TKK Reports in Forest Products Technology, Series A7
Espoo 2009

ON THE APPLICATION OF GRITS TO THERMOMECHANICAL PULP REFINING

Doctoral Thesis

Phichit Somboon

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission by the Faculty of Chemistry and Materials Sciences, for public examination and debate in Auditorium Puu II at the Helsinki University of Technology (Espoo, Finland) on the 27th of February, 2009 at 12.00 noon.

Helsinki University of Technology
Faculty of Chemistry and Materials Sciences
Department of Forest Products Technology

Teknillinen korkeakoulu
Kemian ja materiaalitieteiden tiedekunta
Puunjalostustekniikan laitos

Distribution:
Helsinki University of Technology
Faculty of Chemistry and Materials Sciences
Department of Forest Products Technology
P.O. Box 6300
FIN-02015 TKK

ISBN (printed) 978-951-22-9750-4
ISSN (printed) 1797-4496
ISBN (PDF) 978-951-22-9751-1
ISSN (PDF) 1797-5093
URL: http://lib.tkk.fi/Diss/

Yliopistopaino, Helsinki 2009

ABSTRACT OF DOCTORAL DISSERTATION

HELSINKI UNIVERSITY OF TECHNOLOGY
P.O. BOX 1000, FI-02015 TKK
http://www.tkk.fi

Author Phichit Somboon

Name of the dissertation
On the application of grits to thermomechanical pulp refining

Manuscript submitted September 9, 2008
Manuscript revised December 11, 2008

Date of the defence February 27, 2009

☐ Monograph
☒ Article dissertation (summary + original articles)

Faculty Chemistry and Materials Sciences
Department Forest Products Technology
Field of research Paper and Printing Technology
Opponent(s) Dr. Esko Härkönen, Dr. Tom Lind
Supervisor Professor Hannu Paulapuro

Abstract

The objective of this thesis was to develop a mechanical pulping process capable of producing good-quality pulp, while consuming less electrical energy. The study focused on applying of grits to TMP refining to enhance the breaking of the fiber cell wall promoting faster development of pulp fibers to the desired quality for papermaking. The study comprises tests at laboratory scale and development of an application for industrial, including trials at pilot scale

A preliminary trial with the grit application in TMP refining was conducted at laboratory scale. The results showed that the grits should be introduced between the first and second stages in TMP refining. The grit treatment on the TMP fibers caused disruption of the wall structure, opening of the outer layers and peeling-off of the cell wall. The efficient disruption with minimal shortening and weakening of fibers was found to be operated at a low-intensity and high-frequency of treatment. According to an experiment with first-stage TMP pulp, the disrupted pulp developed faster during subsequent refining, while the energy consumption was reduced by up to 30% without a significant loss of pulp quality.

With the aim of developing an industrial application, the refiner segments were modified by applying grits on the refiner segment surfaces. The grits were made from self-fluxing tungsten-carbide powder and a Ni-base alloy powder, which were laser-clad onto the surface of breaker bars, the inner part of a segment. Trials with grit segments were carried out on a pilot refiner. The grit segments were applied in first-stage TMP refining, followed by treatment with base segments operated under normal mill conditions. The grit segments were found to have no negative effects on the refining system. A refiner equipped with grit segments, operated at a speed of 2400 rpm, produced pulp with a higher level of disruption of fiber cell walls than a refiner equipped with the reference segments. According to the results, the energy consumption can be reduced by at least 10% with minimal negative impacts on pulp and paper properties.

Keywords Thermomechanical pulp, refining, segments, grits, disruption, energy consumption

ISBN (printed) 978-951-22-9750-4
ISSN (printed) 1797-4496
ISBN (pdf) 978-951-22-9751-1
ISSN (pdf) 1797-5093
Language English
Number of pages 58 p. + app. 53 p.

