for single fibres, it is quite tedious for large fibre populations. As the method is based on optical sectioning and stacking a series of line scans, the lower part of the fibre image will become less intense than the upper part. The intensity gradient demands an effective thresholding technique.

A Scanning Electron Microscope (SEM) provides very high resolution as well as a large depth of field. Used in backscatter mode (SEM-BEI), a SEM produces images where the intensity is linked to the atomic weight of the specimen. Due to a satisfactory difference in atomic weight between epoxy and fibre wall, one gets clear grey-scale images that can easily be thresholded. This technique has been used to digitize images of fibre cross-sections [155]. Fibre transverse dimensions have been assessed using image analysis on such images.

2.5.3 Fibre collapse

The ability of a fibre to conform well in a paper, i.e. its flexibility, is an important property. The fibre flexibility is a function of both the modulus of elasticity (the rigidity of the material) and the moment of inertia. A flattening of the fibre cross-section reduces the moment of inertia, and consequently even the fibre flexibility. Hence, the degree of fibre flattening is an interesting parameter. Various methods exist to measure fibre collapse. However, most of the work has been done on chemical pulp fibres. Since mechanical pulp fibres seldom collapse totally, but rather develop a range of cross-sectional shapes, fibre flattening may be a better term.

Page [156] described a method for estimating the number of totally collapsed fibres in a fibre population. The method was based on examination of fibres in light microscope under transmitted light, while the fibres were surrounded by a medium with a refractive index close to that of the cell wall. Under these conditions, collapsed fibres were almost invisible, and uncollapsed fibres visible. However, the method could not quantify degrees of flattening, only whether a fibre was totally collapsed or not. In more recent investigations, fibre collapse has been expressed through various geometrical parameters or indexes. The aspect ratio has been defined both by the ratio between the largest and the smallest diameter in a cross-section [157] or by the ratio between smallest diameter and largest diameter [83,94]. The latter has the advantage that the values are limited between 0 and 1, where a value close to 0 corresponds to a collapsed fibre. The form circle is defined by the per cent ratio between the cross-sectional area and the area of the cross-section spanned out to a circle [83] (Equation 2.2). Here *FC* denotes form circle,

$$FC = \frac{A_{tot}}{A_{circ}} = \frac{4 \cdot \pi \cdot A_{tot}}{P^2} \quad (2.2)$$

A_{tot} the total cross-sectional area (including wall area and lumen area), A_{circ} the area of the cross-section spanned out to a circle and P the outer perimeter. This parameter describes the circularity of the cross-section. A value close to 0 corresponds to a totally collapsed fibre. Jang et al. [94] introduced what they termed a collapse index (Equation 2.3). Here, *CI* denotes collapse index, *LA* denotes lumen area and LA_0 the calculated

$$CI = 1 - \frac{LA}{LA_0} \quad (2.3)$$

uncollapsed lumen area.

2.6 Concluding remarks

Much work has been done on the alteration of wood fibres in refining, and the basic mechanisms including defibration and fibre development are well known. As thickwalled latewood fibres represent special problems in papermaking and converting processes, special attention should be paid to how earlywood and latewood fibres are affected in a refining process. Several papers have discussed this topic, but the conclusions differ strongly. More research is therefore needed to describe how different groups of fibres behave in a TMP refining process. The behaviour of different raw materials in TMP refining has often been suggested to be related to basic density. No clear correlations have been found between wood basic density and pulp properties. It seems that further investigations are needed where TMP-pulp properties are related to the tracheid dimensions of the wood raw material.

Print quality is affected by properties like surface smoothness, formation, gloss and opacity. Although an increase in fines content improves surface smoothness and light scattering, restrictions set by runability will in practice limit the amount of fines in the pulp. At a realistic fines content, fibre properties will therefore control important paper properties. A smooth paper surface is crucial for a good printing result. Thickwalled fibres protruding from the paper surface can be detrimental to the print quality [e.g. 2,4]. It has been shown (both mathematically [141] and experimentally [142]) that a decrease in wall thickness improves light scattering. The effect of other structural fibre parameters on paper properties, such as fibre splitting, should be examined. Further quantification of how fibre dimensions and structure affect paper properties is also needed.

As new technology has made it possible to characterize fibres more detailed, fibre cross-sectional dimensions can be assessed based on light microscopy [92,102,151], confocal laser scanning microscopy [152] or electron microscopy [155]. Due to the heterogenous nature of wood, large numbers of fibre cross-sections should be assessed. There is need for a method for assessment of the wall thickness of split fibres. Improved methods for detailed characterization of transverse dimensions of wood tracheids are also needed.

CHAPTER 3

MATERIAL AND METHODS (PAPER I AND II)

3.1 Introduction

Development of new methods and improvement of existing methods for characterizing fibre cross-sectional dimensions was one of the objectives in this thesis work. The cross-sectional analyses were the most important parts of the experimental work. Detailed descriptions and discussions of the methods are given in Paper I and II. Table 3.1 gives an overview of the experimental methods applied and the pulps/trees that were investigated in the different papers. This chapter gives an overview of the methods that were used in the study, and a reasoning for the choices that were made during the development of the methods.

3.2 Existing methods for assessment of fibre transverse dimensions

When this study started, assessment of fibre transverse dimensions had been going on for some time at the Norwegian University of Science and Technology [e.g 83,155]. The cross-sectional dimensions were assessed by image analysis on Scanning Electron Microscope (SEM) images. A Scanning Electron Microscope provides very high resolution as well as a large depth of field. Used in backscatter mode (SEM-BEI), a SEM produces images where the intensity is linked to the atomic weight of the specimen. Due to sufficiently high differences in atomic weight between epoxy and the fibre wall, one gets clear grey-scale images that can be easily thresholded, i.e. converted to binary images.

To minimize the number of SEM-images and the costly time spent at the SEM, each image should contain a large amount of fibre cross-sections. The fibres should also be aligned parallel to each-other. It was also an important issue that the fibres were randomized, assuring a representative selection of the fibre population. The alignment was done using the grid shown in Fig. 3.1. While stirring, a suspension of fibres was drained through the spacings (1 mm) between parallel plates. Water was added to the fibre suspension until all fibres had entered the slits between the plates. The aligned

Table 3.1: Overview of experimental methods and pulps/trees investigated in the different studies.

Paper no:	Main objective of study	Experimental methods applied	Trees/pulps investigated
I	Improving the methods for assessment of fibre transverse dimensions	• Cross-sectional analyses of fibre cross-sections	• Pilot scale TMP-series (three stages)
II	Develop new methods for assessment of transverse dimensions of tracheids in a wood trunk.	• Cross-sectional analyses of tracheid cross-sections in wood trunks	• Trunk from Norway Spruce • Trunk from Scots Pine
III	Examine how fibre splitting affects paper surface roughness	• Cross-sectional analyses of fibre cross-sections • Assessment of split length fraction using light microscope	• Mill scale SGW (35 ml CSF) • Mill scale TMP (35 ml CSF) • Pilot scale PGW (35 ml CSF) • Pilot scale PGW (85 ml CSF)
IV	Examine how earlywood fibres and latewood fibres are affected in refining	• Cross-sectional analyses of fibre cross-sections	• Mill scale TMP-pulps (Three succeeding refining stages)
V	Examine the composition (latewood/earlywood) of shives in various mechanical pulps	• Cross-sectional analyses of fibre and shive cross-sections	• Mill scale TMP-reject • Mill scale reject refined TMP-reject • Mill scale screened TMP-accept • Mill scale SGW-reject • Mill scale reject refined SGW-reject • Mill scale screened SGW-accept • Pilot scale PGW (85 ml CSF) • Mill scale TMP (35 ml CSF) • Pilot scale TMP-series (two stages, 1st stage run at high disc speed) • Pilot scale TMP-series (two stages, 1st stage run at normal disc speed)
VI	Verify findings regarding the alteration of earlywood and latewood fibres in refining from study IV	• TMP refining, pilot scale, 20” disc refiner • Cross-sectional analyses of fibre cross-sections • Cross-sectional analyses of tracheid cross-sections in wood trunks	• Norway Spruce chips from single trees • Scots Pine chips from single trees • Pilot scale TMP-pulps from 3 Norway Spruce trees and 4 Scots Pine trees
VII	Examine how Norway Spruce and Scots Pine fibres develop in a TMP-process	• Measurement of extractives content (SCAN-CM 49:93) • TMP refining and cross-sectional analyses of fibre cross-sections as for study VI	• Same as for study VI

fibres were formed to a fibre bundle, and freeze-dried. The freeze-drying was done in order to prevent the fibres from coming too close to each-other in the preparate. Improved alignment was achieved by wrapping the fibre bundles firmly in cellophane

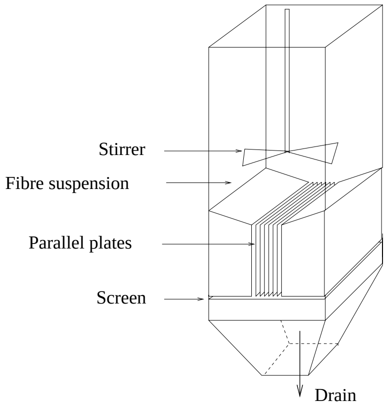


Figure 3.1 Equipment used for aligning of fibres.

folio. Preparates were made by casting the fibre bundles in epoxy. The preparates were then cut perpendicularly to the fibre direction, ground (using abrasive papers) and polished (using a polishing disc with diamond grinding particles) until the surface was smooth. After carbon coating, grey-scale images were taken in a Scanning Electron Microscope in BEI-mode. The grey-scale images were thresholded to binary images. Shives, fibres with broken cross-sections and material judged as “noise” were interactively removed from the images. Small discontinuities in the images were mended. Assessment of the cross-sectional dimensions was then undertaken by an image analysis system. The fibre wall thickness was calculated, assuming the fibre to be tubular (Eq. 3.1).Here *WT* denotes average fibre wall thickness, *P* denotes outer perimeter and A_w fibre wall area.

$$WT = \frac{P - \sqrt{P^2 - 4\pi A_w}}{2\pi} \qquad (3.1)$$

3.3 Identification of needs for improvement and development

The preparation procedure worked very well, and it has been used throughout the entire study. A detailed description is given in Paper I. The image analysis was the procedure’s bottleneck being very time-consuming. This part of the procedure had much potential for further improvement.

The following shortcomings were identified:

1. The transverse fibre dimensions were assessed only on intact fibres. Quite many of the fibre cross-sections were split, and it seemed likely that the split fibres constituted a separate fraction of the fibre population along with the fraction of intact fibres. Further, the fraction of split fibres most probably varied from pulp to pulp and between different process stages. Hence, an error was introduced, both to the absolute values as well as the relative differences between process stages. This weakness applies to all other methods for assessing fibre transverse dimensions.
2. The procedure for calculating wall thickness (Eq. 3.1) was not sufficiently precise. Most thin-walled fibres were calculated correctly. However, for raising wall thickness, the assessed wall thickness was increasingly underestimated. This behaviour introduced an error in the fibre wall thickness distribution curve, causing it to contract.

The following new applications were identified as beneficial:

1. One should be able to measure the variation of fibre wall thickness around the perimeter of each cross-section.
2. One should make the procedures as automatic as possible, to minimize the time-consumption and to reduce operator bias.
3. One should develop methods to assess tracheids' transverse dimensions in a wood trunk. SEM-images should be used as an image source, maintaining the same resolution and image quality in the wood as for the defibrated fibres. The motivation was to be able to study changes of the fibre cross-sections during the process stages from wood to finished pulp.

3.4 The image analysis procedure - assessment of transverse dimensions of pulp fibres

3.4.1 Description of fibre cross-section images

The SEM-micrographs were grey-scale images, with 256 greytones. Fig. 3.2 shows an example of a SEM-micrograph of TMP-cross-sections. The image illustrates that the cross-sections vary very much in a fibre population. The complexity is high in such an image, and noise and artefacts should be removed. Small grinding particles rich on Si may be stuck in the epoxy surface, creating very bright areas. Fibres both from Norway Spruce (*Picea Abies* (L.) Karst.) and Scots Pine (*Pinus Silvestris*) have pores in the fibre wall. These pores can be seen in the fibre cross-section as small discontinuities in the fibre wall. (An example is shown in Fig. 3.2.) Cross-sections of undefibrated fibre bundles or shives may appear in the images. In other cases, defibrated fibres might touch each-other by chance, hence appearing as one object in the image. In the refining process, fibres receive damages and splits in the fibre wall. Such fibres will have broken cross-sections. Often fibrils or small parts of the fibre wall will appear in the images. It is important that the image analysis system is able to handle all artefacts and variations.

3.4.2 Image analysis procedure applied in Paper III, IV and V.

The image analysis techniques applied were further refined during the studies. New and improved techniques were included in the last projects. However, the same procedure was always applied when various pulps in a specific project were compared.

The greyscale images were converted to binary images. The threshold value was chosen to be between the two peaks in the greyscale intensity distribution (Fig. 3.3). In the binary image, small particles were removed (e.g Si grinding particles, fine material,

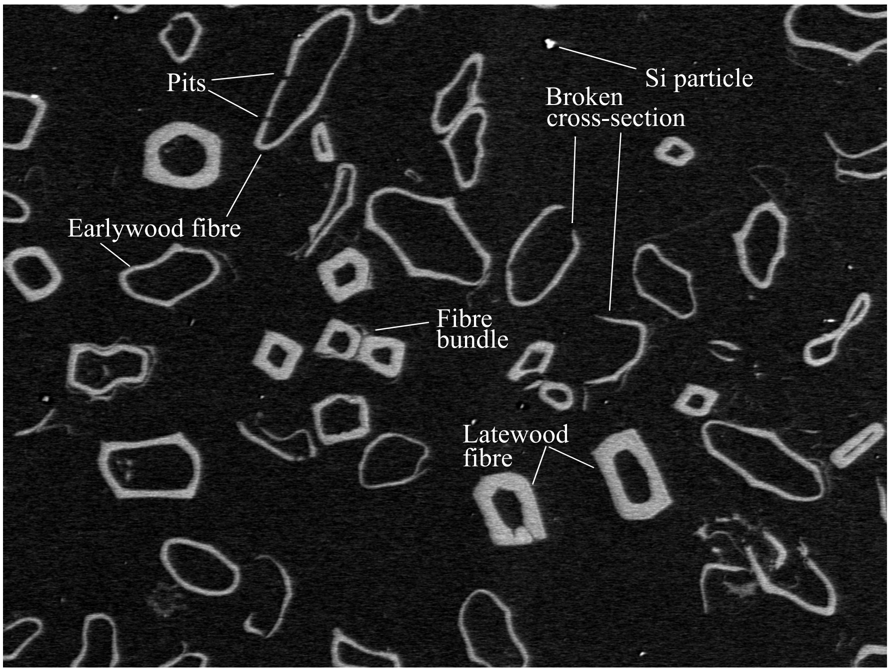


Figure 3.2 Grey-scale SEM-micrograph, 1024 x 768 pixels, showing fibre cross-sections from a TMP-pulp.

noise etc.). All edges were smoothened using the morphological operations *open* and *close* on the images. The images were now edited manually:

- Small discontinuities in the fibre wall recognized as pits were closed.
- Fibres touching each-other by chance were separated.
- Undefibrated fibre bundles or shives were removed from the image.
- Fibres with broken cross-sections were moved into a separate image.

Examples of edited binary images are shown in Fig 3.4. These images were now thinned, using a Matlab routine, meaning that each object in the image was replaced with its one pixel wide skeleton (Fig. 3.5). Cross-sectional parameters such as fibre wall area, outer perimeter, lumen perimeter, lumen area, longest diameter and shortest diameter were

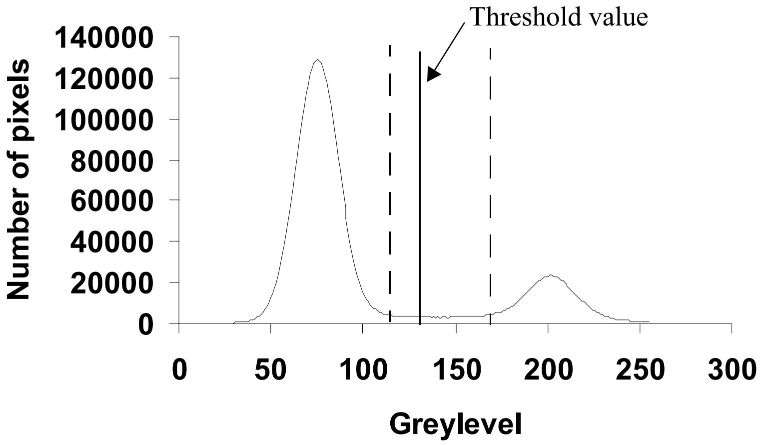


Figure 3.3 Grey level histogram for the image in Fig. 3.2. The threshold value is chosen to be 1/3 of the distance on the baseline between the two peaks.

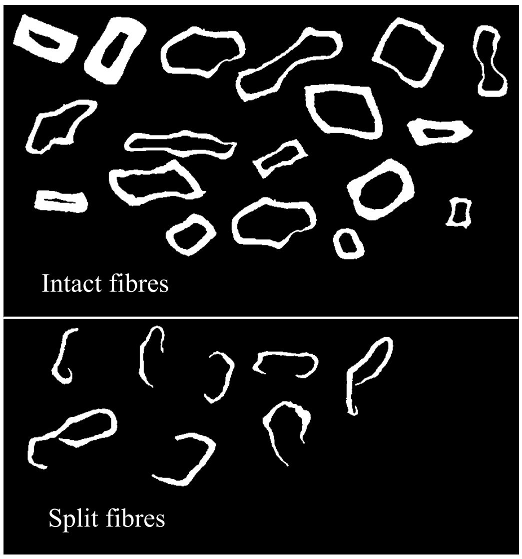


Figure 3.4 Edited binary images of fibre cross-sections, TMP-pulp. Top: Intact fibres, Bottom: Fibres with broken cross-sections.

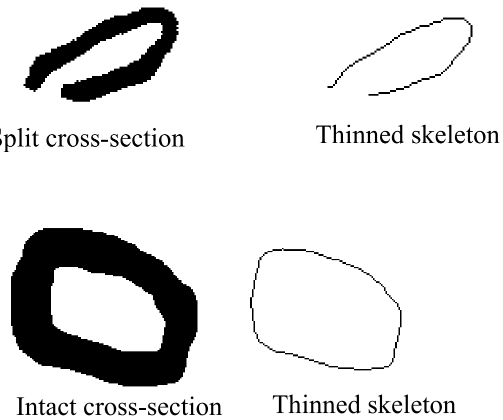


Figure 3.5 Examples of TMP-fibre cross-section (left), together with their thinned skeletons (right).

assessed using an image analysis system from Carl Zeiss (Kontron KS-300). Mean fibre wall thickness was calculated according to Equation 3.2. Here, A_w denotes fibre wall area, and L_{skel} denotes length of the corresponding thinned skeleton (Fig. 3.5).

$$WT = \frac{A_w}{L_{skel}} \qquad (3.2)$$

3.4.3 Image analysis procedure applied in Paper I, VI and VII

An improved image analysis procedure was implemented in the experiments described in Paper I, VI and VII. Greyscale SEM-images of size 2732 x 2048 pixels were smoothened using lowpass filtration followed by median filtration. The images were then converted to binary images. The best thresholding value was automatically found. Small objects were removed, and edges were smoothened using the morphological operations *open* and *close*. Fibres with broken cross-sections were automatically recognized and moved to a separate image. The images were edited in the same way as described in section 3.4.2. The fibre wall thickness was calculated using the Euclidian Distance Map (EDM). This algorithm measures the radius of the smallest circle inscribed in the fibre wall at every point along the median perimeter (Fig. 3.6). Both the mean wall thickness and the variance of the wall thickness along the perimeter were calculated. In Fig. 3.7 fibre wall thicknesses assessed by the thinning algorithm (section 3.4.2) and the EDM-algorithm (section 3.4.3) are plotted against each other.

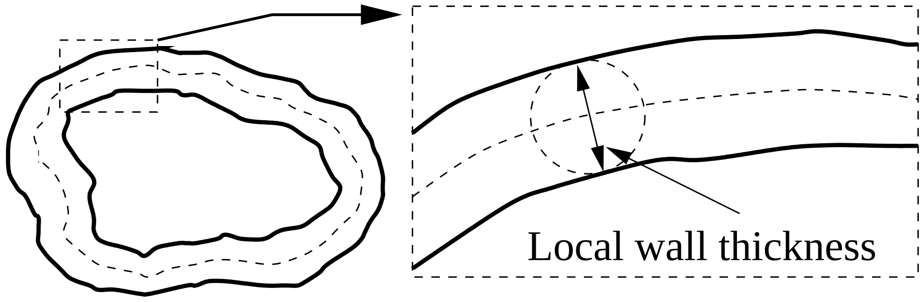


Figure 3.6 Measurement of fibre wall thickness using the EDM-algorithm.

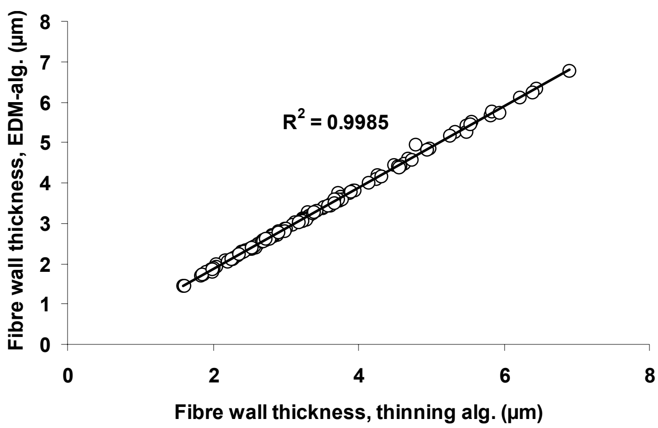


Figure 3.7 Fibre wall thickness assessed by thinning algorithm plotted against wall thickness assessed by the EDM-algorithm.

3.5 Method for assessment of transverse dimensions of wood tracheids

3.5.1 Preparation procedure

A detailed description of the preparation procedure is given in paper II. From the wood cross-sections, a strip of wood (5 x 15 mm in cross-section) was sawn in the radial direction from pith to cambium. The strip was divided into smaller pieces (2.5 cm length). The pieces were soaked in water (5 min.) and the surface was then evened by a microtome. After drying, the wood-pieces were glued together, so that the surfaces to be examined faced the same direction. The glued wood-piece was then soaked in water (5 min.), and the surface was evened by the microtome anew.

After drying, the wood was impregnated with epoxy. Wood is much more difficult to impregnate than defibrated fibres, and an epoxy of very low viscosity had to be used. EpoTek 301 proved to be well suited for the purpose. The sample was evacuated in a vacuum chamber for minimum 15 min. It is important that the surface of the wood-piece that is to be examined, is exposed to the epoxy, and hence faces upwards during impregnation. To avoid boiling, the pressure was raised to 200 mbar before impregnation with epoxy. After impregnation, this pressure was maintained for 15 minutes, to remove trapped air bubbles from the preparates. The wood sample was then turned upside down, having the surface to be examined facing downwards. The wood piece was fixed against the bottom of the mould by a clamp.

The preparates were left for curing at room temperature for 24 hours. The epoxy will not be able to impregnate completely throughout the preparate. One should therefore not remove more than maximum 1 mm of the surface layer during grinding and polishing. Grinding was done carefully using 1200, 2400 and 4000 grits abrasive paper, followed by surface polishing with 3 and 1 μm diamond particles. The preparates were carbon coated. Micrographs were taken in a Scanning Electron Microscope at BEI mode.

3.5.2 Image analysis procedure

Greyscale images of size 2732x2048 pixels were converted to binary images (Fig. 3.8, left). The images had to be manually edited. Ray cells were thus "filled". Pits were "removed", and replaced with an intact cell wall (Fig. 3.8, middle). The image was thinned, giving a 1 pixel wide skeleton. The thinned image was then subtracted from the unthinned image, dividing the tracheids into single cells. Cells along the image border and cells adjacent to wood rays were removed (Fig. 3.8, right). Cross-sectional parameters such as cell wall thickness, perimeter and cell wall area, were measured automatically by the image analysing software.

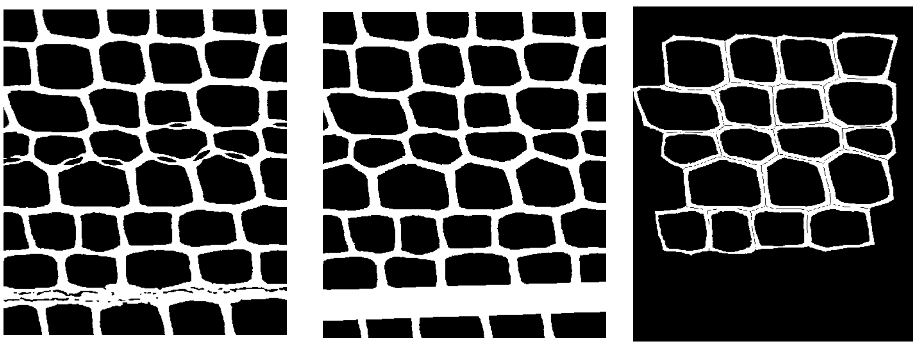


Figure 3.8 Left: Thresholded binary image, details of wood cross-section. Middle: Pits are removed and replaced by intact cell wall, Ray cells are filled. Right: Image ready for measurement.

3.6 Accuracy of the method

3.6.1 Sampling of fibres

The wall thickness varies considerably around the fibre perimeter. However, there may also be a large variation in wall thickness along the fibre length. To get representative and reproducable results a correct sampling of fibres is important. The point on the fibre length at which the cross-sectional parameters should be assessed, must be randomized. This randomization is accomplished through the alignment of fibres. All measurements applied in the present study are done at the same cross-section of the preparate. Since the chance of picking a fibre increases with the fibre length, the method will automatically give length-weighted parameters.

3.6.2 Uncertainty due to sample preparation

In the applied procedure, the fibres are assumed perfectly aligned. In practice, perfect alignment may be difficult to accomplish. A firm wrapping of the samples in cellophane folio is important to improve the fibre alignment. Fig. 3.9 shows a sketch of a fibre skewcut at an angle of a °. It can easily be verified that we get for the skewcut cross-section:

$$A_{w,\,skew} = \frac{x^2 - y^2}{\cos(a)} \quad (3.3)$$

$$P_{av,\,skew} = x + \frac{x}{\cos(a)} + y + \frac{y}{\cos(a)} \quad (3.4)$$

$$WT_{skew} = \frac{x^2 - y^2}{x \cdot \cos(a) + y \cdot \cos(a) + x + y} \quad (3.5)$$

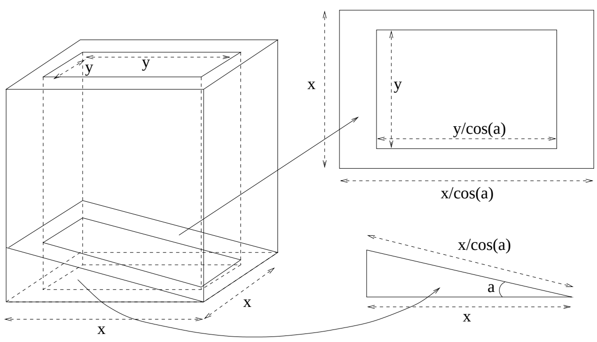


Figure 3.9 Sketch showing a fibre not cut perpendicularly to the fibre length.

Here *WT* denotes wall thickness, and P_{av} denotes the average of outer and inner perimeter. For a typical fibre cross-section, x = 30 µm, and y = 24 µm. With a tilting of

10 °, the wall area will be overestimated by 1.5%, and the wall thickness will be overestimated by 0.77%. Clearly skewcut fibres were removed from the images. The number of such fibres was rather low (some 0.5%).

3.6.3 Uncertainty caused by having digital images

Since the images are digital, the uncertainty for every wall thickness around the perimeter is ± 0.5 pixels. At the magnifications applied here, the perimeter of a fibre is typically some 300 pixels. The uncertainty of the average wall thickness caused by having digital images is then:

$$\Delta WT_{dig} = \pm\frac{0.5}{\sqrt{300}}\text{pixels} = 0.029\text{pixels} \quad (3.6)$$

At the applied magnifications, the length of one pixel is 0.3 µm. Hence, the value of the mean wall thickness will not be significantly affected by having digital images.

3.6.4 Uncertainty due to thresholding

When the greyscale image is converted to a binary image, the object areas depend on the threshold value. The greylevels of SEM-images may vary from time to time. Hence, the threshold value should always be chosen using the same rules, as described in section 3.4.2. In Table 3.2, it can be seen that increasing brightness and contrast on the image in Fig. 3.2 had no effect on the mean object area after thresholding. However, the thresholding may cause an offset in the measured value. Considering Fig. 3.3, with corresponding grey level histogram in Fig. 3.3, the correct threshold value is surely between the values 120 and 170. For these two threshold values, the mean fibre wall area varied by 0.2%. Hence, a reasonable estimation of the *maximum* offset is ± 0.1%. When comparing the effect of a treatment, such as refining, the offset does not matter. In this thesis, all values are presented together with their 95% confidence interval limits.

Table 3.2: Various brightness and contrast increases had no effect on the mean object area after thresholding.

Image nr	Brightness increase (%)	Contrast increase (%)	Mean object area (pixels)
1	0	0	976
2	10	10	976
3	10	15	976
4	5	15	976

3.7 Effect of population size

3.7.1 Means

When a parameter should be compared for two fibre populations, it is common to compare the population means. The variance of the mean is given by Equation 3.7.

$$Var(\bar{y}) \approx \frac{\sigma^2}{N} \qquad (3.7)$$

Here, σ^2 is the sample variance, and N the size of the population. A higher significance is thus reached in the t-test as the number of fibres increases.

The variance of a population, σ^2, is approximated by the square of the standard deviation, s^2, so that

$$\lim_{N \to \infty} s^2 = \sigma^2 \qquad (3.8)$$

The sample standard deviation for a parameter will accordingly approach a finite value when the number of fibres increases. The fibre wall thickness was assessed for a large number of fibres from a TMP-pulp. A small MATLAB program drew a number of fibres randomly from the large population, and the standard deviation of the new population was calculated. This procedure was repeated, yielding a number of populations in the number of 10 to 2500 fibres. Fig. 3.10 shows how s approaches a limit value for a large number of fibres.

The number of fibres that should be included in a fibre wall thickness assessment is dependent on how large errors that can be tolerated. The error can be expressed through a confidence interval, and a significance level of 95% is commonly applied. When the

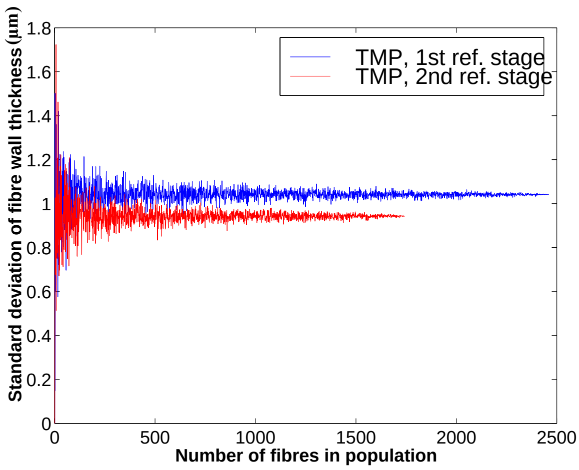


Figure 3.10 Standard deviation of fibre wall thickness plotted versus the number of fibres in the population for a TMP-pulp after 1st and 2nd refining stage.

degrees of freedom exceed far beyond 100, the value of $t_{0.025}$ is close to 1.960. The following expression returns the 95% confidence interval:

$$\bar{y} \pm \left(\frac{1.960 \cdot s}{\sqrt{N}}\right) \qquad (3.9)$$

With an error limit of n%, we get the following equation:

$$\frac{1.960 \cdot s}{\sqrt{N}} \leq \frac{n \cdot \bar{y}}{100} \qquad (3.10)$$

Rearranged, and solved with respect to *N* we get Equation 3.11.

$$N \geq \left(\frac{196 \cdot s}{n \cdot \bar{y}}\right)^2 \qquad (3.11)$$

The mean fibre wall thickness and sample standard deviation were assessed for 31 TMP-pulps. The numbers of fibres in each population were between 600 and 3000. The values of $s/\bar{y}$ for the 31 populations were distributed around 0.41, as the normal distribution in Fig. 3.11 (right axis). In the same figure (left axis) Equation 3.11 is plotted for three different error limits (2, 3 and 4%). In order to be sure to achieve an uncertainty level of ± 3%, the value of $s/\bar{y}$ should be 0.48. Hence, one should at least include 980 fibres.

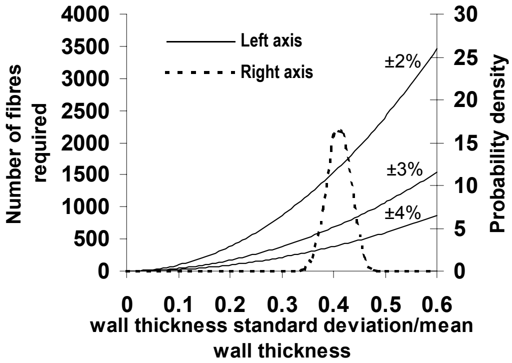


Figure 3.11 Left axis: Numbers of fibres required for three different uncertainty limits (2, 3 and 4%) plotted against $s/\bar{y}$. Right axis: Distribution of $s/\bar{y}$ for 31 TMP-pulps.

3.7.2 Distributions

Based on the data, a frequency distribution can be plotted, either as a histogram or as a frequency polygon. The interval length should be optimized, in order to give smooth and precise curves. If a histogram is to be used, the length of intervals should according to Scott [158] be chosen to be approximately $0.6 \cdot N^{-1/3}$ times the range of the variate. N represents the total number of fibres in the population. When a frequency polygon is used instead, Scott [159] points out that the length of each interval should be approximately $0.35 \cdot N^{-1/5}$ times the range. For a population of 3000 fibres, about 14 intervals should be included.

3.8 Concluding remarks

Limitations of an existing method [155] for assessment of fibre cross-sectional dimensions were identified. The method, which was based on image analysis of Scanning Electron Microscope micrographs, was further developed. The method allows precise assessment of large populations of processed pulp fibres. Both intact and split fibres may be assessed. The variation of fibre wall thickness around the perimeter may be measured for all fibres. In order to achieve an accuracy (95% confidence interval) of ± 3% for fibre wall thickness, approximately 1000 fibres should be assessed. The method may e.g. be applied to:

- study changes in transverse dimensions for different groups of fibres throughout a process.
- examine differences between various raw materials.

A new method was developed for precise assessment of transverse tracheid dimensions in wood trunks. The method may e.g be used to:

- study changes in transverse dimensions for tracheids/fibres throughout a process, all the way from wood to paper.
- map transverse tracheid dimensions between and within growth rings of a wood trunk.

CHAPTER 4

IMPORTANT FIBRE PARAMETERS FOR WOOD-CONTAINING PRINTING PAPER (PAPER III AND VI)

4.1 Introduction

Manufacturers of wood-containing publication paper actually sell printing surfaces. For these paper grades print quality and runability are the key quality parameters. As discussed in chapter 2, surface smoothness and opacity may be improved by increasing the fines content [110,115]. However, the fines content is in practice restricted by runability limitations. The quality of the mechanical pulp fibres therefore governs important paper parameters such as surface smoothness and opacity. In this chapter the objective is to explore which fibre parameters that have largest influence on surface smoothness and light scattering coefficient. Paper made from SGW pulp tends to have print quality superior to TMP-based paper. The fibres from SGW, PGW and TMP pulps were investigated to find if GW-fibres had any special characteristics beneficial for surface smoothness.

4.2 Example of paper surface roughening during printing

As mentioned in chapter 2.4.1, a calendered paper surface subjected to moistening (e.g during printing or coating) will tend to roughen. The SC-paper in Fig. 4.1 was exposed to water in a Prüfbau laboratory printing press to simulate the dampening water in offset printing. The water transferred in the printing nip was 1.5 g/m^2, and the paper was exposed to water in four nips, to simulate four colour offset printing. Fig. 4.1 shows a small area of the SC-paper, before printing (top), and after printing and drying (bottom). It can clearly be seen that areas containing coarse mechanical pulp fibres in the upper layers of the paper have experienced a local surface roughening.

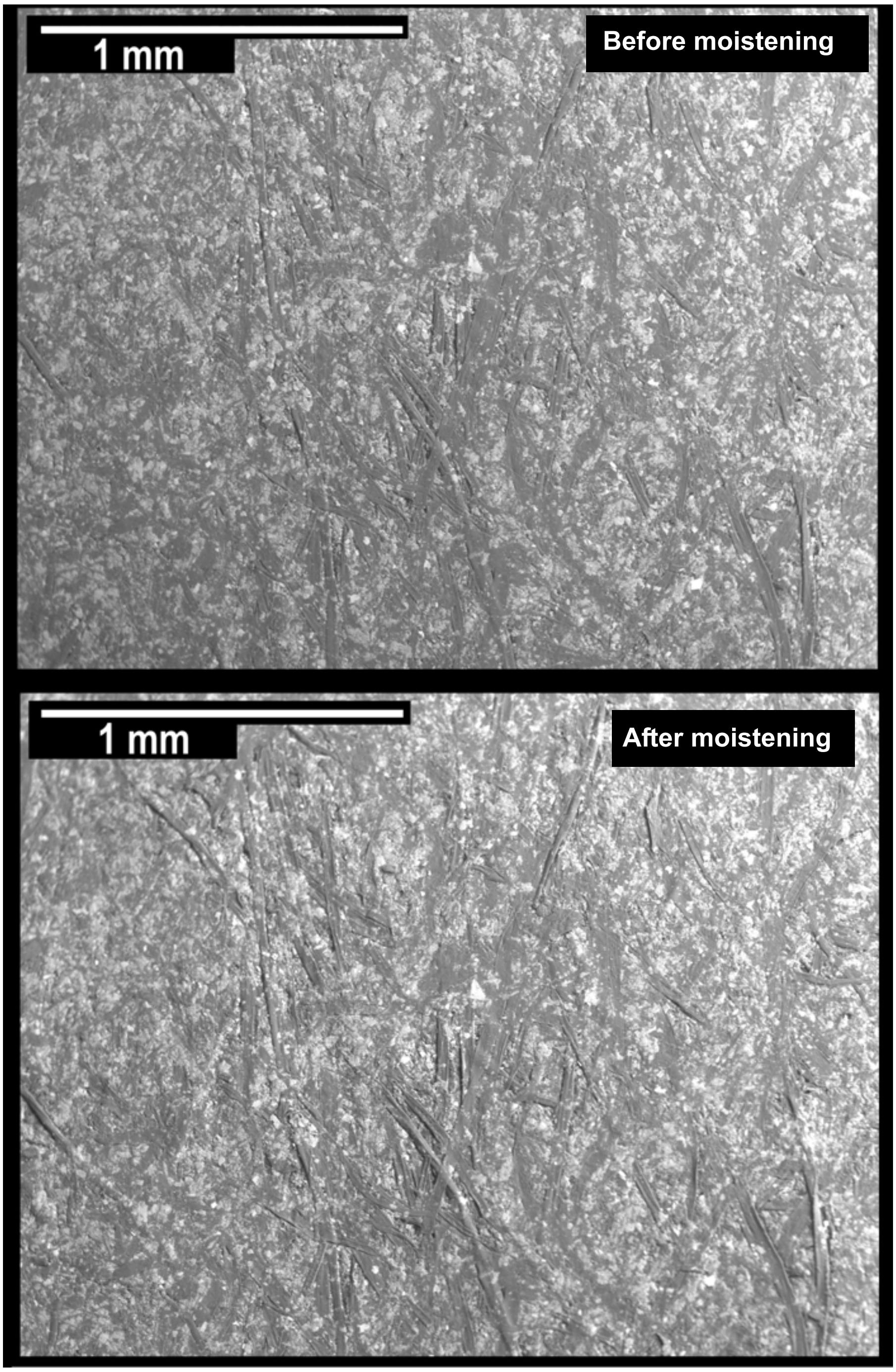


Figure 4.1 Details of the surface of a super calendered magazine paper prior to printing (top) and after 4 nips of printing (just dampening water) in a Prüfbau press (bottom).