Publisher Helsinki University of Technology, Department of Forest Products Technology

Print distribution Helsinki University of Technology, Department of Forest Products Technology

☒ The dissertation can be read at http://lib.tkk.fi/Diss/

PREFACE

The research work for this doctoral thesis was carried out at the Laboratory of Paper and Printing Technology, Helsinki University of Technology during 2005-2007. The research was part of the ESA project, “Energy Saving in TMP refining”, funded by the Finnish Funding Agency for Technology and Innovation (TEKES), Metso Paper, UPM-Kymmene and Stora Enso, which is gratefully acknowledged. The thesis work was accomplished in cooperation with Tampere University of Technology and research partners, i.e., the Finnish Pulp and Paper Research Institute, KCL and the Technical Research Center of Finland, VTT.

Many people helped and supported me during the thesis work, and I am very grateful to all of them. First and foremost, I would like to express my sincerest thanks to Professor Hannu Paulapuro for giving me the opportunity to work in this project and for supervising my thesis work. I wish to thank all members of the steering group of the ESA project. Special thanks are due to Dr. Esa Viljakainen (Vice president of Metso Paper) for his input as project coordinator, Tuomo Pynnönen and Juha Vuorela for their work as project managers, Dr. Taegeun Kang for helping with the grinding experiments and for co-authoring, Kaarlo Nieminen for helping to solve mathematical problems and for co-authoring, Alexey Kononov for his advice, and Leena Nolvi for her laboratory work. I also wish to thank Professor Richard J. Kerekes, University of British Columbia, for his technical review of the publications.

Finally, I would like to thank Dr. Kari Koskenhely for the support to work in his project during my studies for the Master of Science degree, and the first year of my doctoral studies. The International Doctoral Program in Pulp and Paper Science Technology (PaPSaT) provided part of the financial support for the study and the travels for international conferences, for which I am very grateful. The Commission of Higher Education, Ministry of Education of Thailand, and Kasetsart University also provided financial support for my master’s and doctoral degrees, which is gratefully acknowledged.

Otaniemi, February 2009

Phichit Somboon

CONTENTS

LIST OF PUBLICATIONS

Paper I Somboon, P. and Pynnönen, T., Performance of abrasive segments in mechanical pulp refining. A review, Paperi Ja Puu-Paper and Timber, Vol.90, No.5, 2008, pp.41-45.

Paper II Somboon, P. and Paulapuro, H., Determination of wet fiber strength. The manuscript has been accepted for publication in TAPPI Journal.

Paper III Somboon, P. and Paulapuro, H., Surface mechanical treatment of TMP pulp fibers using grit material. TAPPI Journal, Vol.7, No.12, 2008, pp.4-9.

Paper IV Somboon, P., Kang, T., and Paulapuro, H., Disrupting the wall structure of high-freeness TMP pulp fibers and its effect on the energy required in the subsequent refining. Pulp and Paper Canada, Vol.108, No.10, 2007, pp.30-34.

Paper V Somboon, P., Nieminen, K., and Paulapuro, H., Finite element analysis of the fatigue behavior of wood fiber cell walls. Bioresources, Vol.3, No.4, 2008, pp.983-994.

Paper VI Somboon, P., Vuorela, J., Pynnönen, T., and Paulapuro, H., Grit segments in TMP refining. Part 1: Operating parameters and pulp quality. Appita Journal, Vol. 62, No.1, 2009, pp.37-41.

Paper VII Somboon, P., Vuorela, J., Pynnönen, T., and Paulapuro, H., Grit segments in TMP refining. Part 2: Potential for energy reduction. Appita Journal, Vol. 62, No.1, 2009, pp.42-45, 59.

Author's contribution

The author's role in each of the publications has been the following:

Paper I	first version of the manuscript,
Paper II	all experiments, analysis, first version of the manuscript,
Paper III	all experiments, analysis, first version of the manuscript,
Paper IV	all experiments, analysis, first version of the manuscript,
Paper V	experiments in part, analysis, first version of the manuscript,
Paper VI	main part of experiments, analysis, first version of the manuscript,
Paper VII	main part of experiments, analysis, first version of the manuscript.

Other related publications

Paper VIII Kang, T., Somboon, P., and Paulapuro, H., Fibrillation of mechanical pulp fibers. Paperi ja Puu-Paper and Timber, Vol.88, No.7, 2006, pp.409-411.

LIST OF ABBREVIATIONS AND SYMBOLS

CD refiner	Conical disc refiner
CSF	Canadian standard freeness
CTMP	Chemithermomechanical pulp
DD refiner	Double disc refiner
LE segment	Low energy segment
LWC	Lightweight coated paper
P	Primary layer of fiber cell wall
RMP	Refiner mechanical pulp
S1, S2, S3	Secondary layer of fiber cell wall
SC	Supercalendered paper
SD refiner	Single disc refiner
SEC	Specific energy consumption
TMP	Thermomechanical pulp

A	Active area under the clamp jaws of zero-span tester
F	Fiber strength
Lc	Contoured length of fibers
Lp	Projected length of fibers
n	Number of fibers per unit weight
W	Basis weight of testing paper
ZS	Zero-span tensile

1. INTRODUCTON

1.1 Background

Thermomechanical pulp (TMP) is the dominating raw material in the production of high-quality magazine paper grades, e.g., lightweight coated paper (LWC), and super-calendered paper (SC). Currently, there is a trend towards lower basis weights in the production of these paper grades. This puts increasing demands on the high bulk, opacity and strength properties of paper sheets, which can be obtained by using TMP pulp. This pulp not only maintains good paper quality but also allows profitable paper production. Consequently, demand for this pulp grade is increasing [1].

In the production of TMP pulp, energy consumption is one of the most important factors affecting the production cost. The production of TMP pulp requires an electrical energy input of more than 3000 kWh/t, while theoretically calculated the energy consumption in the refining process is about 0.22-300 kWh/t [2-5]. Previously, there was less concern about the energy consumption, because the wood raw material accounted for a larger share of the total production cost, while researchers concentrated on developing new methods to improve pulp quality. Since the 1970s, the energy cost has been a serious competitive factor, as the cost of mechanical pulp turned out to be extremely vulnerable to the rising price of electricity [6]. For example, at present, electricity accounts for 35-40% of the total production cost of TMP [7]. Thus, the rising price of electricity might become a critical factor, and erode the economic advantages of TMP pulp in the future [6]. To secure sustainable and competitive paper production based on mechanical pulp, the refining process needs to be developed to reduce the energy consumption and achieve better pulp quality.

Theoretically, it has been estimated that the potential for reducing energy consumption offered by the proposed new technology could be about 50% [1]. There are several ways to lower energy consumption, e.g., pretreatment of raw materials, optimization of process conditions, and new designs of refiner segments [7]. Industrially, one of the most practical solutions for reducing energy consumption is to redesign refiner segments. The segment is vital in defibering and fibrillating fibers to the desired quality for making paper. Its pattern has a major effect on the dissipation of energy to the wood matrix and pulp fibers. Over the past few decades, refiner segments have been studied intensively. Several new designs have been introduced to improve the energy efficiency in the refining process, for example, a new geometrical design and a modification of segment surfaces. Recently, segments with a new geometry have been introduced for industrial use, e.g., LE^{TM} segments [8] and Turbine^{TM} segments [9]. These segments apparently provide lower energy consumption. The principal idea of these segments is to reduce the residence time of pulp in the refiner. The short residence time contributes to high refining intensity and a less turbulent flow, allowing energy to be efficiently transferred to wood fibers.

Another approach is to design segment surfaces to serve as an abrasive, as a means to increase the friction in the plate gap, and to direct energy intensively to breaking down the wood structure. The research and development related to abrasive segments is reviewed and presented in Paper I. Several techniques to produce an abrasive surface have been published, for example, filling the grooves and coating the surface of the refiner plate with abrasive materials. These segments have been tested in laboratories, at pilot scale and in short mill trials. The results have indicated potential for reducing the energy consumption. However, these segments have not been taken into industrial use because of problems with the operation of the refiners, the operating life of segments and the severe degradation of pulp quality. At present, the underlying mechanism of mechanical pulping is better understood, and an innovative technology for metal base coating is also available. Thus, manufacturing a new design of abrasive layers on segment surfaces and solving earlier problems would now seem to be possible. In addition, this technique could possibly be combined with the new geometrical design of the segments to achieve a highly energy-efficient process.