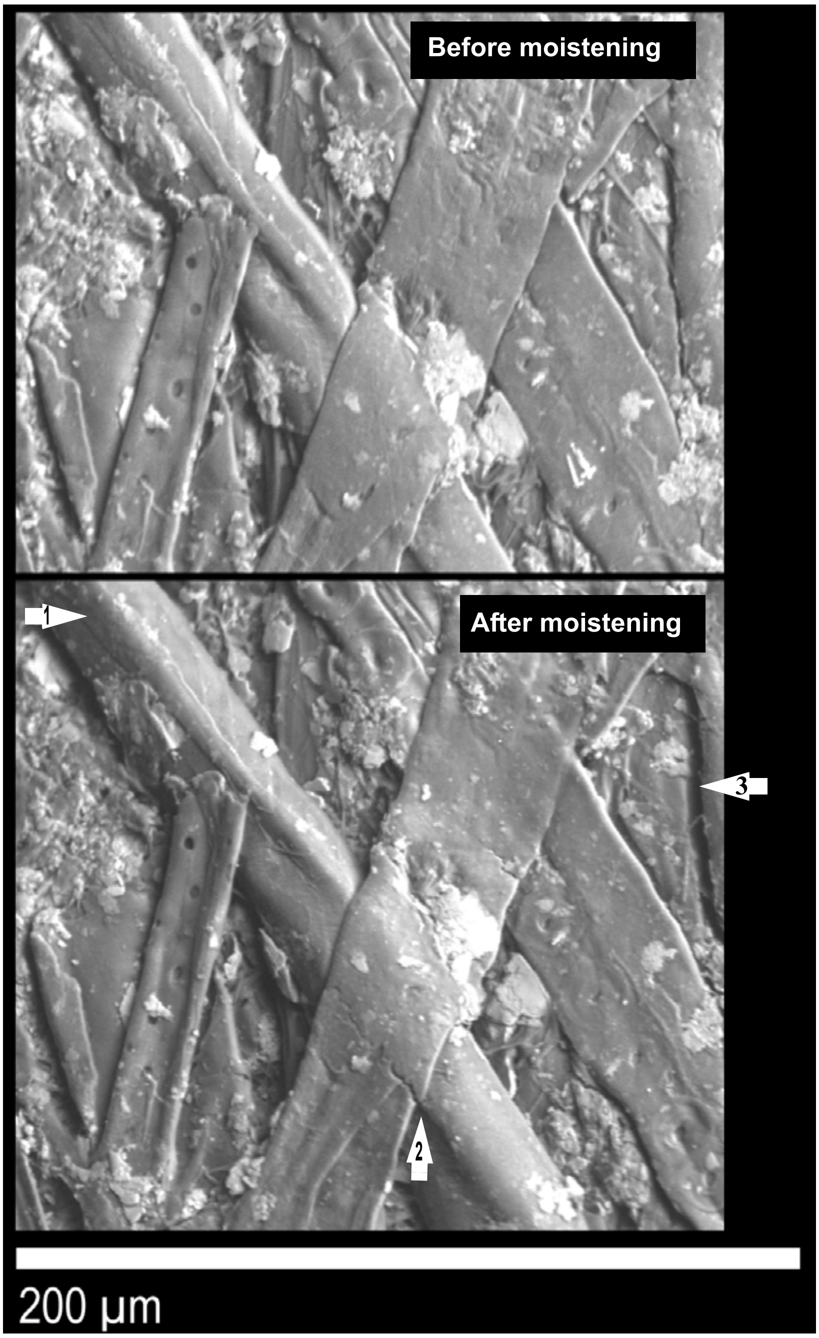


Figure 4.2 Selection from the area depicted in Figure 4.1, before and after water moistening in a Prüfbau printing press.

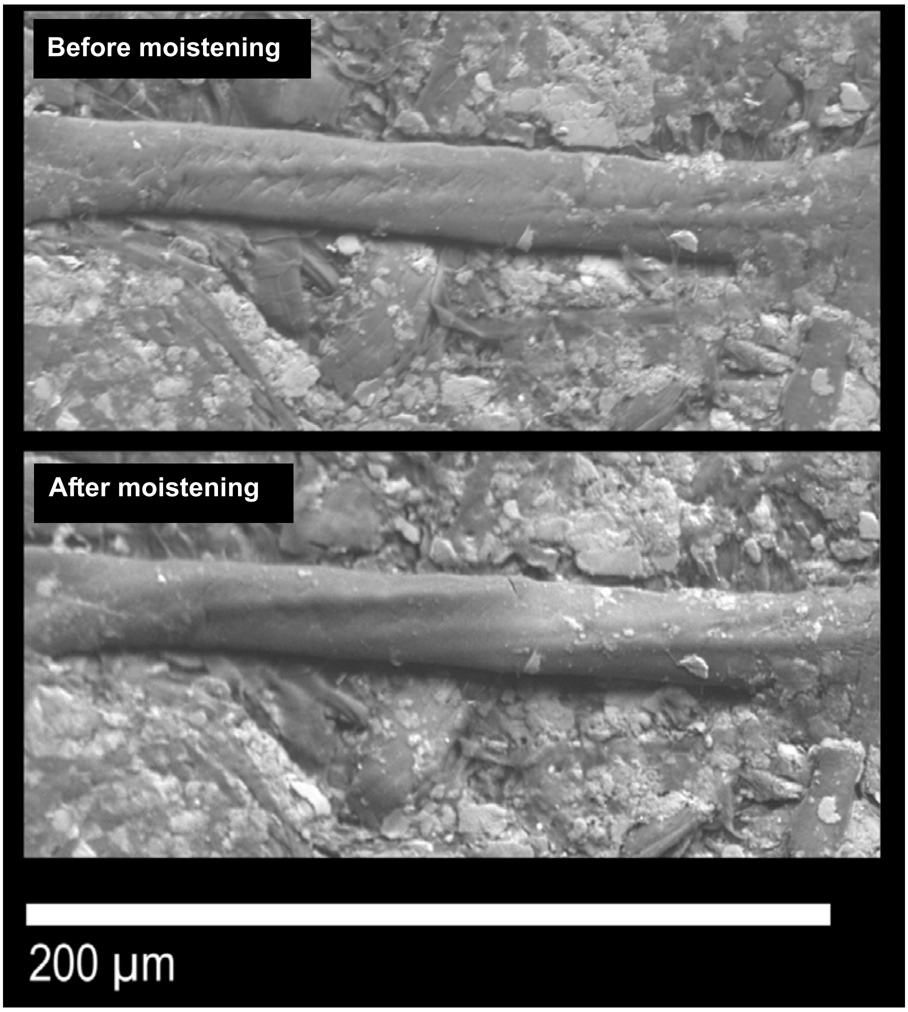


Figure 4.3 Selection from the area depicted in Figure 4.1, before and after water moistening in a Prüfbau printing press.

Figs 4.2 and 4.3 depict details from Fig. 4.1 In Fig. 4.2, the fibre marked "1" seems to partly recover its shape as it probably was prior to calendering. A crack (marked "2") has been introduced to a crossing fibre during moistening. The moistening has also caused a fibre to raise from the surface (arrow "3"). Fig. 4.3 also depicts a surfacing fibre that partly expands back to its pre-calendered shape upon moistening.

In this case, the paper sample was not subjected to heating after the Prüfbau nips. One might expect more severe changes to the paper surface during heat-set offset printing.

4.3 Quantification of fibre splitting

To quantify the degree of fibre splitting for TMP and SGW fibres, various pulp samples, including pilot scale and mill scale pulps, were collected (Table 4.1).

Table 4.1: Overview of the pulp grades investigated

Code	Freeness (ml)	Pulp grade
TMP1	35	Thermomechanical pulp, mill scale
TMP2	35	Thermomechanical pulp, mill scale
SGW1	35	Stone groundwood pulp, mill scale
SGW2	35	Stone groundwood pulp, mill scale
PGW1	85	Pressure groundwood pulp, pilot scale
PGW2	35	Pressure groundwood pulp, pilot scale

The split lengths of cracked fibres were quantified and related to total fibre length as described in Paper III. Even some other fibre characteristics were assessed, Table 4.2.

Table 4.2: Measured fibre parameters for various mechanical pulp grades and fractions, together with their respective 95% confidence interval limits.

Fraction	Pulp grade	Average length (mm)	Average width (µm)	Fibre split (%)	Fibre wall thickness (µm) (intact fibres)
+28 mesh	TMP1	2.20±0.06	34±1	4±1	Not measured
+28 mesh	SGW1	2.05±0.05	35±1	27±5	Not measured
+48 mesh	TMP2	2.30±0.05	31±2	10±2	2.2±0.1
+48 mesh	SGW2	1.73±0.04	35±3	46±5	2.5±0.2
+48 mesh	PGW1	1.96±0.05	32±2	30±5	2.2±0.2
+48 mesh	PGW2	1.85±0.06	33±2	39±5	2.3±0.1

GW-fibres (including PGW) have 3-4 times as large degrees of fibre splitting compared to the TMP-fibres. When all the +48-fraction fibres are considered, a much higher split fraction was found compared to the +28-mesh fraction fibres. Partly damaged fibres appear to have a tendency to be reduced in size, moving from the +28 into the +48 mesh fraction. Figs 4.4 and 4.5 show SEM-micrographs of fibres from the SGW-pulp. From Fig. 4.6 the different appearance of the SGW-fibres and the TMP-fibres is obvious. The SGW-fibres are split and damaged, especially at the fibres' ends, Fig. 4.4, Fig. 4.6, top.

Also, there are fibres with fibre wall cracks as seen from Fig. 4.5. These cracks some times result in a helix-like structure.

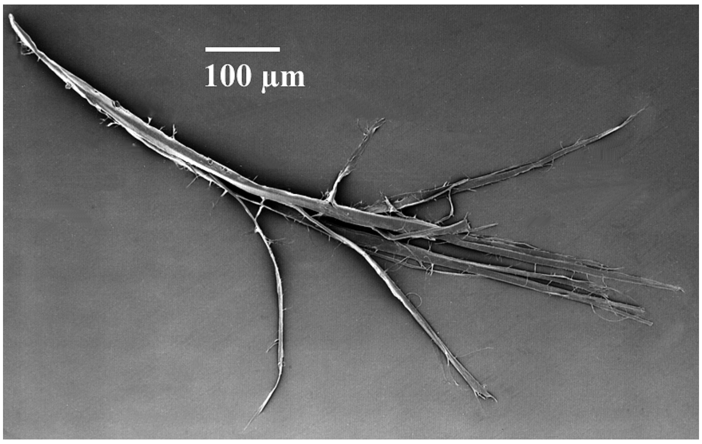


Figure 4.4 SEM-micrograph of a typical SGW-fibre. A clear split can be observed in the end of the fibre.

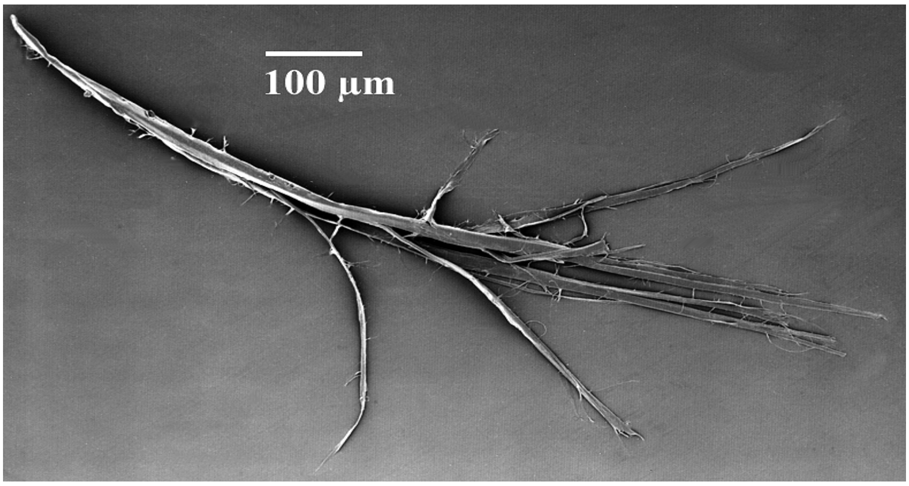


Figure 4.5 SEM-micrograph of parts of a SGW-fibre. The fibre has a crack in the fibre wall, parallel to the fibril axis in the S2-layer.

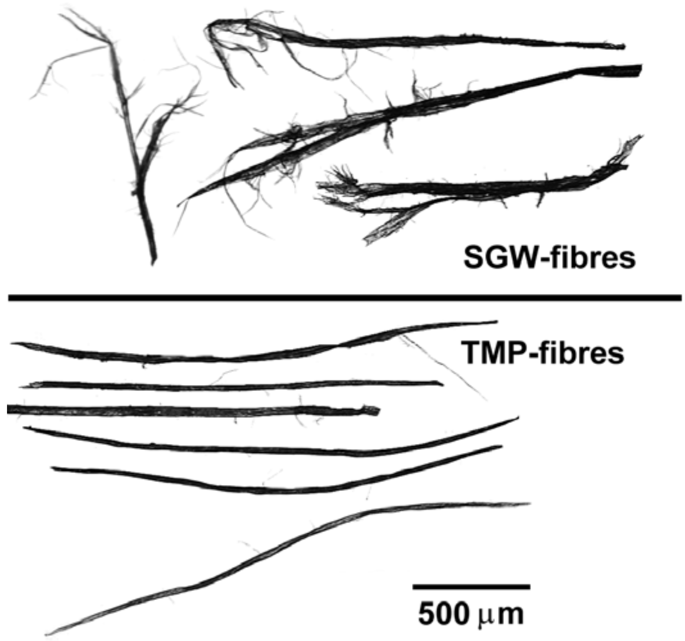


Figure 4.6 Micrographs of SGW-fibres and TMP-fibres. Clear splits can be observed in the ends of the SGW-fibres.

There is a characteristic difference between the TMP fibres and the various GW fibres with respect to fibre wall cracks (Fig. 4.6). Without trying to give a full explanation for the differences in pulp fibre characteristics, a few comments may be justified. The differences have to be related to the TMP and GW processes. In the GW processes, the fibres are always subjected to forces perpendicularly to their axis. In the TMP refining, the defibrating forces attack in a much more random fashion. In both processes high temperature softens the lignin. This plasticization of the middle lamellae in addition to repeated stresses and relaxations on the wood substance will release the fibres. The grinding process involves the fast passage by the stone's grains over the log's surface, scraping over parts of the fibres. When the fibres in the wood surface have been sufficiently softened and weakened by the mechanical action, they are released from the wood in one end of the fibre. The fibres still attached to the wood matrix are further treated by the passing grits (regrinding) until they are completely released and removed from the grinding zone. In the regrinding process, the fibres may get cracks and splits in the fibre wall.

4.4 The impact on moisture-induced surface roughening by fibre splitting

Fig. 4.7 depicts the degree of fibre splitting vs fibre width for the +28-mesh fractions. There is a linear relationship for the SGW-pulp, and it even holds for the TMP. A fibre with large width typically is an earlywood fibre with thin walls. With increasing fibre width, the fibre surface subjected to the grinding stone increases, resulting in larger splits.

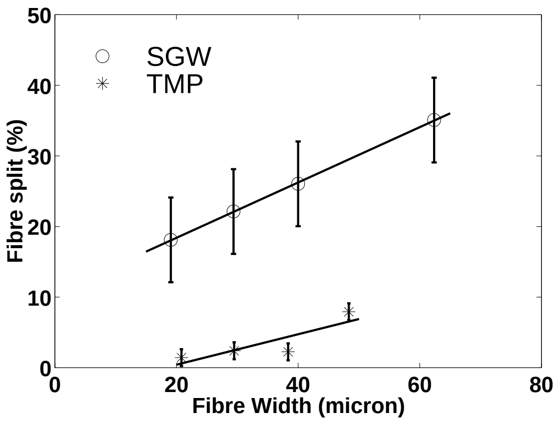


Figure 4.7 Plot of fibre split vs fibre width together with the corresponding 95% confidence interval limits. The plot is given for the +28-mesh fraction of pulp grades TMP1 and SGW1.

Fibre splittings were then related to the fibres' surface roughening effect on papers. Gane and Hooper [160] reported increased roughening of TMP base sheets upon coating compared to SGW and PGW. Structural differences in the fibres will cause at least parts of the observed variance in surface smoothness. Skowronski [128] stated: "Because of the presence of intrafibre stresses, the surface changes caused by calendering are not permanent. These stresses can be released by water during coating. Fibres show a tendency to recover their original uncollapsed shape". Such a decollapsing behaviour was also found by Forseth [1,115,126]. It seems likely that the fibres' resistance to compression upon calendering affects their ability to recover their original shape upon moistening. TMP fibres are known to be relatively stiff, and fibrillated only to a minor extent [15]. As shown, SGW and PGW fibres are to a large degree split. Damages in the fibre walls reduce the fibres' mechanical resistance to compression. A probable effect will be less roughening of the paper surface on sheets made from these particular pulp grades. To isolate the effects of fibre structural differences, the fines were removed by fractionation. Hand sheets were made from the +48-mesh fraction. By such an approach, the fibre retention was close to 100%, and the composition of the papers known.

To assess paper roughness, Parker Print Surf was utilised. The paper roughness was measured on the sheets before and after calendering, and after moistening. Fig. 4.8 lists the results, with roughness measured on the wire sides, at a clamp pressure of 1.0 MPa. Roughness was also measured on the top side, and similar trends were observed. The

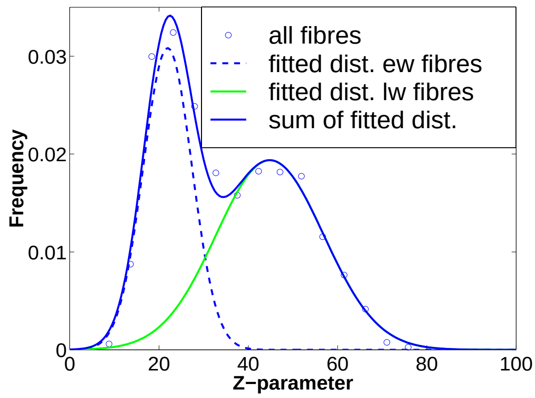


Figure 4.8 The roughness of laboratory sheets (PPS, 1.0 MPa, wire side) presented for various mechanical pulp grades before and after calendering, and after subsequent moistening. The standard deviation is ± 0.1 µm.

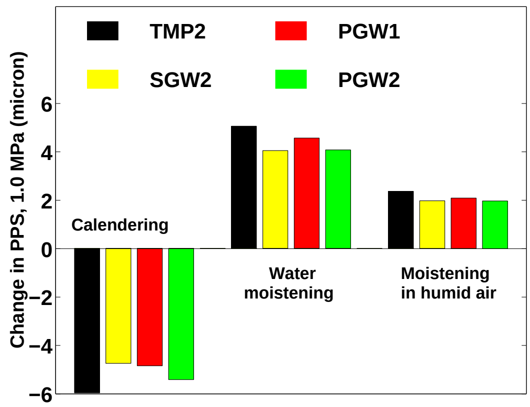


Figure 4.9 Changes in roughness (absolute values) when the laboratory sheets were subjected to calendering and moistening. The standard deviation of the changes is ±0.1 µm.

changes in roughness (absolute values) when subjecting the sheets to calendering and moistening are shown in Fig. 4.9. Untreated base papers from TMP were significantly rougher than base papers made from groundwood. A likely cause is the larger extent of fibre splitting and fibrillation in the SGW and PGW fibres, as shown. Large degrees of splitting and fibrillation give the fibres ability to conform to the surrounding surfaces. After calendering, the differences in roughness among the various pulp grades were partly evened out. The reductions in PPS were between 6.0 and 4.7 µm for paper made from TMP2 and SGW2, respectively. Calendering compressed the rather stiff TMP-fibres more than the damaged groundwood fibres, which are already flattened, having less potential for further compression. Tensions are introduced in the fibres, as explained by Skowronski [128]. These stresses should, according to Skowronski [128], partly be released upon moistening.