1.2 Objectives

The goal of this research was to develop a mechanical pulping process which is capable of producing good-quality pulp, while consuming less electrical energy. The research was based on the hypothesis that ***"increasing the disruption and opening of the fiber wall structure during the defibration stage by applying grit material would promote the development of pulp fibers in the fibrillation stage and thus reduce energy consumption"***.

The study focused on applying grit treatment to TMP refining and on reinventing refiner segments with grits on their surfaces to enhance breaking of the fiber cell wall and to ensure faster development of pulp fibers to the desired quality for papermaking. The research results were expected to yield a simple solution to reduce the energy consumption and a practical application for industrial use. To achieve this goal, the following objectives were set for the study:

1. Understanding the behavior of innovative abrasive segments with the grit materials on their surfaces in mechanical pulp refining, the critical problems in the operation of refiners equipped with abrasive segments, and the effects of abrasive treatment on pulp quality.

2. Understanding the mechanical treatment of TMP pulp fibers using grit materials at laboratory scale, with the aim to find an efficient method to disrupt the fiber wall structure while minimizing the degradation of fiber quality, and to exploit the potential for reducing the energy consumption in refining.

3. Designing the grit treatment for industrial use through modification of the refiner segments, and to gain a deeper understanding of the mechanism governing the breakdown of the fiber cell wall under grit treatment and TMP refining conditions.

4. Testing the modified segments at pilot scale to evaluate the potential for reducing energy consumption, optimizing the process variables in the refining process, and finally examining pulp and paper quality properties.

1.3 Structure of study

The study was composed of a review of previous research related to this work, a test of the hypothesis at laboratory scale, design of refiner segments combined with grit materials, a simulation for understanding the underlying mechanism governing the disruption of the fiber cell wall, and finally the design of a practical application for industrial use, as shown in Figure 1.

Chapter 2 contains a review of the structure of wood and fibers, including their mechanical properties, and a study of how to determine the strength properties under various degrees of mechanical treatment. Chapter 3 describes the fundamentals of the thermomechanical pulping process and the effect of process and equipment parameters on pulp quality and energy consumption. Chapter 4 describes the testing of the hypothesis and how to evaluate the potential for energy reduction. Chapter 5 contains modeling of the fiber structure and a simulation of the breakdown of fiber cell walls by using grit segments. Chapter 6 describes the application of grit treatment for industrial use and examines pulp quality, including the potential for reducing electrical energy. Further details of the experiments and discussions are found in publications I-VII.

Literature review **Publication I**

- Previous research on abrasive segments
- Designs of segments and potential for energy reduction
- Effects of abrasive segments on pulp quality
- Critical operating problems when using abrasive segments

Laboratory testing **Publication II, III, IV**

- Disruption of fiber cell wall using grit materials
- Study parameters affecting the disruption of the fiber cell wall
- Evaluating the potential for reducing electrical energy consumption
- Examination of pulp and paper quality

Simulation of grit application **Publication V**

- Dynamic simulation of the fatigue of fiber cell walls
- Study of an efficient technique to break down the fiber cell wall
- Optimizing the refining process

Application of grits in thermomechanical pulping **Publication VI, VII**

- Reinventing grit segments and pilot trial
- Optimization of refining process
- Evaluation of energy reduction
- Examination of pulp and paper quality

Figure 1. Structure of the study. The publications are put forward to fulfill the objectives of the study.

2. WOOD FIBERS

2.1 Introduction

Wood species are classified into two broad categories known as softwoods and hardwoods. Softwoods are referred to as coniferous or needle-leaved species (gymnosperms) whose seeds develop inside cones and are not covered. The wood cells are mainly fibrous in form, termed “fibers” (tracheids). Hardwoods are referred to a broadleaved species (angiosperms or dicotyledonous angiosperms), which produce covered seeds within flowers. The wood cells have a variety of different cell types such as fibers, vessels (pores), and parenchyma cells [10].

In the production of TMP pulp, softwood species are generally used as a raw material. Spruces are considered to be the most suitable wood species. Norway spruce (*Picea abies*) has been considered as a reference for the best-quality wood species. North American spruces, e.g., Black spruce (*Picea mariana*) and White spruce (*Picea glauca*) are comparable with Norway spruce. In addition to spruces, other species such as Balsam and Silver firs are also used [11]. In this research, Norway spruce was used as a raw material.

According to the main objective of this research, it was to find a way to increase the breakdown of wood fibers in the mechanical pulping process with a minimal weakening and shortening of fibers. To be able to accomplish this task, a comprehensive understanding of the basic structure of the fiber cell wall focusing on softwood fibers is essential. In this chapter, the fiber cell wall structure in detail, including their chemical, physical and mechanical properties, are reviewed. The study of practical methods to determine the strength of individual fibers is presented.

2.2 Structure of softwood fibers

Softwood fiber cells consist to 90-95% of longitudinal tracheids, which are thin and long cells called prosenchyma cells. The rest are rectangular and relatively short cells, i.e., ray tracheids, ray parenchyma, and epithelial parenchyma, as shown in Figure 2.

The average fiber length is in the range of 2 to 6 mm. The average width of thracheid fibers is between 20 and 50 μm [10].

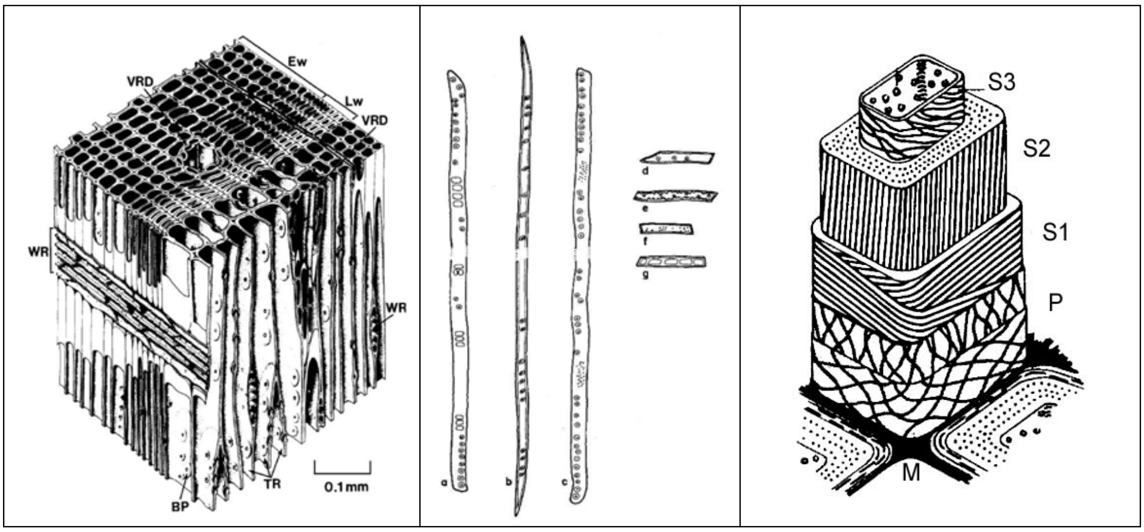

Figure 2. Cross-section of softwood (left), typical softwood cells (middle), and structure of fiber cell wall (right) [10, 12].

The wood fiber cell wall consists of cellulosic fibrils surrounded by a matrix of hemicelluloses and lignin. Each fibril consists of about 36 parallel cellulose molecules [13]. Basically, the cellulosic fibrils are organized into larger units with a diameter of about 5-30 nm, which are visible in an electron microscope known as microfibrils [10, 13, 14]. In the architecture of the fiber cell wall, the microfibril is an elementary material for the modeling of its structure. Fundamentally, the wall structure comprises two distinct layers: the primary wall and the secondary wall. The primary wall is a thin layer of about 0.05-0.1 μm covering the secondary layer. The secondary wall is a relatively thick layer of about 2-9 μm comprising several sets of helically winding microfibrils [10, 14]. This layer is considered to be the most important part of the cell wall, controlling the mechanical properties of fibers.