After water moistening, a raise in roughness (absolute values) of some 5.1 to 4.1 µm were observed for TMP2 and SGW2 papers, respectively (Fig. 4.9). Larger stress relaxations took place in the TMP based sheets than in the SGW and PGW based papers upon moistening. Hence, the degree of roughening of the paper surface seems to depend on:

- the amount of tensions present in the paper

which in turn depends on

- the fibres' mechanical properties, condition and shape before calendering

When subjecting calendered papers to humid air, the same effects were observed, however less pronounced. The observed roughness increases were between 2.4 µm (TMP2) and 2.0 µm (SGW2, PGW2). The same reasoning as above explains the experienced differences.

Paper density can be expected to correlate well with roughness values. Fig. 4.10 shows absolute changes in density upon calendering and moistening. The decrease in density from the calendered state is less for SGW and PGW (431 - 435 kg/m^3) than for TMP based papers (486 kg/m^3).

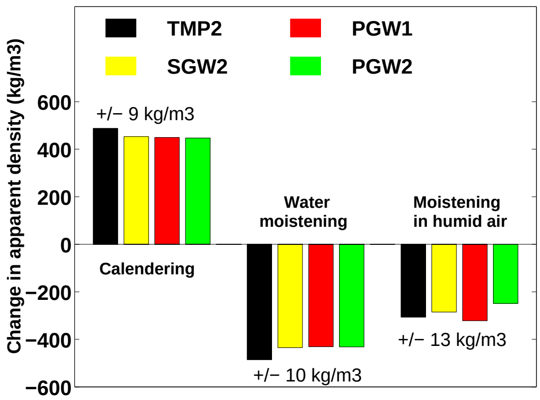


Figure 4.10 Changes in apparent density (absolute values) when the laboratory sheets were subjected to calendering and moistening. 95% confidence interval limits are included for each treatment.

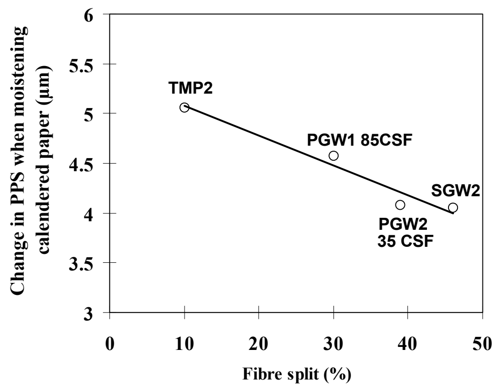


Figure 4.11 Plot of moisture-induced roughening (PPS) on the wire side vs. extent of fibre splitting.

The fibre splitting was measured, Table 4.2. A correlation between this variable and the roughening by moistening was found, Fig. 4.11. The increase in PPS is decreasing linearly with the degree of fibre splitting, at comparable freeness values. This correlation is a direct implication of what has been discussed above, that split fibre parts contribute very little to the roughening of the paper surface upon moistening.

4.5 The effect of calendering and moistening on fibre cross-sections

The changes in sheet density by calendering and moistening reflect changes in fibre properties. Fibres respond differently, depending on cross-sectional properties. How important will fibre splitting be to calendered papers' response to moistening? Will undamaged fibres respond differently? The lumen "form circle" (FC) was assessed for intact fibres using paper cross-section micrographs. The lumen form circle serves as a proper descriptor of the lumen opening shape. It describes the circularity of the lumen, and is defined by Equation 4.1.

$$\text{Lumen FC} = \frac{4\pi A_{lum}}{P_{lum}^2} \qquad (4.1)$$

A_{lum} denotes lumen area, and P_{lum} lumen perimeter. This expression yields values between 0 and 1, where a value of 1 indicates a perfect circle.

The effects on fibre lumen FC by calendering and moistening were explored. Lumen FC was assessed using fibre cross-sections in SEM-images of paper cross-sections. Fig. 4.12 depicts average lumen FC for three pulp grades before and after calendering, and after subsequent moistening. This parameter was not evaluated for PGW1. Judging Fig. 4.12, one should remember that only intact fibre cross-sections were assessed. Calendering reduced lumen form circle by 0.25 for all pulp grades. Moistening with water in 20 s caused a lumen FC recovery of 80 to 88%. The recovery is characterized by the fractional lumen FC increase upon moistening relative to the initial decrease in lumen FC upon calendering. Air moistening caused lumen FC recoveries of 48 - 52%. It appears that the fibre populations behave similarly when subjecting the sheets to calendering and moistening. Both the initial lumen form circle and the lumen form circle after moistening were larger for groundwood pulp grades than for TMP. Intact groundwood fibres were coarser than TMP fibres (Table 4.2), causing less initial collapse. Still, the SGW-pulp and the PGW2-pulp both yield smoother base paper, and also sheets less affected by moistening than TMP-based sheets. This result may be explained by the fibre splitting phenomenon, suggesting that fibre splitting is responsible for the favourable surface smoothness properties of the GW-based sheets. A high degree of fibre splitting thus appears desirable for paper smoothness, and intact fibres should have thin walls. The GW and the TMP-processes appear complementary in this respect. GW-fibres have large extents of splitting, but the intact fibres have thicker walls. The TMP-fibres are, conversely, long and slender, but have a low degree of splitting.

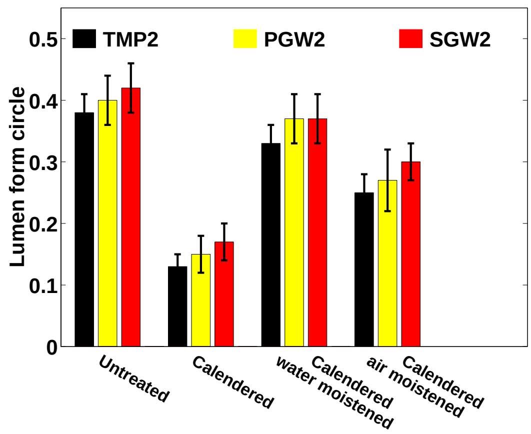


Figure 4.12 The average lumen form circle for various pulp grades before and after calendering, and after moistening. The 95% confidence interval limits are included.

Water moistening is a far rougher treatment than moistening in humid air. Still investigating fibres in paper with fines and middle fraction removed, the TMP-fibres were divided into three groups ranged by fibre wall thickness. Fig. 4.13 shows that the fibres respond differently to calendering and moistening, depending on wall thickness. The initial lumen form circle increases with increasing fibre wall thickness. Lumen FC recovery appeared independent of fibre wall thickness when subjecting calendered sheets to water. When moistened in humid air, fibres with wall thickness less than 1.7 µm were very little affected, with a recovery of 18%. Fibres having wall thicknesses larger than 1.7 µm recovered by some 50%. For each treatment, some 200 fibres were processed. Larger tensions have to be introduced to thickwalled fibres than to thinwalled ones during calendering. It appears reasonable that coarse fibres, having larger latent tensions, will relax more when moistened. Fig. 4.13 indicates that light treatment in humid air is insufficient to relax thinwalled fibres, but suitable to relax some of the more thickwalled fibres. There was no increase in lumen form circle recovery when increasing the fibre wall thickness from the 1.7 - 3.3 µm interval to the 3.3 - 5 µm interval. When subjected to water, it seems logical that both thinwalled and thickwalled fibres could be relaxed, partly restoring their original shape.

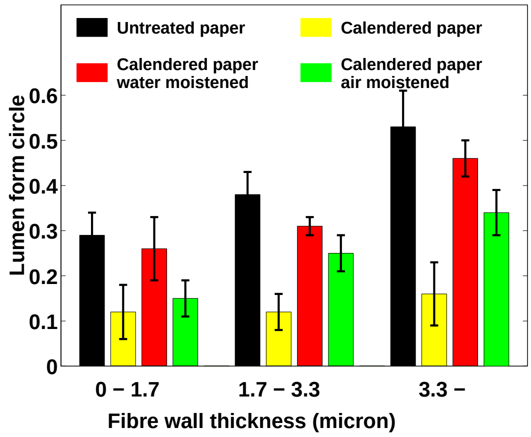


Figure 4.13 The average lumen form circle for various fibre wall thickness intervals before and after calendering, and after moistening. The fibres were investigated in sheets made from TMP long fibre fraction (TMP2). 95% confidence interval limits are included.

To sum up, TMP-based paper is favourable with respect to strength properties, while GW-based papers have smoother surfaces with less tendency to roughening when moistened. The fibre coarseness should be low and the degree of split fibres high in order to get a smooth surface. GW-fibres are split and fibrillated, but the intact fibres have thick walls.

It is desirable to improve the surface smoothness on TMP-based paper, but the demand for strength puts restrictions on the fibre length. A target is then to crush or split the fibres, maintaining the fibre length. If such a modification is possible, one would also benefit from the TMP-fibres' low coarseness. When reaching a degree of splitting in the order of 40-50%, as for GW-fibres, and the fibre length maintained, one could in fact expect a resulting pulp giving paper smoothness properties comparable with those of GW-pulp.

4.6 Effect of fibre parameters on surface smoothness and light scattering coefficient

4.6.1 Statistical approach

A linear regression analysis (backward stepwise regression) was performed on a range of pilot scale TMP pulps (Paper VI) to see which pulp parameters that influenced the surface roughness and light scattering coefficient. The parameters studied were:

- fines content (-100 mesh)
- long fibre content (+48 mesh)
- fibre length
- fibre wall thickness
- perimeter
- shives content
- number fraction of split fibres.

When doing such an analysis, precautions should be taken against overinterpreting its results. A general problem is that many variables correlate strongly. Secondly, the test span for the fibre splitting degree should be fairly large. In this study, this parameter ranged from 6 to 14%. In mill refiners, the larger disc speed and the use of double disc refiners may cause higher refining intensity. Hence, mill refiners may be expected to yield higher fibre splitting degrees than what was found in this pilot trial. Ideally, to give more reliable models, one should make pulps from a range of different raw materials, freeness levels and varying refining intensity. Secondly, one should fractionate the pulps, and make model pulps in such a way that the various parameters do not correlate. Although the conditions are not that ideal in this study, one may still get a good impression of trends, at least within the span that was investigated. The variance in fibre wall thickness, fines content, long fibre content and fibre splitting degree appears to explain 96% of the variance both for surface roughness and light scattering. The model found for surface smoothness is given by Equation 4.2, and for light scattering coefficient by Equation 4.3.

$$PPS1.0 = -26.4 + 0.85 \cdot WT + 0.25 \cdot F + 0.33 \cdot LF - 0.331 \cdot FS \quad (4.2)$$

$$LSC = 234 - 5.46 \cdot WT - 1.60 \cdot F - 2.05 \cdot LF + 0.441 \cdot FS \quad (4.3)$$

Here, *PPS1.0* is surface roughness assessed by the Parker Print Surf instrument(μm), *LF* is long fibre content (w%), *F* is fines content (w%), *WT* is wall thickness (μm), *FS* is fibre splitting degree (%) and *LSC* is light scattering coefficient (m^2/kg). Using the models of Equations 4.2 and 4.3, one may examine the effect of changing wall thickness or fibre splitting degree on surface roughness and light scattering coefficient, while keeping other parameters constant.

4.6.2 Effect of changing fibre wall thickness and fibre splitting on surface roughness

Fig. 4.14 shows the effect on surface roughness by changing fibre wall thickness at a constant level of fines and long fibres and constant degree of fibre splitting. The different

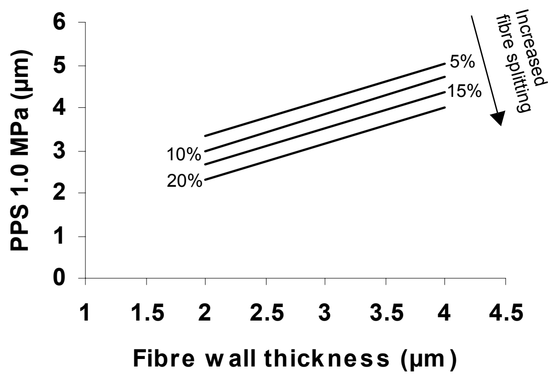


Figure 4.14 PPS (1.0 MPa) calculated at constant levels of fines (-100 mesh = 20.4 w%), long fibre fraction (+48 mesh = 73.9 w%) and fibre splitting plotted versus mean fibre wall thickness. The different lines show the effect of changing the fibre splitting degree.

lines show the effect of changing the fibre splitting degree. By increasing wall thickness, the model shows that surface roughness increases. Increased wall thickness will increase the rigidity of the fibres. Hence, they will be harder to flatten and will conform poorer in the paper sheet. The result will be a paper with increased surface roughness. According to the model, increasing fibre splitting at constant wall thickness will also reduce surface roughness. It seems logical that a split fibre will have less resistance against flattening than an intact fibre.

4.6.3 Effect of changing fibre wall thickness and fibre splitting on light scattering coefficient

Fig. 4.15 shows the modelled effect on light scattering coefficient by changing wall thickness at constant fines and long fibre content levels and constant degree of fibre splitting. An increase in wall thickness is predicted to give a proportional decrease in light scattering coefficient. The light scattering coefficient is correlated with the specific surface area of the sheet. Through a geometrical calculation it has been shown [44] that the total surface area of smooth fibres is governed by the wall thickness as in Equation 4.4. A reduction in wall thickness will thus raise the light scattering coefficient. An

$$\text{Specific surface area} = \frac{2}{WT \cdot 0.00153} \qquad (4.4)$$

increase in fibre splitting, at constant wall thickness, is predicted to give increased light scattering coefficient. It was somewhat surprising that fibre splitting yielded such a large effect on light scattering. According to Braaten [142], fibre splitting does not affect light scattering, but fibrillation does. Fibre splits may increase the specific surface area somewhat. It should also be remembered that fibre splits have very different characters. Splits in the fibre ends may cause a rather fibrillated fibre structure. This result could be an effect of fibre splitting being correlated with fibrillation, a parameter that was not quantified in this study. Varying degree of outer fibrillation will affect the specific surface area, and also the light scattering coefficient.

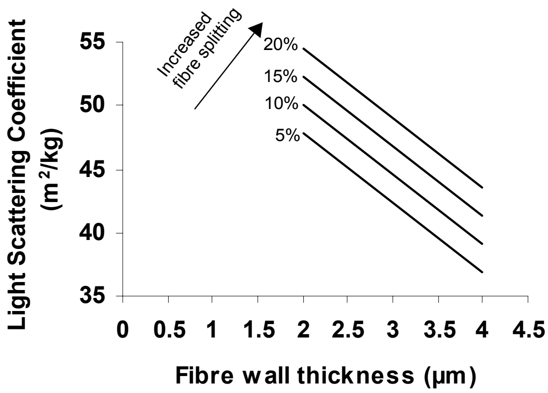


Figure 4.15 Light scattering coefficient calculated at constant levels of fines (-100 mesh = 20.4 w%), long fibre fraction (+48 mesh = 73.9 w%) and fibre splitting plotted versus mean fibre wall thickness. The different lines show the effect of changing the fibre splitting degree.

4.7 Concluding remarks

Fibres from SGW-pulp and PGW-pulp were found to be much more split and damaged than fibres from TMP-pulp. The degree of splitting, expressed in percent of fibre length, was between 40 and 46% for GW-fibres, and only 10% for TMP-fibres. Intact groundwood fibres had thicker walls than intact TMP-fibres from pulp with the same freeness. The intact fibres of groundwood pulp (in sheet cross-sections) had larger lumen openings than TMP-fibres at the same freeness. Still, super calendered laboratory sheets made from GW-fibres were less roughened by moistening than TMP-based sheets. The raise in roughness upon moistening increased with larger degrees of fibre splitting.

From a linear regression analysis of a range of TMP-pulps it was found that a reduction in wall thickness or an increase in fibre splitting caused a considerable reduction of surface roughness and increase of light scattering coefficient.

CHAPTER 5

DEFIBRATION AND FIBRE DEVELOPMENT IN MECHANICAL PULPING (PAPER IV, V AND VI)

5.1 Introduction

Wood is a heterogeneous material, incorporating a diversity of tracheid structures depending on wood age (juvenile wood/mature wood) and growth season (earlywood/latewood). Both defibration and fibre development may proceed differently for fibres of different morphology.

As pointed out in chapter 2, runability is an important parameter for wood-containing printing paper. Shives are common causes of paper web breaks [161,162,163,164]. Although modern screening equipment has reduced the amount of shives considerably, shives are still assumed to cause newsprint breaks. The weakening effect of shives has been partly related to local high grammage microspots appearing after calendering [164]. In a study where newsprint paper was strained to failure, Gregersen [165] found that more than 90% of the cracks causing web failure contained a shive. Further studies of these particular web-rupture initiating shives indicated that they consisted mainly of latewood fibres. One objective of this chapter is to examine the morphological composition of shives in various mechanical pulps. There are two motives for this investigation. First motive is to map the amount of harmful latewood shives in different mechanical pulping processes and process stages. Secondly, by investigating the character of undefibrated fibres, one can obtain information on which fibres that defibrate most easily in a refining process.

As discussed in chapter 4, surface roughness is closely related to fibre wall thickness and degree of fibre splitting. An important objective of refining is therefore to reduce fibre wall thickness and to develop the fibre properly. It seems likely that fibres with contrasting morphology may be differently affected during refining. A second objective of this chapter is to discuss how refining develops earlywood and latewood fibres. Both mill pulps (paper IV) and pilot plant pulps (paper VI) were studied.

5.2 Procedure for classification of earlywood and latewood fibres

5.2.1 Definition of an appropriate parameter to describe the transverse fibre dimensions

Runkel's ratio [166] has been used extensively in the literature for classification of tracheids, and is defined by the double cell wall thickness divided by the lumen width, or the ratio between fibre width and lumen width, minus one, measured in the radial direction. Mühlsteph suggested a similar parameter, also measured in wood cross-sections, known as Mühlsteph's ratio [167]. This parameter is defined by the tracheid wall area divided by the tracheid cross-sectional area including lumen. Although Runkel's ratio and Mühlsteph's ratio both are very good measures of the tracheid morphology in wood, they are hard to use on processed pulp fibres. (The large variations in cross-sectional shapes among processed fibres would make the definitions of Runkel's ratio and Mühlsteph's ratio unclear.) However, if the fibre cross-section is imagined spun out to a circle, the geometry of the fibre cross-section would become standardized. In this way one could derive modified versions of the Runkel's ratio as well as the Mühlsteph's ratio, applicable both to wood cross-sections as well as to processed fibres. The modified Runkel's ratio (RR_{mod}) then becomes:

$$RR_{mod} = \frac{D_o}{D_i} - 1 = \frac{P_o}{P_i} - 1 \qquad (5.1)$$

Here, D_i denotes the lumen diameter, D_o the outer diameter, P_i the lumen perimeter and P_o the outer perimeter. The modified Mühlsteph's ratio (MR_{mod}) becomes:

$$Z = MR_{mod} = \frac{A_w}{\pi \cdot r_o^2} = \frac{4\pi A_w}{P_o^2} \qquad (5.2)$$

Here, A_w denotes fibre wall area and r_o outer radius. Both modifications could in principle equally well be used to discriminate between earlywood and latewood fibres. The ratio between outer and inner perimeter, which is the important part of the modified Runkel's ratio, was applied by Mohlin [92]. In this work we choose to work with the modified Mühlsteph's ratio, here denoted Z and expressed in percent. Doing so, one avoids problems with finding the lumen perimeter for collapsed fibres. Further the assessment of wall area is more precise than the calculation of the inner perimeter.

5.2.2 Use of the Z-parameter to create fibre classes

A distribution curve of Z for TMP-fibres with intact cross-sections typically has two peaks (Fig. 5.1), suggesting that it may be represented as the sum of two distributions. Two normal distributions may be fitted to the data. For the example in Fig. 5.1 (paper IV) a correlation coefficient of 0.98 was achieved.