The secondary wall consists of three layers, i.e., the outermost S1 layer followed by the S2 and S3 layers, respectively, as shown in Figure 2. The S1 layer has a crossed microfibrillar structure in which the microfibrils wind around the cell axis with an alternating right-handed helix (S-helix) and a left-handed helix (Z-helix), with an angle of about 50-70°. The thickness of S1 is in the range of 0.1-0.3 μm. The S2 layer is located in the middle of the secondary wall with a right-handed helical orientation of microfibrils. The winding angle is in the range of 5-30° from the cell axis. The average thickness of S2 is about 1-8 μm, and the average volume is in the range of 75-80% of the total volume of the cell wall. Basically, the thickness and the microfibril angle of the S2 layer could be used to determine the strength of pulp fibers. The S3 is the inner layer with a thin wall of approximately 0.1 μm. The microfibrils are oriented in different directions either to the right-handed or left-hand helices with an angle of 60-90° from the cell axis [10, 13-15]. Modelling of the cell wall structure and its mechanical properties are further discussed and presented in Chapter 5 and Paper V.

2.3 Chemical and rheological properties

Softwood fiber cell walls consist chemically of three major nature polymers, i.e., cellulose, hemicelluloses and lignin. Cellulose is mainly a linear crystalline macro molecule and in part an amorphous polymer. Hemicelluloses and lignin are amorphous. Amorphous celluloses and hemicelloses of the water-saturated cell wall are softened at about 20 °C, and the lignin is softened at about 90 °C [5]. In each layer of the cell wall, these polymers are distributed in various proportions (Figure 3), which contribute to its mechanical and rheological properties [5, 10, 12].

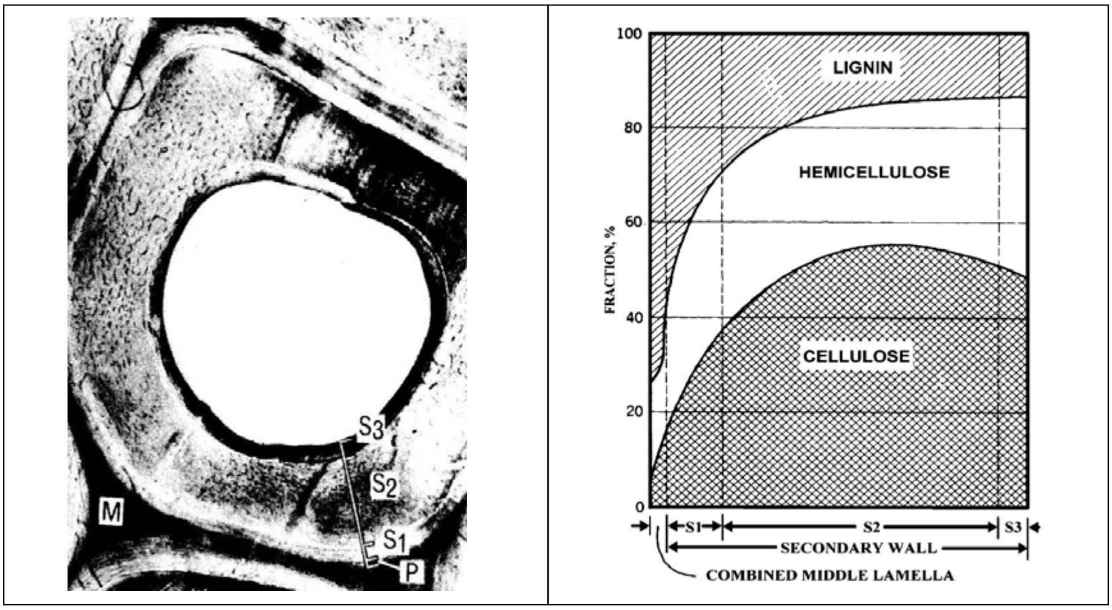

Figure 3. Cross-section of softwood fibers (left): M is middle lamella, P is primary wall, S is secondary wall. Distribution of the major chemical components in the softwood fiber cell wall (right) [5, 12].

Rheologically, the wood fiber is a viscoelastic plastic material [5, 16]. Its deformation depends on the applied force and its duration. Under mechanical pulping conditions, rheological properties can also be affected by temperature and the frequency of the applied load. Softening of lignin is considered to play an important role in mechanical pulping. It has an influence on the breakdown of the fiber cell wall, pulp quality, and energy consumption. The deformation and fatigue behavior of wood material are further discussed in Chapter 5.