Basically, the terms earlywood and latewood refer to growth seasons. However, to the papermaker, what matters is the fibre dimensions, not the time of growth. A functional definition, based on dimensions is therefore more applicable. Instead of choosing an absolute definition to classify the fibres, one should keep in mind that the cross-sectional dimensions of latewood fibres and earlywood fibres partly overlap each-other. Hence, it seems likely to believe that the fibre population may be divided into two partly superimposed fibre populations; one "latewood fibre population" and one "earlywood fibre population".

The high *Z*-value distribution will basically correspond to the “latewood” fibre population and the low *Z*-value distribution to the “earlywood” fibre population. This definition of earlywood and latewood fibres is strictly based on cross-sectional dimensions, and not on time of growth. The area fraction of each distribution corresponds to the number fractions of intact earlywood and intact latewood fibres, respectively. From the data in Fig. 5.1 (only intact fibres) 57.8% of the fibres were found to be latewood fibres. A value for *Z* could be found, so that 57.8% of the fibres had larger value of *Z*. It is then possible to draw wall thickness distributions for the intact latewood fibres and earlywood fibres. Similarly, perimeter distributions may be plotted for the two groups of fibres.

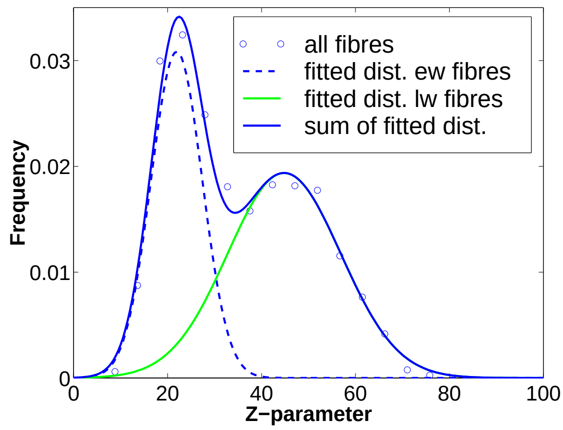


Figure 5.1 *Z*-distribution curve for intact TMP-fibres after one refining stage. (Paper IV)

5.2.3 Examination of how the *Z*-parameter distinguishes between earlywood fibres and latewood fibres

An attempt was made to investigate how adequately the *Z*-parameter distinguished between earlywood and latewood fibres. The fibre cross-sections in the SEM-images were divided into earlywood and latewood fibres by eye. Two sets of images were made, one containing only latewood fibres, and one containing only earlywood fibres. The *Z*-parameter was then assessed by image analysis on each of these two image sets. Fig. 5.2 shows the resulting *Z*-distributions for earlywood and latewood fibres discerned by eye. The corresponding distributions achieved using mathematical fitting of two normal distributions are shown in the same figure. The resemblance is good between the mathematically fitted distributions, and the distributions achieved by sorting the fibre images.

The wall thickness distributions for intact earlywood and intact latewood fibres were

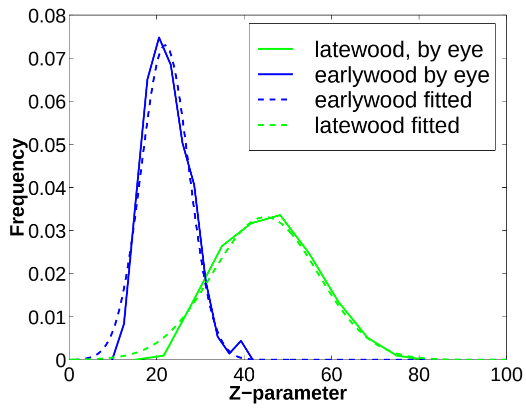


Figure 5.2 *Z*-distribution curves for earlywood and latewood fibres, separated by eye and separated by fitting normal distributions. All distributions are normalised.

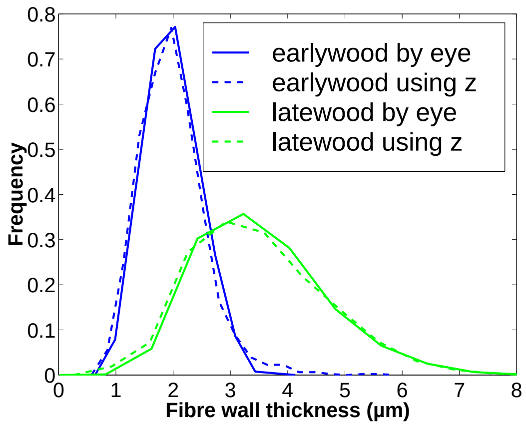


Figure 5.3 Wall thickness distribution curves for earlywood and latewood fibres, separated by eye and separated by using the *Z*-parameter.

calculated as described in chapter 5.2.2. The validity of this method was verified by checking against the wall thickness distributions of earlywood and latewood fibres, judged by eye, Fig. 5.3. A similar test was done for fibre perimeter, Fig. 5.4. In both cases, the curves based on sorting fibre images closely resembled the curves based on *Z*.

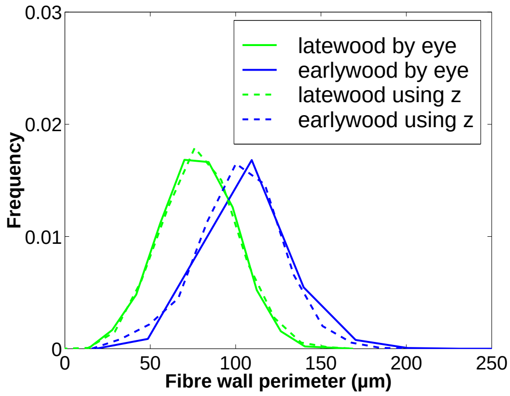


Figure 5.4 Perimeter distribution curves for earlywood and latewood fibres, separated by eye and separated by using the *Z*-parameter.

Fig. 5.5 shows wall thickness plotted against perimeter for some 60 000 fibres in a wood cross-section. Cell wall thickness and perimeter are poorly correlated. One will notice that for most of the fibre wall thicknesses the corresponding perimeter range varies by a factor of more than 2. If the Z-parameter is used to separate the fibres into two groups, the result is the two scattered clouds in Fig. 5.5. Within each group, cell wall thickness and perimeter are better correlated. It can be seen that the dimensions of the earlywood and latewood fibres significantly overlap.

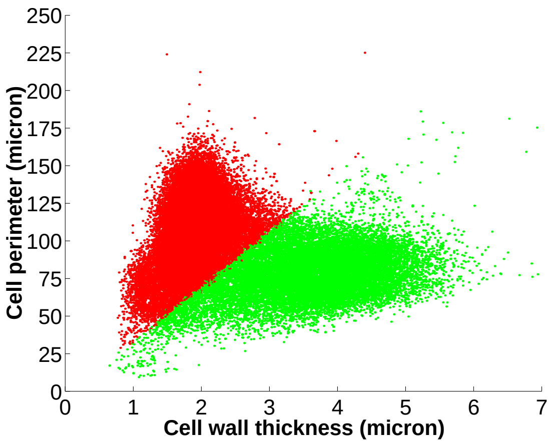


Figure 5.5 Wall thickness plotted against perimeter for some 60 000 fibres in a wood trunk of Scots Pine.

5.3 Fibre composition of shives in various mechanical pulp grades

5.3.1 Differences between TMP and groundwood

Various mill scale and pilot scale pulps were collected, including TMP, SGW and PGW (Table 5.1). A description of the applied refining parameters and experimental procedure is given in Paper V.

Table 5.1: Overview of the pulp samples investigated

Code	Pulp grade	Process stage	Mill/ Pilot
TMP1-BR	Thermomechanical pulp	Before reject refining	Mill
TMP1-AR	Thermomechanical pulp	After reject refining	Mill
TMP1-P	Thermomechanical pulp	Screened accept	Mill
SGW-BR	Stone groundwood	Before reject refining	Mill
SGW-AR	Stone groundwood	After reject refining	Mill
SGW-P	Stone groundwood	Screened accept	Mill
TMP2	Thermomechanical pulp	Screened accept	Mill
PGW	Pressure groundwood	Screened accept	Pilot
TMP-1800	Thermomechanical pulp	1st and 2nd stage, unscreened, 1st stage: 1800 RPM	Pilot
TMP-2600	Thermomechanical pulp	1st and 2nd stage, unscreened, 1st stage: 2600 RPM	Pilot

Using the procedure described in section 5.2, the fractions of latewood fibres were found to be 48.9% and 44.1% for defibrated fibres (including split fibres) in pulp samples TMP1 and TMP2, respectively (Figure 5.6). Earlywood fibres were clearly

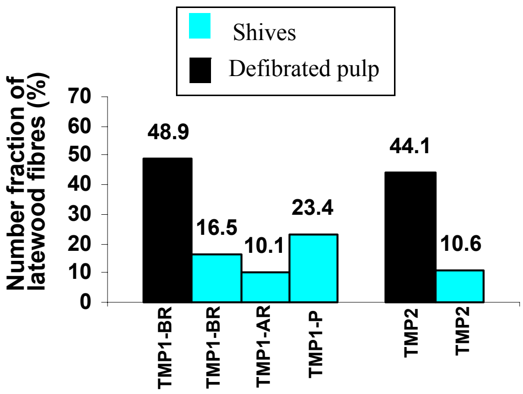


Figure 5.6 Number fraction of latewood fibres in shives and defibrated pulp for various TMP-pulp samples.

overrepresented in TMP-shives, compared to the fibre population. For the TMP-pulps investigated, only between 23.4% and 10.1% of the *undefibrated* fibres were latewood fibres. A quite different situation was found for the groundwood samples. The latewood fibres fraction in groundwood shives was between 28.1% (PGW) and 58.8% (SGW-BR), much more than what was found for TMP shives (Fig. 5.7). The composition of one of

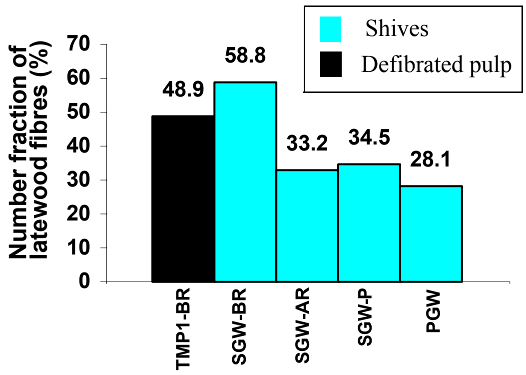


Figure 5.7 Number fraction of latewood fibres in shives for various SGW-pulp samples. The fraction of latewood fibres in one of the TMP-pulps is included as reference.

the TMP-pulps is included as a reference. Due to the very split and fibrillated structure of groundwood fibres, it was impossible to obtain the relative fractions of defibrated latewood fibres for groundwood pulps. However, it can be assumed that the composition is in the same range as was found for the TMP-pulps. Hence, TMP-shives have an overrepresentation of earlywood compared to defibrated pulp. GW-shives on the other hand are rich on latewood.

As the latewood fibre shives establish the dangerous components causing web breaks [162], the focus should be on the amount of such shives, rather than the total amount of shives. Fig. 5.8 shows the number fraction of *undefibrated* latewood fibres in various TMP-pulps and SGW-pulps. For simplicity it is assumed that the weight of latewood fibres and earlywood fibres are similar. If not, the values will be shifted, but the relative differences will remain the same. The groundwood pulps contain far more undefibrated latewood fibres than do the corresponding TMP-pulps. Even after screening, the groundwood pulp has more than three times as many undefibrated latewood fibres than the TMP-pulp at same freeness.

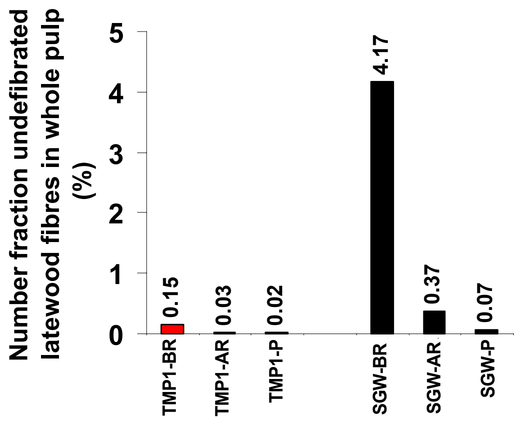


Figure 5.8 Number fraction of undefibrated latewood fibres in the whole pulp, considering the total amount of shives in the pulps.

Reject refining reduced the fraction of latewood fibre shives significantly, in a similar fashion for both groundwood and TMP (Figs. 5.6 and 5.7). The relative reduction in the number fraction of such shives during reject refining was 39% and 44% in the TMP and SGW process, respectively. The effect is even more striking when inspecting the fraction of *undefibrated* latewood fibres in the pulp (Fig. 5.8). It is obvious that reject refining plays a very important role by reducing the amount of web rupture initiating shives. In contrast to grinding, refining tends to selectively defibrate latewood. These findings are consistent with the results of Braaten [44], who found that thinnings, which are rich on earlywood, gave TMP with large amount of shives.

5.3.2 Some implications on screening efficiency

Having established which components that threaten the runability the most, the natural next step is to find ways to remove these components from the pulp flow. Both conventional screens and hydrocyclones may be suggested. Screens separate on the basis of size and stiffness. However, by inspection, earlywood shives have cross-sectional areas approximately 3-4 times larger than latewood shives (Fig. 5.9). Consequently, latewood shives will pass the screen slots more easily than will earlywood shives. Such a behaviour is indicated from Fig. 5.6, where it can be seen that the fraction of latewood in shives in screened pulps (TMP1-P and SGW-P) is larger than in shives after reject refining (TMP1-AR and SGW-AR). A hydrocyclone separates on the basis of size, shape or specific gravity. It therefore seems to be a more natural choice for discrimination between earlywood shives and latewood shives. Further studies in this area should be undertaken.

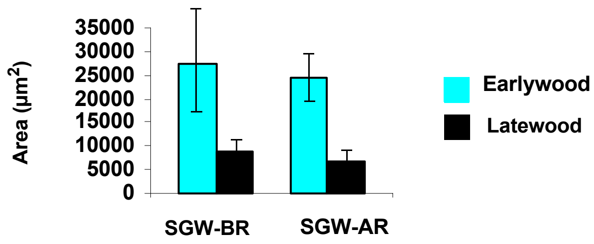


Figure 5.9 Cross-sectional areas of earlywood and latewood shives of a SGW-pulp before and after reject refining. The error bars show 95% confidence interval limits.

5.4 Some aspects on defibration mechanisms in refining

Fig. 5.10 shows the latewood fibres fraction in shives plotted against specific energy consumption for two TMP-series.The raw material was the same for both series, only the disc speed in the primary stage differed. For both series, the fraction of latewood fibres in shives decreased at increasing energy consumption. Thus, latewood fibres are more easily defibrated than earlywood fibres during refining. For the first series, the disc speed was 1800 rpm in all three stages. The fraction of latewood fibres in shives here decreased at a steady rate at increasing energy consumption. When increasing the disc speed, the fraction of latewood fibres in shives seemed to decrease at a faster rate. During the 2nd to 3rd stage, the shives' latewood fibres fraction decreased at the same rate for both series. Hence, the results indicate that increased refining intensity may promote a selective defibration of the latewood portion of the wood.

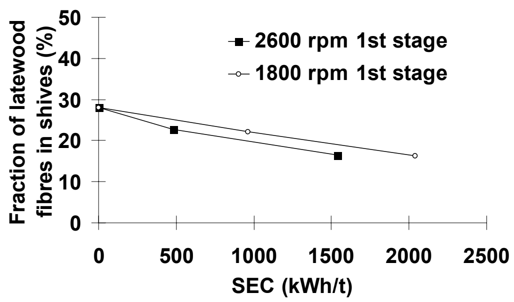


Figure 5.10 Number fraction of latewood fibres in shives plotted against specific energy consumption. In the first series, the disc speed in the primary stage was 1800 rpm. In the second series, the primary stage disc speed was 2600 rpm.

A consequence of the above results is that a wood material with more thickwalled fibres may yield pulp with less shives than wood with thinner walled fibres. The mean value of the *Z*-parameter describes how compact the pulp fibres are. In Fig. 5.11, the weight fraction of shives (at SEC = 2500 kWh/t) is plotted against the mean value of *Z*, both for spruce pulps and pine pulps (at SEC = 1250 kWh/t). The pulps were provided by pilot scale refining of chips from selected trees (Paper VI). The more compact fibres (larger *Z*) gave less shives.

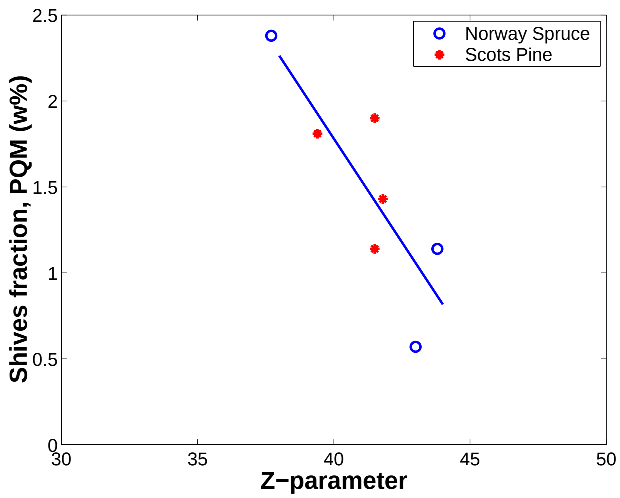


Figure 5.11 Weight fraction of shives (PQM) at a specific energy consumption of 2500 kWh/t plotted versus Z-parameter at a specific energy consumption of 1250 kWh/t.

It is generally accepted that the fibre separation rupture does not occur through the middle lamellae itself, rather somewhere at the middle lamellae (ML)/fibre wall interface. However, it is not clear where the fracture occurs most frequently. Kibblewhite [13] found some 30% of the fibres to separate within the S1-layer, and about 60% within the S2-layer. The middle lamellae will be separated from both fibres, or attach to one of them. Maximum middle lamellae coverage on the fibres is thus 50%. Johnsen et al. [83] found a middle lamellae coverage of 13% after first stage, supporting the theory that middle lamellae may separate from both fibres. They further concluded that the interfibre rupture occurs mainly through the S1, the interface S1/S2 or through the S2-layer. Both mechanisms suggested here will give a more uneven fibre wall.

A spruce tree was chipped and refined in three succeeding refining stages (Paper IV). The wall thickness standard deviation around the perimeter was measured both for tracheids in the wood and for each refining stage as described in sections 3.4 and 3.5. The wall thickness standard deviation increased from 0.61 µm to 0.66 µm during 1st refining stage, and decreased upon further refining (Fig. 5.12). These findings support the following hypotheses:

- During defibration, ML/P1/S1 may stick to one fibre, and be separated from another.
- Refining tends to reduce wall thickness most for *thickwalled* areas of the fibre, thus causing a reduction of the wall thickness variation.

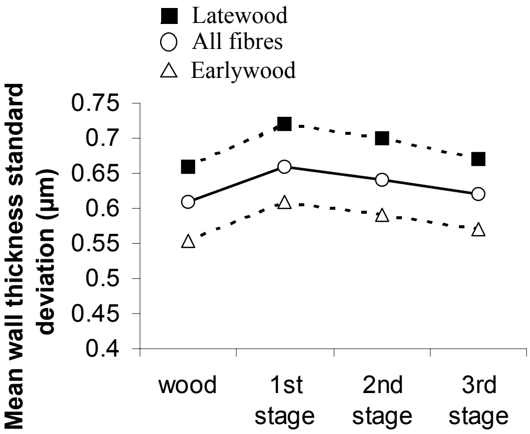


Figure 5.12 Mean wall thickness standard deviation around the perimeter for fibres from a spruce tree in the wood and after 1,2 and 3 stages of refining.

5.5 Development of earlywood and latewood fibres during refining

5.5.1 Fibre splitting

The importance of fibre splitting to paper surface smoothness was explored in chapter 4.

TMP-pulps from succeeding refining stages were studied, including both mill pulps (paper IV) and pilot plant pulps (paper VI). Fig. 5.13 depicts the wall thickness distribution curve for split fibres and intact early- and latewood fibres. The curve for split fibres fits relatively well with that for intact earlywood fibres. Hence, it seems that the split fibres are mainly earlywood ones. This finding is valid for all TMP-pulps under study.

Fig. 5.14 shows the number fraction of split fibres plotted versus specific energy consumption for various pilot plant TMP-pulps (Paper VI). Most of the fibre splitting occurred during the primary refining stage, while the fibres still were firmly attached to chips or fibre bundles. The same results were found for a mill scale TMP-pulp (Paper IV). Lai and Iwamida investigated wood samples strained to failure by shear forces [87]. They found that earlywood fibres tended to split, as the fracture line during defibration went through the cell and lumen. Latewood fibres, on the other hand, remained intact. Hence, if one attempts to raise the fraction of split fibres in the TMP-process, a logical choice may be to modify the conditions in the primary refining stage, for instance by increasing the refining intensity. In fact, recent pilot trials have shown that increasing rotational speed [168] or changing to more aggressive segment patterns [110] in the primary stage may give a raise in the fraction of split fibres.

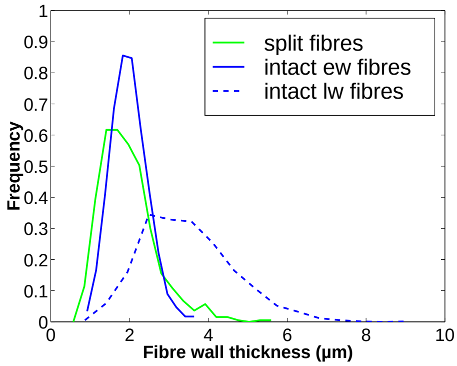


Figure 5.13 Fibre wall thickness distribution curves for TMP-pulp after 1st refining stage. All curves are normalised. (Paper IV)

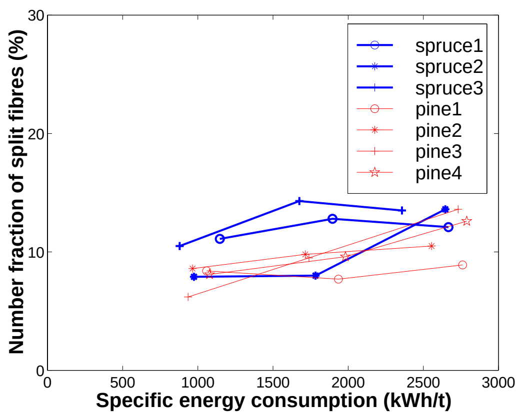


Figure 5.14 The number fraction of split fibres plotted versus specific energy consumption. Most splitting occurs in the initial defibration stage. (Paper VI)

5.5.2 The reduction of fibre wall thickness

TMP-pulps from successive refining stages were studied, including both mill pulps (paper IV) and pilot plant pulps (paper VI).

Fig. 5.15 shows the mean wall thickness of various pilot plant TMP-pulps plotted against specific energy consumption. For one of the pulp series, the wall thickness value in the wood is included. The wall thickness decreased linearly with increasing energy consumption for all pulps.

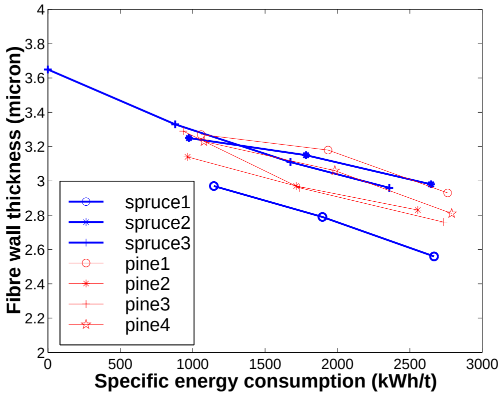


Figure 5.15 Fibre wall thickness plotted versus specific energy consumption.

In refining, fibre wall material is peeled off, creating fines. This reduction of wall thickness will, obviously, shift the wall thickness distribution curve towards lower readings at increased degree of refining. However, as can be seen from Fig. 5.16, also the shape of the distribution curve is considerably changed. The shape of the wall thickness

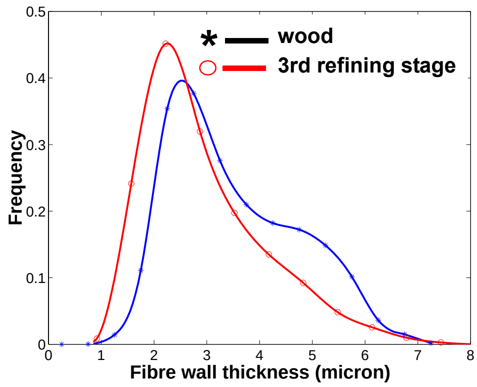


Figure 5.16 Fibre wall thickness distribution for a TMP-pulp from Norway Spruce before (in wood) and after 3 stages of refining.

distribution curve of 3rd stage fibres in Fig 5.16 is typical for TMP-pulps. These distribution curves are characterized by having one peak, with a tail on the thick-walled side. The wall thickness of wood tracheids are distributed otherwise. In wood, two peaks can be identified. The refining reduces wall thickness for all wall thickness classes. Yet, the largest reduction in wall thickness is observed for thick-walled latewood fibres, forcing the right peak to shrink, Fig. 5.16.

Using the procedure described in chapter 5.2, the fraction of latewood fibres and wall thickness distributions for latewood and earlywood fibres were found for each refining stage. Fig. 5.17 shows the reductions in fibre wall thickness from 1st to 3rd refining stage for earlywood and latewood fibres. For all pulps under study, latewood fibres revealed a larger reduction (both absolute and relative) in wall thickness than did earlywood fibres. These findings support the results of Mohlin [92] and Kure [93], both of whom showed results indicating a more extensive stripping of latewood fibres.

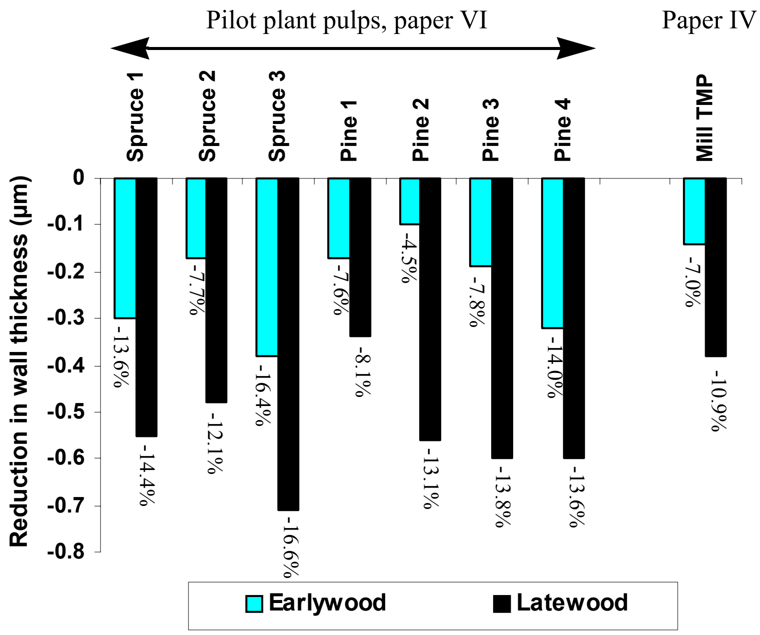


Figure 5.17 Reduction in fibre wall thickness from 1st to 3rd refining stage, latewood and earlywood fibres. The numbers show relative reductions in fibre wall thickness. (Papers IV and VI)

5.5.3 Variation in wall thickness around the fibre circumference

As described in Paper I, the fibre wall thickness varies significantly around the circumference. The standard deviation of the wall thickness around a fibre cross-section was assessed for latewood and earlywood fibres for a range of pilot scale TMP-pulps (Paper IV). The applied method is described in section 3.4.3. Latewood fibre wall thickness varied more around the perimeter than did earlywood fibre wall thickness. Refining reduced the standard deviation of the wall thickness around its circumference, both for latewood and earlywood fibres (Fig. 5.12) Hence, it seems that the wall thickness reduction in refining happens more often for the *thickwalled* parts, reducing the variations around the perimeter.

The differences between earlywood and latewood fibres are probably either due to genetic differences or to variations in defibration. Fig. 5.12 shows that the latewood tracheid wall thickness in wood varies more around the perimeter than does earlywood tracheid wall thickness. This difference may be attributed to genetic differences, and seems to remain during the refining.

5.5.4 Change in fibre cross-sectional shape

The form circle (defined in chapter 2.5.3) decreased with increasing degree of refining (Fig. 5.18). Refining may affect the fibre shape in two ways. A reduction in wall

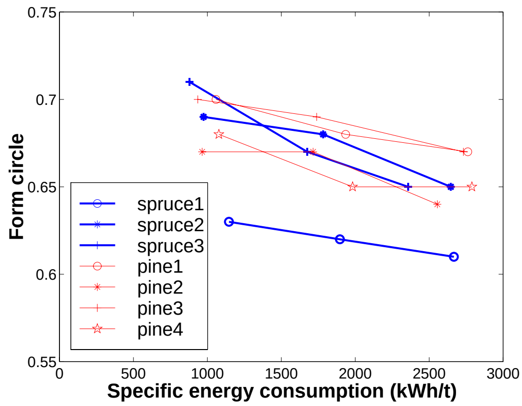


Figure 5.18 Mean form circle of fibres plotted versus specific energy consumption.

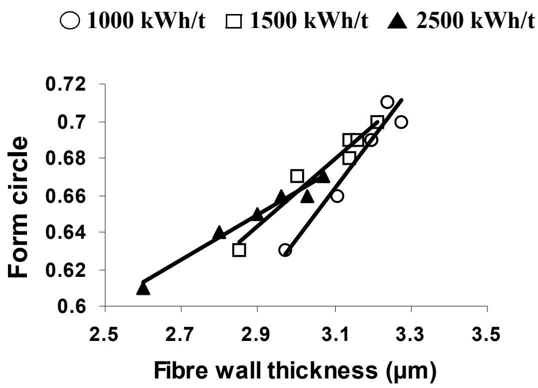


Figure 5.19 Mean form circle plotted against mean fibre wall thickness for various degrees of refining.

thickness will inevitably increase the fibre's compressibility, and yield a flatter fibre. Secondly, refining may cause a flexibilization of the fibre wall, for instance through delamination. What would then be the more flexible fibre; a fibre with initial low wall thickness, however low energy consumption, or a fibre with initial large wall thickness, however refined down to a low wall thickness? Fig. 5.19 shows the mean form circle plotted against mean wall thickness for three energy levels. Each curve includes both spruce and pine pulps. At each energy level, the mean form circle increases linearly with increasing fibre wall thickness. The curve slopes decrease at increasing energy levels. At a given fibre wall thickness, a fibre refined to 1500 kWh/t with initial low thickness was found to be flatter than an initially thickwalled fibre, refined to 2500 kWh/t. This result indicates that reduction of fibre wall thickness is important to increase the compressibility and flexibility of the fibres. Nevertheless, it seems hard to achieve the same degree of flattening through large extent of refining of thickwalled fibres, compared to using thinwalled fibres as raw material.

Fig. 5.20 shows the mean form circle plotted against mean wall thickness for earlywood fibres and latewood fibres at various specific energy consumptions. The slopes are considerably steeper for earlywood fibres than for latewood fibres. It thus appears that at a certain specific energy consumption, a larger reduction of wall thickness is necessary for latewood than for earlywood fibres to get a certain form circle reduction. A reason for the lower form circle levels, and steeper curve slopes for earlywood fibres could be that earlywood fibres have larger perimeters than latewood fibres, increasing the compressibility. Another reason might be that continued compressions and relaxations and kneading in the refiner have made the cell wall material of earlywood fibres more flexible. A fibre population varies widely in perimeter/wall thickness combinations, as shown in Fig. 5.21 for TMP-fibres. A brighter shade corresponds to a larger form circle (less flat) and a darker shade to a flatter fibre. Fibres from three successive refining stages for a spruce TMP-pulp were examined. In the left-side plots, all fibres are included. Earlywood fibres and latewood fibres are plotted separately in the middle and right-hand-side plots, respectively. Determination of earlywood and latewood fibres were done as described in chapter 5.2.

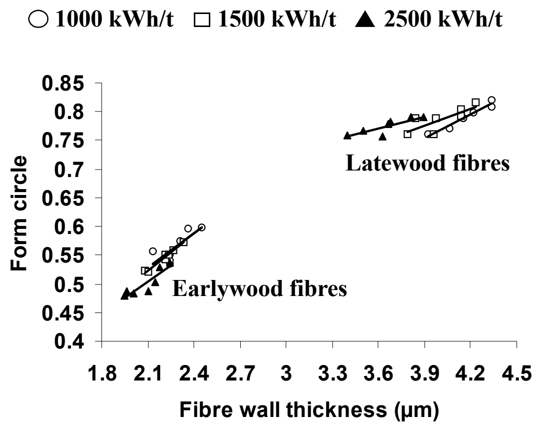


Figure 5.20 Mean form circle earlywood and latewood fibres plotted against mean fibre wall thickness for various degrees of refining.

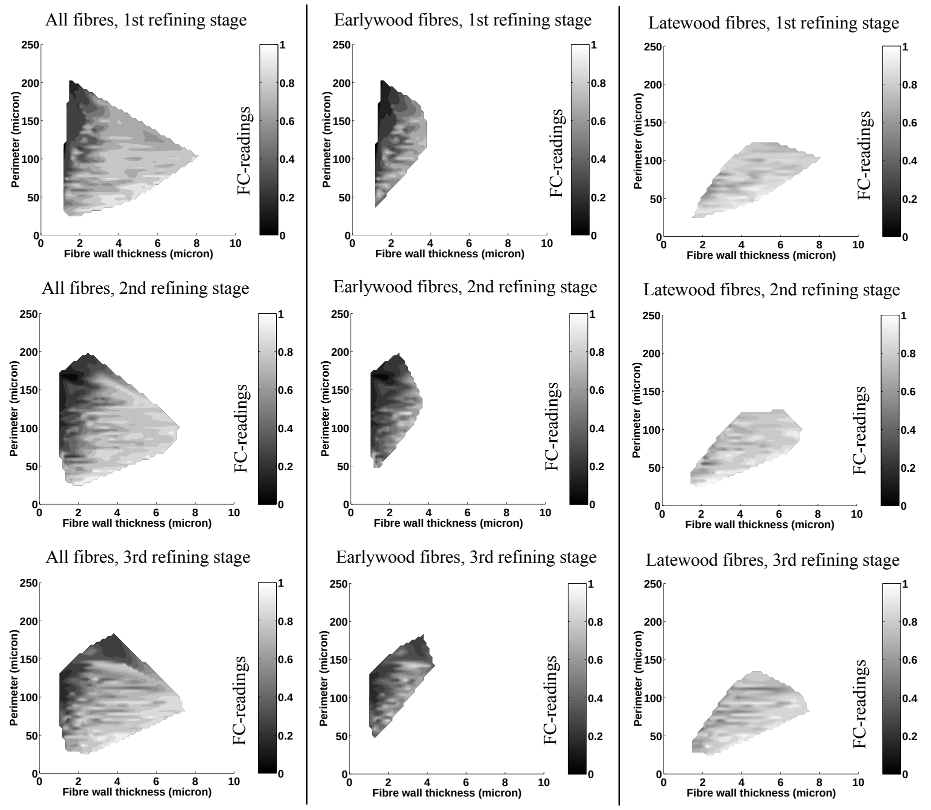


Figure 5.21 Contour plots showing how the form circle varies with different combinations of perimeter and wall thickness for TMP fibres from Norway Spruce in three refining stages. A brighter colour corresponds to a larger form circle (more circular shape), and a darker colour to a more collapsed fibre. The contour plots are shown for all fibres in the population (left), earlywood fibres (middle) and latewood fibres (right).

As could be expected, fibres with small wall thickness and large perimeter were the flattest ones. Increased degree of refining will reduce the wall thickness of the fibres. Hence, the compressibility increases, and the fibres become flatter. However, it can be seen that reduction in wall thickness is not the only reason for form circle decrease. At same wall thickness, the fibres have become flatter when subjected to increased specific energy consumption.

Logically, earlywood fibres were flatter than latewood fibres. However, further refining will flatten earlywood fibres much more than latewood fibres. The repeated compressions and relaxations and kneading of earlywood fibres may have loosened the fibre wall structure, increasing the wall flexibility.

5.6 Concluding remarks

Earlywood fibres were shown to be clearly overrepresented in shives in TMP-pulp, compared to the fibre population of the whole pulp. On the other hand, grinding was found to give shives rich on latewood. In both cases, reject refining caused a large relative decrease in the amount of latewood fibres in the shives. The rather stiff latewood seems to defibrate easier than earlywood in refining. Wood containing more compact tracheids (higher value of Z) gave pulp with less shives. The flexible earlywood fibres will flex and compress more easily, and thus be less able to transfer the rupture forces to the interfibre bonding material. In screened pulps, GW-shives contained more latewood fibres than did TMP-shives. Hence, with a given total weight fraction of shives, groundwood pulps seem to be of poorer quality with respect to content of shives potentially harmful for web-rupture.

Earlywood fibres and latewood fibres behave differently when they are subjected to the shearing and compression forces in the refiner. Most of the split fibres are earlywood ones. The fibre splitting mainly takes place during the primary refining stage, while the fibres are firmly attached to chips or fibre bundles. Material is peeled off from the fibres, reducing the fibre wall thickness. The wall thickness reduction (both absolute and relative) is largest for latewood fibres. Earlywood fibre wall structure seems to loosen more than latewood fibre wall structure during refining. Choosing an appropriate raw material is more effective than using excessive energy on reducing the wall thickness of thickwalled fibres.

It seems that both increased fibre quality and reduced energy consumption may be achieved if the coarse latewood fibres and shives are refined separately after the primary refiner. The separation should be done after the primary refining stage, where the fibre dimensions are most diverse and most of the fibre splitting already has occurred. Most energy should be directed towards the flow rich on latewood fibres. It seems likely that the fraction of split fibres could be increased by modification of the primary refining stage. In a parallel thesis work [28] it was found that raised refining intensity in the primary refining stage increased the fraction of split fibres. It was also found that fractionation could be done using a system of hydrocyclones.

CHAPTER 6

NORWAY SPRUCE AND SCOTS PINE AS TMP RAW MATERIAL (PAPER II AND VII)

6.1 Introduction

In Scandinavia Norway Spruce is the major raw material for mechanical pulp. The high resin content of Scots Pine may cause deposit problems in the refiner and on the paper machine. A high specific energy consumption and poor strength properties also make Scots Pine an unfavourable raw material. While the inferior strength properties of Scots Pine TMP are caused by the high resin content [52], the higher specific energy consumption of Scots Pine TMP has been attributed to the high density and presumably more thickwalled fibres. However, the reasons for the high energy consumption are not clear. Further knowledge is needed on the cross-sectional dimensions of pine fibres, and how pine fibres are developed in a refining process. At decreased extractives content and energy consumption, Scots Pine could become an attractive raw material due to good accessibility and lower wood cost. This chapter will focus on cross-sectional fibre dimensions of Norway Spruce and Scots Pine in wood and pulp, and how the fibres are developed during refining.

6.2 Cross-sectional tracheid dimensions in wood trunks

6.2.1 Cell wall thickness distributions

The cell wall thickness was measured for tracheids in cross-sections of 2 m long trunks from Scots Pine and Norway Spruce as described in Chapter 3.5. Populations of the entire trunks were provided by weighting the dimensions according to the number of fibres in each growth ring. Since only two trees were investigated in this study, the results in section 6.2 should be considered as examples of variations of transverse tracheid dimensions within spruce trees and pine trees.