2.4 Mechanical properties of fibers

The mechanical properties of wood fibers are considered to be controlled by the microscopic structure of microfibril alignment and the thickness of the cell wall. The longitudinal shrinkage of fibers has been found to be related to the primary wall, the S1 and S3 layers [17]. The strength properties are largely controlled by the S2 layer [18, 19]. Based on laboratory measurements, the longitudinal elastic modulus of wood fibers is in the range of 20-80 GPa [20], and the transverse elastic modulus of the cell wall about 0.7-3.0 GPa [21]. The strength of individual pulp fibers measured in terms of their breaking length reportedly varies in the range of 100-300 mN [14, 22-24]. In addition to empirical measurement, the modulus can be determined using a finite element method, as discussed in Chapter 5 and Paper V.

2.5 Wet fiber strength measurement method

In this chapter, a practical method to determine the strength of individual fibers during mechanical breakdown of the fiber cell wall is examined. This method makes it possible to prevent severe damage to fiber quality. Based on laboratory experiments, the strength of wood fibers can be examined by measuring the breaking strength of individual fibers. In practice, there are two main approaches to determine fiber strength based on the breaking of pulp fibers. One is direct measurement of the breaking stress of individual fibers using special tensile devices [22, 24]. This method is unsuitable for testing numerous samples because it requires a large amount of work and great care in testing, and results in an uncomfortably wide variation of results [14, 23].

The other approach involves measurement of the breaking force of a paper strip at a zero span [25], as shown in Figure 4. This is a fast and economical method for assessing the strength of various types of papermaking pulp [26, 27]. However, there are many uncertainties related to the concept of zero-span tensile. Conflictingly, in the refining process, the zero-span tensile is found to increase and decrease with the degree of refining [28, 29]. The ambiguous results might interact with several parameters, e.g., paper structure [24], fiber bonding [30-32], amount of fibers in the rupture zone [24, 30, 31], fiber length distribution [30, 33], and fiber deformation [34, 35].

The proposed method, presented in Paper II, allows the zero-span tensile test to be applied for determining the strength of individual fibers. The strength derived from the breaking stress of a sheet of paper, the number of rupture fibers, and the orientation factor, is given by:

$$F = k \cdot \frac{ZS}{nAW} \qquad (1)$$

where F is the fiber strength (mN), ZS is the breaking stress of a paper sheet (mN), n is the number of fibers per unit weight obtained by using an optical analyzer (number of fibers/g), A is the active area (m^2) obtained by the project length of fibers (Lp) and the width of the sheet tested (the width of tester jaws), W is the dry basis weight of the testing strip (g/m^2), and k (4.44) is derived from the combinations of the orientation factor and possibility of fibers carrying the load. The modeling of the rupture zone of a testing strip for determining the active fibers is shown in Figure 4 and discussed in Paper II.

Based on the equation (1), the average strength of the wet long-fiber fraction was found to be approximately 100-200 mN, as shown Figure 5. This range is close to the breaking force of wood fibers measured by the straining of a single fiber [22, 23]. The proposed method allows differentiation of fiber strength under different levels of mechanical treatment. Apparently, the wet strength of fibers decreases in line with the degree of treatment. In accordance with the fundamentals of mechanical pulping, during the treatment, pulp fibers are disrupted and peeled off, resulting in reduced coarseness and strength [36, 37]. Concerning the results obtained from the typical zero-span test, it was found that zero-span tensile strength is about 80-90 Nm/g with no distinct differences between the R30 and R50 fiber fractions and gives an unclear measure of fiber strength under various degrees of refining, as shown in Figure 5 [Paper II].