Fig. 6.1 shows the cell wall thickness distribution in an 84 years old pine tree (more than 60 000 tracheids were assessed). As can be seen, the large number of measurements provides a very smooth distribution curve. The wall thickness distribution is well represented by the sum of two normal distributions, the left one corresponding to earlywood like fibres and the right one to latewood like fibres. In the pine sample, the wall thickness of latewood tracheids varied between 2 and 6 µm and earlywood tracheids between 1 and 3 µm. The two distinct peaks in the distribution curve suggest that there is a rapid change in tracheid transverse dimensions during the growth seasons. Fig. 6.2 shows how the wall thickness changes within a growth ring during various growth periods. There is a sudden increase in wall thickness going from the earlywood zone towards the latewood zone. Towards the end of the latewood zone the wall thickness tends to decrease again.

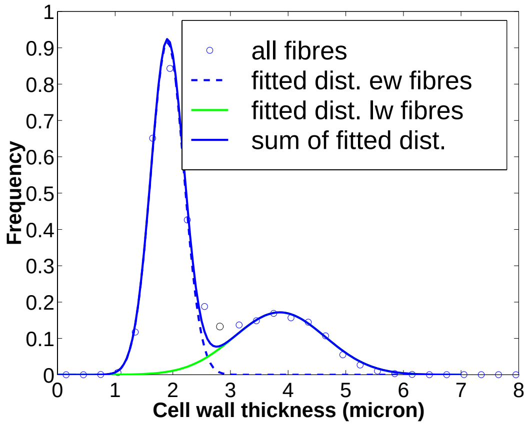


Figure 6.1 Cell wall thickness distribution, based on some 64000 fibres in a cross-section of an 84 years old Scots Pine. Two normal distributions were fitted to the distribution data.

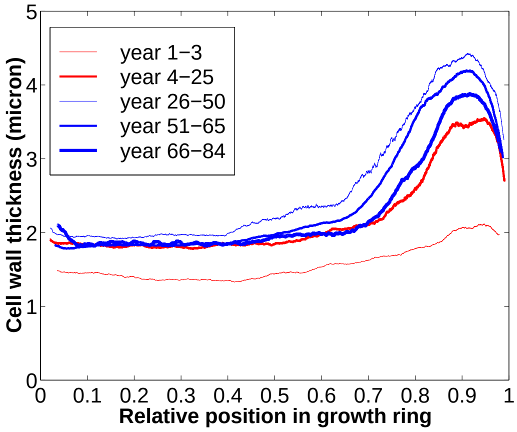


Figure 6.2 Cell wall thickness plotted versus relative growth ring position for different growth ring intervals. (Cross-section of an 84 years old pine). Each reading is a moving average of 50 cells.

For the Norway Spruce tree, the wall thickness increased much more gradually during the growth seasons (Fig. 6.3). The reduction in wall thickness towards the end of the latewood zone was less for the spruce tree than for the pine tree. A gradual transition from earlywood to latewood causes a wall thickness distribution with less pronounced peaks than for pine (Fig. 6.4). Fibre wall thickness distribution curves in TMP-pulps from Norway Spruce typically have a tail on the right-hand side (e.g. [28]).

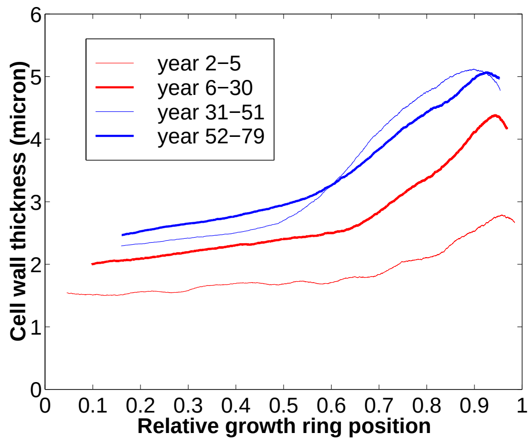


Figure 6.3 Cell wall thickness plotted versus relative growth ring position for different growth ring intervals. (Cross-section of an 80 years old Norway Spruce). Each reading is a moving average of 50 cells.

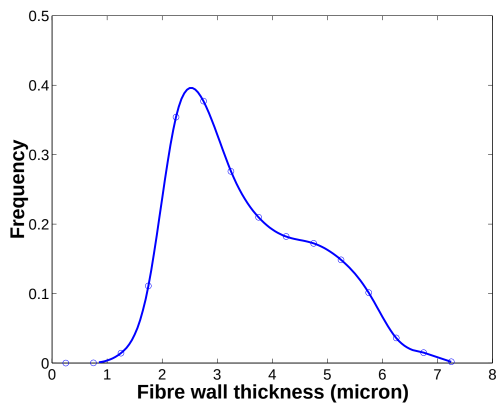


Figure 6.4 Cell wall thickness distribution, for a cross-section of an 80 years old spruce.

For wood-containing printing paper, thick-walled latewood fibres are harmful to the surface smoothness [115,134]. It was shown in section 5.5.2 that wall thickness is more effectively reduced for latewood than for earlywood fibres. Separate treatment of these two fibre classes thus seems beneficial [28]. Hydrocyclones fractionate on the basis of particle shape and specific gravity, and latewood fibres will therefore tend to enrich in the reject flow. Sharper differences between the fibre dimensions may improve the efficiency of the fractionation. Hence, one could expect a better fractionation of TMP-pulp made from the pine tree (Fig. 6.1) than for a TMP-pulp made from the spruce tree (Fig. 6.4).

6.2.2 Changes in tracheid dimensions from the pith to the cambium

For Norway Spruce, tracheid wall thickness and tracheid width (radial and tangential) are known to change systematically from the pith to the cambium of a wood trunk. During the first 20 growth rings (Scandinavian climate conditions), there is a large increase in tracheid wall thickness and width, after which the parameters tend to even out with increasing growth ring number in the radial direction [28,29,31,46]. Due to this systematic variation, it is possible to get a very close approximation to the wall thickness distribution by sampling just a fraction of the growth rings. Fig. 6.5 shows the cell wall thickness distribution estimated both from 12 evenly spaced growth rings, and based on all 84 growth rings. The two distributions pretty well resemble each-other.

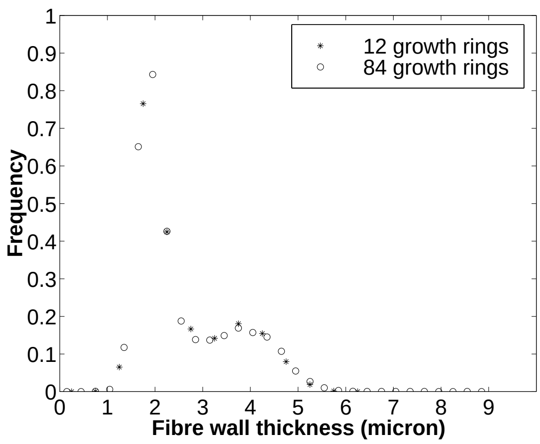


Figure 6.5 Cell wall thickness distribution for an 84 years old pine, both estimated from 12 growth rings as well as based on all 84 growth rings.

Fig. 6.6 shows how the cell wall thickness changes for the Scots Pine sample with increasing growth ring number from the pith. The cell wall thickness increases rapidly for the first 20 growth rings, then seems to go through a peak around growth ring 40, and towards the end there is a slight decrease in wall thickness. This trend is even more pronounced if earlywood cells and latewood cells are assessed separately (Fig. 6.7). The wall thickness of latewood cells peaks approximately after 40 growth rings, while the wall thickness of earlywood cells is almost unaffected by growth ring number after the first 5 growth rings. It has been found that the basic density of pine tends to first increase when going from the pith towards the cambium, and then decreases [29]. These findings correspond with the reductions in wall thickness. The reduction in wall thickness may be related to the decrease of the annual height increment.

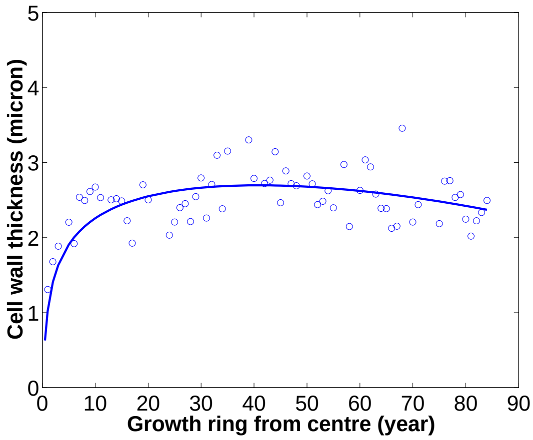


Figure 6.6 Cell wall thickness plotted versus growth ring number (Scots Pine). Each data point is an average of approximately 1000 fibres.

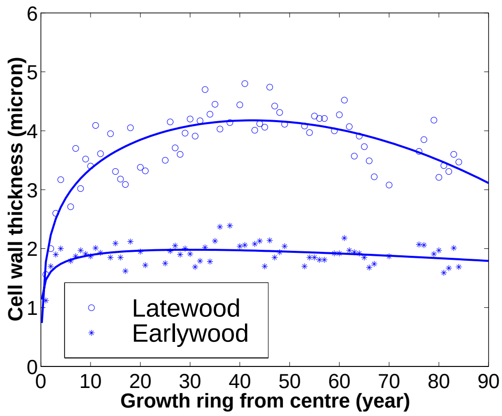


Figure 6.7 Cell wall thickness plotted versus growth ring number (Scots Pine). Each data point is the calculated mean of the "latewood" and "earlywood" wall thickness distribution for each growth ring (see section 5.2).

The perimeter of the pine tracheids increased rapidly for the first 20 growth rings, and then continued to increase at a constant, but slower rate (Fig. 6.8). The largest changes in perimeter were seen for earlywood cells (Fig. 6.9). Fig. 6.9 shows the perimeter variation within growth rings for various growth periods. The perimeter gradually decreased when going from the earlywood zone towards the latewood zone. If we consider Fig. 6.6 and Fig. 6.8 combined, we see that the slabwood tracheids of the pine tree had relatively small wall thickness and large perimeter. Hence, slabwood from this sample should produce fibres of good quality for papermaking.

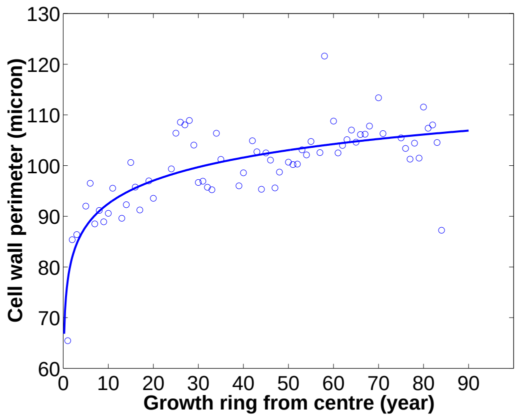


Figure 6.8 Cell wall perimeter plotted versus growth ring number (Scots Pine). Each data point is an average of approximately 1000 fibres.

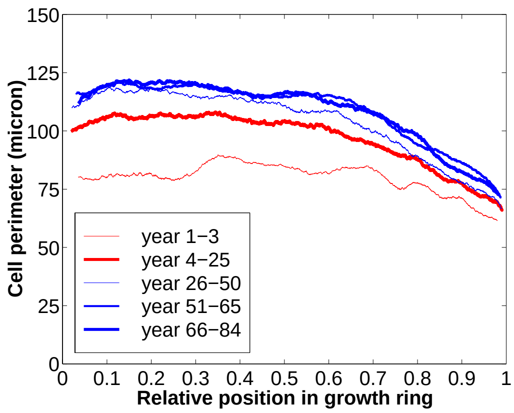


Figure 6.9 Cell wall perimeter plotted versus relative growth ring position for different growth ring intervals. (Cross-section of an 84 years old pine.) Each reading is a moving average for 50 cells

For the Norway Spruce sample, the mean tracheid wall thickness rapidly increased in the first 20 growth rings, and then stabilized at a value slightly below 4 µm (Fig. 6.10). There was no reduction in wall thickness later in the life period as for the pine sample. The tracheid perimeter increased rapidly in the juvenile zone, and then continued to increase at a constant slow rate (Fig. 6.11). As for the pine sample, the changes in perimeter are largest for earlywood tracheids, and less for latewood tracheids (Fig. 6.12). Fig. 6.12

shows the changes of the perimeter within one growth ring for various growth ring intervals of the Norway Spruce. The perimeter gradually dropped from the earlywood towards the latewood zone.

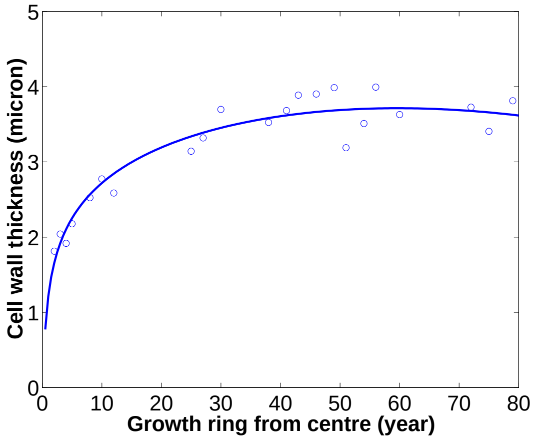


Figure 6.10 Cell wall thickness plotted versus growth ring number. Each data point is an average of approximately 1000 fibres. (Norway Spruce)

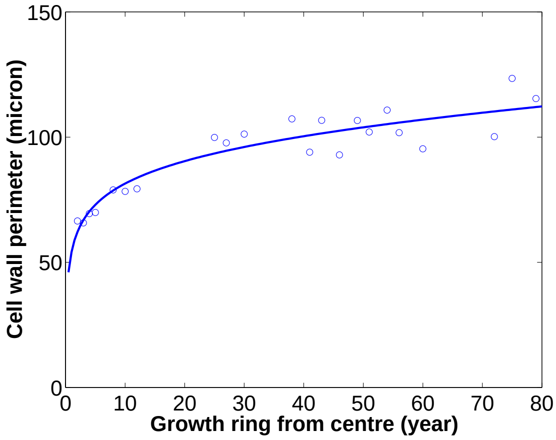


Figure 6.11 Cell wall perimeter plotted versus growth ring number. Each data point is an average of approximately 1000 fibres. (Norway Spruce)

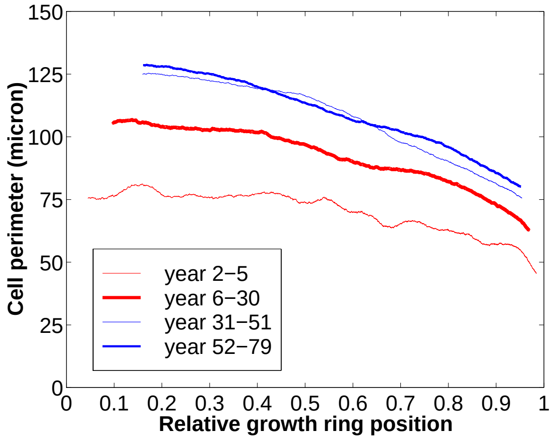


Figure 6.12 Cell wall perimeter plotted versus relative growth ring position for different growth ring intervals. (Cross-section of an 80 years old Norway Spruce). Each reading is a moving average of 50 cells.

In the mature wood zone, the increasing tracheid wall perimeter combined with the constant wall thickness, caused an increasing tracheid wall area (Fig. 6.13). The cross-sectional tracheid wall area corresponds to the fibre coarseness, assuming the cell wall density constant. Fig. 6.13 illustrates well the fact that fibre coarseness is not an ideal measure of the fibres' behaviour in a sheet. In the mature zone, fibre perimeter increases independently of the wall thickness, which both influence the coarseness value. Although the coarseness increases at increasing growth ring number, the potential for fibre collapse will also increase due to the longer perimeter at constant wall thickness.

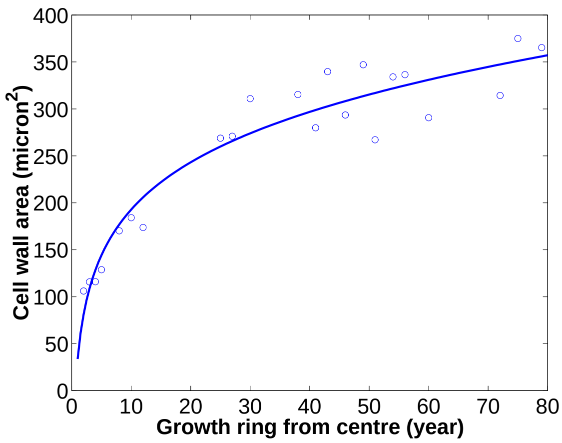


Figure 6.13 Cell wall area (=fibre coarseness) plotted versus growth ring number. Each data point is an average of approximately 1000 fibres. (Norway Spruce)

6.2.3 Variation in transverse tracheid dimensions

Generally, the transverse tracheid characteristics follow certain trends at increasing growth ring number from the pith to the cambium. Around the fitted lines, the data have significant variation (Figs. 6.6, 6.8, 6.10, 6.11). The variation is real. For every growth ring approximately 1000 fibres were assessed, giving 95% confidence intervals of approximately +/- 2.5-3% of the mean value. Comparing Fig. 6.6 and Fig. 6.7, it can be seen that variation in latewood fibre fraction explains some of the variation. Factors, like annual climatical variations, illness or insect attack, dominant or suppressed growth etc. may explain the variation in the data. This should be further explored.

6.3 Defibration and development of Norway Spruce and Scots Pine fibres in refining

6.3.1 Pulp properties

Single trees of Scots Pine and Norway Spruce were chipped and refined thermomechanically in three stages as described in paper VII. Freeness is plotted versus specific energy consumption for the various TMP-series in Fig. 6.14. The pine pulps

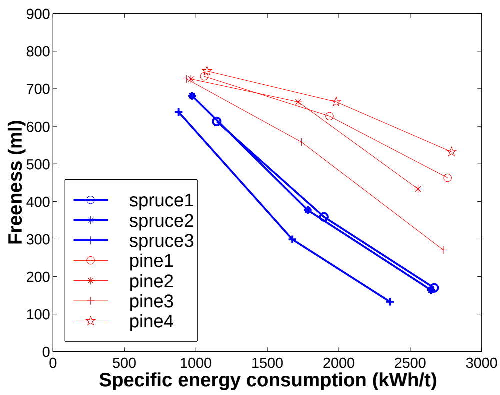


Figure 6.14 Freeness plotted versus specific energy consumption.

required much more energy to reach a certain freeness level compared to spruce pulps. If the curves are extrapolated towards lower energy consumption, it seems that all curves gather in the same point. This behaviour indicates that the energy demand for the initial defibration is rather equal for all pulps. Similar results was found by Corson [79]. However, the energy consumption required for fibre development seems to differ considerably for spruce and pine. The high energy consumption for pine has been observed in several other refining trials on Scots Pine [48,49,50,51]. The differences in energy consumption have been attributed to the presumably more thickwalled fibres for Scots Pine. However, no experimental data have confirmed a difference in wall thickness between TMP-fibres from Norway Spruce and Scots Pine.

The long fibre content was somewhat higher for the pine pulps (Fig. 6.15).The spruce pulps tended to contain more fines (-100 mesh) compared to the pine pulps (Fig. 6.16). Some of the freeness variation can obviously be explained by different particle size distributions. However, as seen in Fig. 6.17, the freeness variation at a given fines content may be large. Parts of the freeness variation may be caused by other factors like outer fibrillation, fines quality, resin content or fibre stiffness.

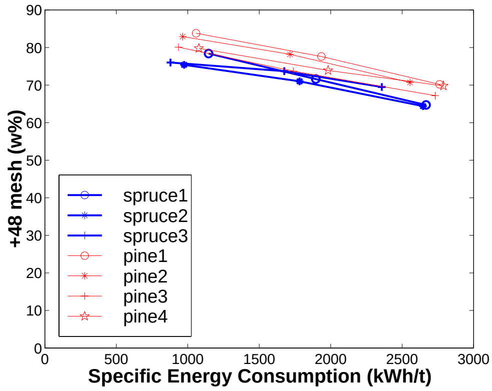


Figure 6.15 Long fibre fraction (BMcN +48 mesh) plotted versus specific energy consumption.

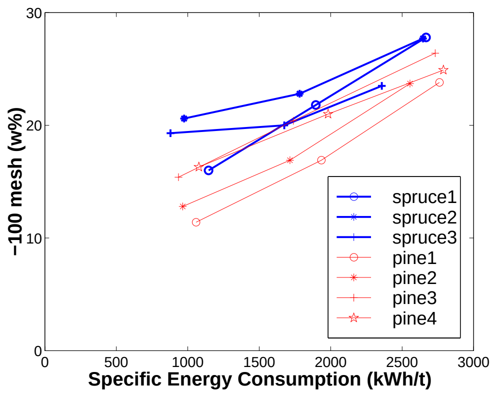


Figure 6.16 Fines fraction (BMcN -100 mesh) plotted versus specific energy consumption.

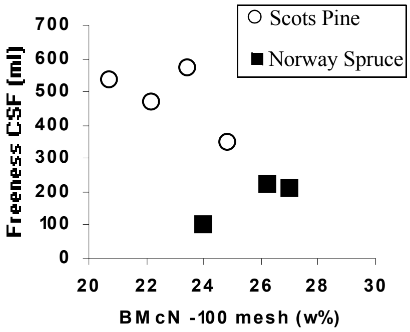


Figure 6.17 Freeness plotted versus fines content (BMcN -100 mesh).

6.3.2 Transverse fibre dimensions

Higher basic wood densities have been reported for Scots Pine than for Norway Spruce [43]. However, Hakkila [43] also found extracted pine wood to have the same basic density as unextracted wood from Norway Spruce. Hence, the higher density of pine wood does not necessarily implicate higher fibre wall thickness. The increased density may simply be caused by the larger amount of extractives, filling in voids in the wood structure. Fig. 5.15 shows the mean wall thickness of the pulp fibres plotted against specific energy consumption. For one of the trees the wall thickness value in the wood is included. The wall thickness decreased linearly with increasing energy consumption for all pulps. There is no indication that the pine fibres had thicker walls than the spruce fibres.

6.3.3 Variation in fibre wall thickness around the perimeter

As shown in Paper I, the fibre wall thickness varies significantly around the perimeter. The standard deviation of the wall thickness around a cross-section was assessed for all fibre cross-sections. Fig. 6.18 shows how the wall thickness standard deviation is related to the mean fibre wall thickness for the different pulps and process stages.The fibre wall thickness varied more for pine fibres compared to spruce fibres. This difference is easily noticed when inspecting fibre cross-sections (Fig. 6.19).

6.3.4 Fibrillation

As already mentioned, the pine pulps differed considerably from the spruce pulps in freeness level at a given energy consumption. Some of these differences may be explained by different degree of fibrillation of the fibres. Fig. 6.19 shows examples of fibre cross-sections (+48 mesh) after 1st and 3rd refining stage for two spruce pulps (left) and one pine pulp (right). The peeling of wall material is readily observed. Even examples of internal delamination may be found. The spruce fibres seemed to be much more fibrillated and developed compared to the pine fibres. For the pine fibres one may even after the 3rd refining stage observe pieces of middle lamellae material attached to

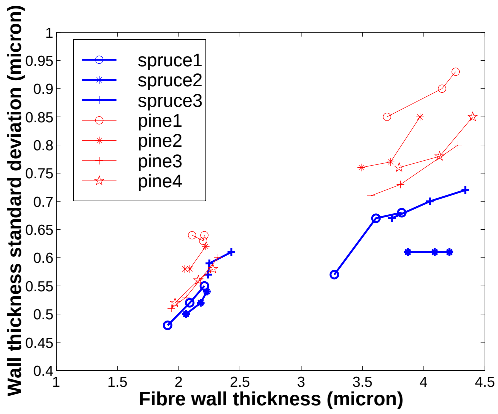


Figure 6.18 Mean fibre wall thickness plotted against mean standard deviation (variation of wall thickness around perimeter) for latewood fibres and earlywood fibres.

the fibres, especially to the edges. The different degrees of fibre development are also apparent from the light micrographs in Fig. 6.20.

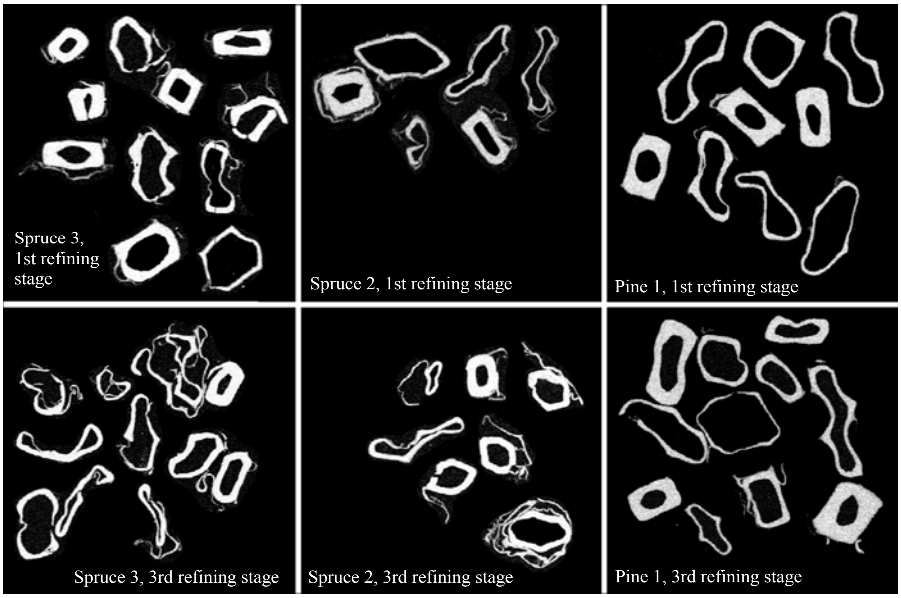
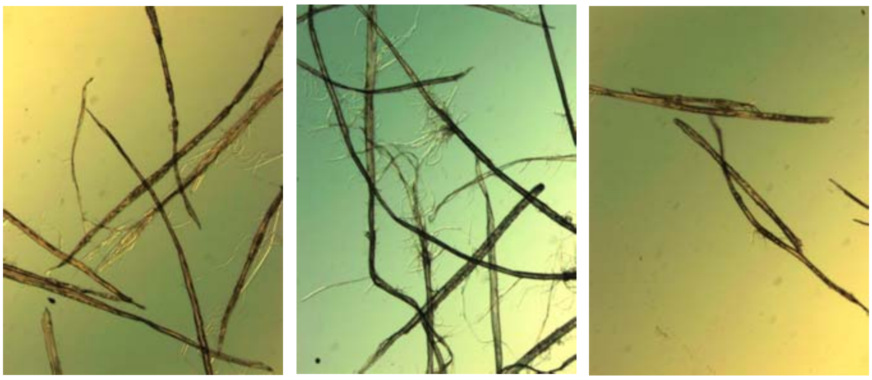


Figure 6.19 Examples of fibre cross-sections sampled after 1st and 3rd refining stage. The pine fibres seem to be less fibrillated and developed compared to the spruce fibres.



Spruce 1 (SEC = 2668 kWh/t) **Spruce 3 (SEC = 2358 kWh/t)** **Pine 1 (SEC = 2761 kWh/t)**

Figure 6.20 Light micrographs of spruce and pine fibres sampled after 3rd refining stage.

6.3.5 Energy consumption in TMP-refining for Norway Spruce as compared to Scots Pine

As mentioned, Scots Pine requires far more energy than Norway Spruce to reach a given freeness, and even more to reach a given strength level. The reduction in strength level has been related to extractives on the fibre surfaces, preventing reactive groups to bond to each-other in the sheet [52]. The high energy consumption has been attributed to the higher density of pine wood, presumably having more thickwalled fibres. In this study no significant difference in wall thickness was found between the pine and the spruce fibres as groups. Nevertheless, the pine fibres consumed far more energy to reach a given freeness level.

It is well known that Scots Pine has a higher content of extractives (2.2% [55]) than Norway Spruce (0.8% [55]). The extractives are located as canal resin and in parenchyma cells. In Scots Pine, some 30% of the resin is located inside the parenchyma cells [55]. Cisneros and Drummond [56] investigated the fate of parenchyma cells during chip compression and refining for *Pinus Contorta*. More than 70% of the parenchyma cells remained intact after chip compression, while more than 90% of the parenchyma cells were damaged after 1st stage refining. Hence, both canal extractives and almost all parenchyma resin are liberated after the primary refining stage.

It appears reasonable that the extractives will redistribute on free surfaces, including fines and fibre surfaces. Back [57] showed that paper-to-paper and paper-to-metal friction dropped with self-seizing. This can be explained by a surface being covered by long aliphatic chains such as those from fatty acids. Resin acids, however, may increase the friction [57]. Hence, a redistribution of extractives on the surface, in particular fatty acids, may decrease the fibre-to-fibre friction in the refiner. A possible consequence seems to be an increase in the energy consumption to a given freeness. It therefore appears reasonable to assume the hypothesis that a drop in fibre-to-fibre friction due to an outer layer of fatty extractives on the fibre surface may cause parts of the increased energy consumption for Scots Pine.

In this study, the energy consumption differed considerably between the pine trees. However, the fibre transverse dimensions did not differ appreciably. Fig. 6.21 shows freeness at a specific energy consumption of 2500 kWh/t plotted against the extractives content in pulps from primary refining stage. All four pine pulps and one spruce pulp were investigated. An increase in extractives content seems to be correlated with an increase in specific energy consumption to a given freeness. Further studies should be done to explore the validity of this hypothesis.

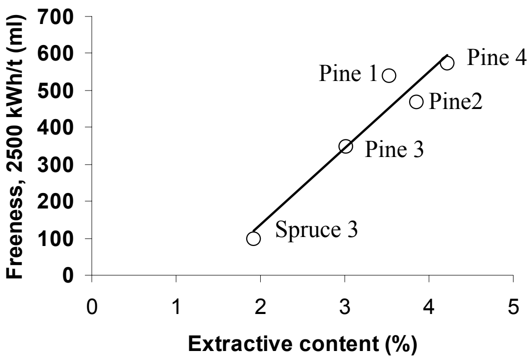


Figure 6.21 Freeness at 2500kWh/t plotted against extractive content of primary stage pulps.

6.4 Concluding remarks

The wood cross-sections of one typical Scots Pine and one typical Norway Spruce tree were investigated. The Scots Pine had a bimodal wall thickness distribution, caused by an abrupt transition from earlywood to latewood. The Norway Spruce had a more gradual transition from earlywood to latewood, causing a wall thickness distribution with less pronounced peaks. For both species, the cell perimeter increased towards the cambium, while the cell wall thickness initially increased and then stabilized or decreased. Hence, for these samples, the slabwood contained fibres with good potential for flattening.

The energy consumption to a given freeness was considerably larger for Scots Pine than for Norway Spruce. However, the fibre transverse dimensions did not differ much between Norway Spruce and Scots Pine. Pine pulps were far less developed than spruce pulps at similar energy level. A possible explanation for the large energy consumption may be that redistribution of extractives at the fibre surface may reduce friction in the refiner. This hypothesis should be further explored.

CHAPTER 7

SUMMARIZING DISCUSSION

7.1 Which parameters should be measured?

In order to establish cause/effect relationships between fibre structure and paper properties, detailed characterizations of the fibres are necessary. There are two fibre properties that have not been examined in this study: Fibre flexibility and fibrillation. As more flexible fibres will conform better in the sheet, it seems logical that increased flexibility will improve bonding properties. A large degree of fibrillation will also increase the specific surface area available for bonding and light scattering.

In this work, the alterations of fibres during TMP-processes have been studied. Links between fibre properties and paper properties have been established. The paper properties were measured only on hand sheets. In practice, the quality of machine made paper may differ quite much from that of handsheets. Surface smoothness was measured using the PPS apparatus. Evaluation of missing dots on printed paper could have provided additional information on the behaviour in the printing press.

Mechanical pulp is a complex material, consisting of a mixture of particles ranging from intact fibres to colloidal fines. Naturally, the quality and amount of fines particles and fibre fragments will have great influence on the paper quality. However, this work deliberately focused on the long fibres, and their effect in the paper. It may be argued that the quality of the long fibres is decisive for the paper quality, as runability puts restrictions on fines content.

7.2 Practical implications

Producers of wood-containing publication paper should produce paper with a certain quality profile, to satisfy the customer's demands. Hence, the product engineer in the TMP-mill should develop and produce tailor-made pulp, designed for specific end purposes. Such production patterns will probably become even more common in the future, as product diversity increases. Future TMP-processes should be designed to give fibres with optimal characteristics for the product. In this respect, detailed fibre characteristics such as fibre wall thickness and fibre splitting should be given more attention. Up to now the design and operation of TMP-plants have been too much related to traditional and easy-measured pulp properties like freeness, fibre length and tearing strength.

This work has shown that low fibre wall thickness and split fibres are beneficial for paper of high density, good bonding, opacity and high surface smoothness, e.g. printing paper. The shives content should be minimized, in particular shives consisting of latewood fibres. The papermaker has at least three possible options for modification of fibre wall thickness and degree of fibre splitting in the TMP-process:

- Selecting raw material with the desired tracheid dimensions
- Changing the specific energy consumption
- Changing refining conditions, e.g by changing refining intensity [28]

This work has shown that reduction of fibre wall thickness through refining is important to increase the compressibility and flexibility of the fibres. Nevertheless, it seems hard to achieve the same degree of flattening through large extent of refining of thickwalled fibres, compared to using thinwalled fibres as raw material. Hence - if feasible - wood sorting may improve product quality and homogeneity.

The results from this work have shown that most fibre splitting occurs for earlywood fibres, and mainly takes place during the primary refining stage. In order to increase the fraction of split fibres, one should modify the refining conditions during the primary refining stage. During refining, fibre wall thickness reduction (both absolute and relative) is larger for latewood fibres than for earlywood fibres. It thus seems favourable to fractionate the pulp into an earlywood rich flow and a latewood rich flow, and direct most of the refining energy towards the latewood rich flow. Since the morphological difference between latewood fibres and earlywood fibres decreases throughout the refining process, the fractionation should be done as early in the process as possible (after the primary refining stage).

7.3 Suggestions for future work

This study has focused on improving the understanding of fundamental mechanisms in the refining process. The natural next step is to apply the new knowledge experimentally in the TMP-process. It would then be of interest to examine the effect of refining at rougher conditions in the primary refining stage on wall thickness reduction and fibre splitting. As hydrocyclons separate on the basis of particle shape and specific gravity, it also seems important to examine how efficiently a system of hydrocyclones may separate earlywood and latewood fibres. If good fractionation is feasible, the effect of separate reject refining should be examined, with respect to total energy consumption and pulp quality. In a parallel thesis study at the department of chemical engineering at NTNU [28] these various unit operations were explored. The results were promising, showing that increased refining intensity in the primary refiner indeed increased the fraction of split fibres. Also, it was found that latewood fibres could be enriched in a hydrocyclone reject.

Shives that are potential web-break initiators typically consist of latewood fibres [165]. Results from this work have shown that the shives in a TMP pulp almost entirely consist of earlywood fibres. Hence, only a small fraction of the shives are potentially dangerous for web failure. Since the latewood shives have very small cross-sections compared to the earlywood shives, the latewood shives may pass the slots in a conventional screen and the earlywood shives not. It thus seems that todays screening equipment does not effectively remove web-break initiators from the pulp. Further research is needed on how effectively different fractionation systems such as screens and hydrocyclones remove potentially dangerous components from the pulp.

It was found that Scots Pine required far more refining energy to reach a given freeness compared to Norway Spruce. However, there was no significant difference between the fibre wall thickness of pine and spruce TMP fibres when compared as groups. It thus seems that other explanations to the difference in specific energy consumption should be sought than the presumably higher wall thickness of pine fibres. An increase in extractives content was found to correlate with an increase in specific energy consumption to a given freeness. It was hypothesized that resin compounds will redistribute on the fibre wall surface during refining, reduce the friction between fibres and between fibre/refiner bars, and thus increase the specific energy consumption. Since some resin compounds may increase the friction (e.g resin acids) and others reduce the friction (e.g fatty acids) the composition of the resin compounds also has importance. Further work is needed to quantify the effect of resin amount and resin composition on specific energy composition in TMP-refining.

It has not been studied how the wall thickness changes along the fibre length. There is also room for more detailed studies of the character of fibre splitting. Are the fibre splits mainly at the ends or in the interior? More detailed information in these areas may contribute to a better understanding of the mechanisms during refining.

CHAPTER 8

CONCLUDING REMARKS

8.1 Method development (Chapter 3)

Methods were developed for precise assessment of cross-sectional dimensions of wood tracheids and processed pulp fibres, based on image analysis of SEM-micrographs. Both intact and split fibres may be assessed.

8.2 Fibre cross-sectional dimensions and fibre structure, and their relevance for important paper properties (Chapter 4)

SGW and PGW fibres were much more split and fibrillated than TMP fibres at comparable freeness. Intact groundwood fibres were more thickwalled than intact TMP-fibres. Nevertheless, calendered paper from SGW-fibres experienced less surface roughening upon water moistening than did calendered paper from TMP-fibres. The moisture-induced surface roughening decreased with increased degree of fibre splitting.

From a study of a range of TMP-pulps it was concluded that a reduction in wall thickness or an increase in fibre splitting caused a reduction of surface roughness and an increase in light scattering coefficient.

8.3 Composition of shives (Chapter 5)

Earlywood fibres were clearly overrepresented in TMP-shives, compared to the fibre population of the whole pulp. On the other hand, groundwood tended to give shives rich on latewood. As latewood shives represent potential web-failure initiators, and earlywood shives not [162], one should focus on removing latewood shives from the pulp. Latewood shives were found to have considerably smaller cross-sections than earlywood shives, and tended to pass the slits in a conventional screen and enrich in the accept. Even after screening, groundwood pulps were found to contain more than three times as many undefibrated latewood fibres than TMP-pulps at the same freeness.

8.4 Defibration mechanisms (Chapter 5)

Latewood was found to defibrate easier than earlywood during refining. While earlywood was heavily distorted during refining, the latewood fibres to a larger extent retained the original shape. In the case of grinding, there was no particular preference for earlywood or latewood to be defibrated. Reject refining of groundwood reject was, however, found to be very important for defibration of latewood-containing shives.

Pulps made from a raw material with more compact fibres (higher Z-value) were found to defibrate easier, and contain less shives. During defibration, the middle lamellae/P1-layer/S1-layer may stick to one fibre, and be separated from the other. It was found that further refining tended to reduce wall thickness most on the thickwalled parts of the fibre, thus causing a reduction of the wall thickness variation around the circumference.

8.5 Fibre development mechanisms (Chapter 5)

Earlywood fibres are preferentially split during refining. Most fibre splitting occurs during the primary stage, while the fibres are firmly attached to chips or fibre bundles. Latewood fibre wall thickness decreases considerably more than earlywood fibre wall thickness during refining. It seems that choosing an appropriate raw material is more effective than using excessive energy on reducing the wall thickness of thickwalled fibres. Earlywood fibres will yield easier than the stiff latewood fibres during refining. It was found that earlywood fibres became more flattened during refining compared to latewood fibres, possibly due to repeated compressions and relaxations in the refiner.

8.6 Differences between Norway Spruce and Scots Pine in refining (Chapter 6)

The wood cross-sections of one typical Scots Pine and one typical Norway Spruce tree were investigated. The Scots Pine had a bimodal wall thickness distribution, caused by an abrubt transition from earlywood to latewood. The Norway Spruce had a more gradual transition from earlywood to latewood, causing a wall thickness distribution with less pronounced peaks. For both species, the cell perimeter increased towards the cambium, while the cell wall thickness stabilized or decreased. Hence, for these samples, the slabwood contained fibres with good potential for flattening.

The energy consumption to a given freeness was considerably larger for Scots Pine than for Norway Spruce. However, the fibre transverse dimensions did not differ much between Norway Spruce and Scots Pine. Pine pulps were far less developed than spruce pulps at similar energy levels. A possible explanation for the large energy consumption may be that redistribution of extractives at the fibre surface could reduce friction in the refiner. This hypothesis should be further explored.

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