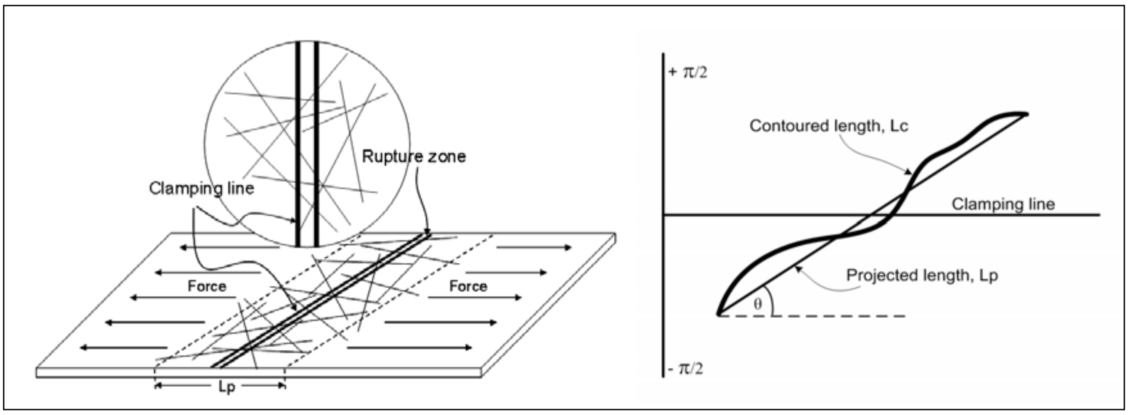

Figure 4. A model of the rupture zone of fibers under the clamp jaws of the zero-span tester [Paper II].

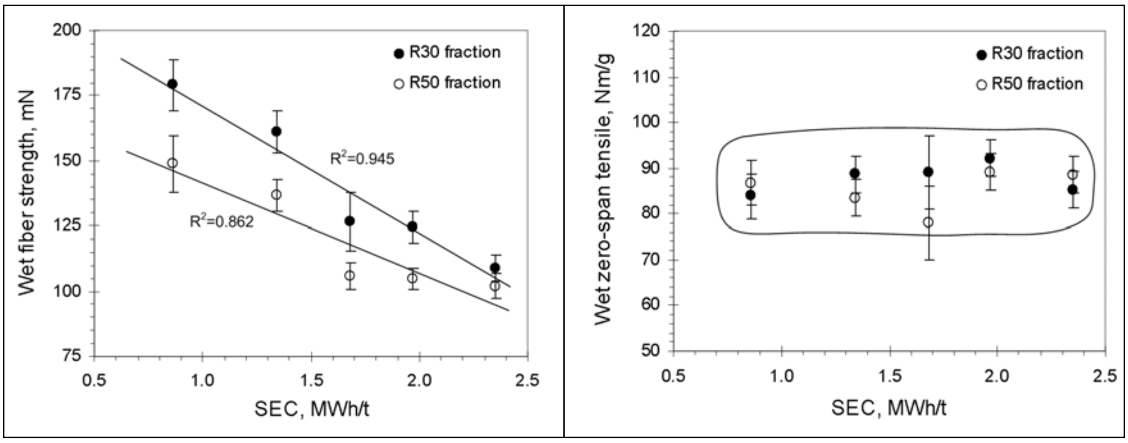

Figure 5. Strength of wet TMP fibers as a function of specific energy consumption (left). Zero-span tensile of wet TMP fibers as a function of specific energy consumption (right) [Paper II].

3. FUNDAMENTALS OF THERMOMECHANICAL PULPING

3.1 Introduction

Thermomechanical pulping (TMP) is a pulping method in which the fibers are separated from the wood matrix by means of mechanical forces at high temperature and pressure. It is typically a refiner-based process. The main tasks of the TMP process are to loosen and separate the fibers from the wood matrix, to break the fiber layer, to peel the fiber cell wall to some extent, and to fibrillate fibers to the desired quality for making paper. A typical TMP process is shown in Figure 6. Initially, wood chips are washed with hot circulation water to remove fines, sand, pieces of metal etc. Then they are fed by a plug screw feeder into a pressurized preheater at relatively low steam pressure and temperature. After steaming, the chips are fed into a refiner operated at a relatively high temperature of about 143-158 °C and a high pressure of about 300-500 kPa. Typically, the chips are defiberized and optimally treated in two refining stages to produce the desired pulp. The refining consistency is kept at about 30%. Then, the pulp is discharged into a latency removal chest designed to remove fiber curl. Finally, the pulp is screened and bleached before it is sent to a storage tower [38].

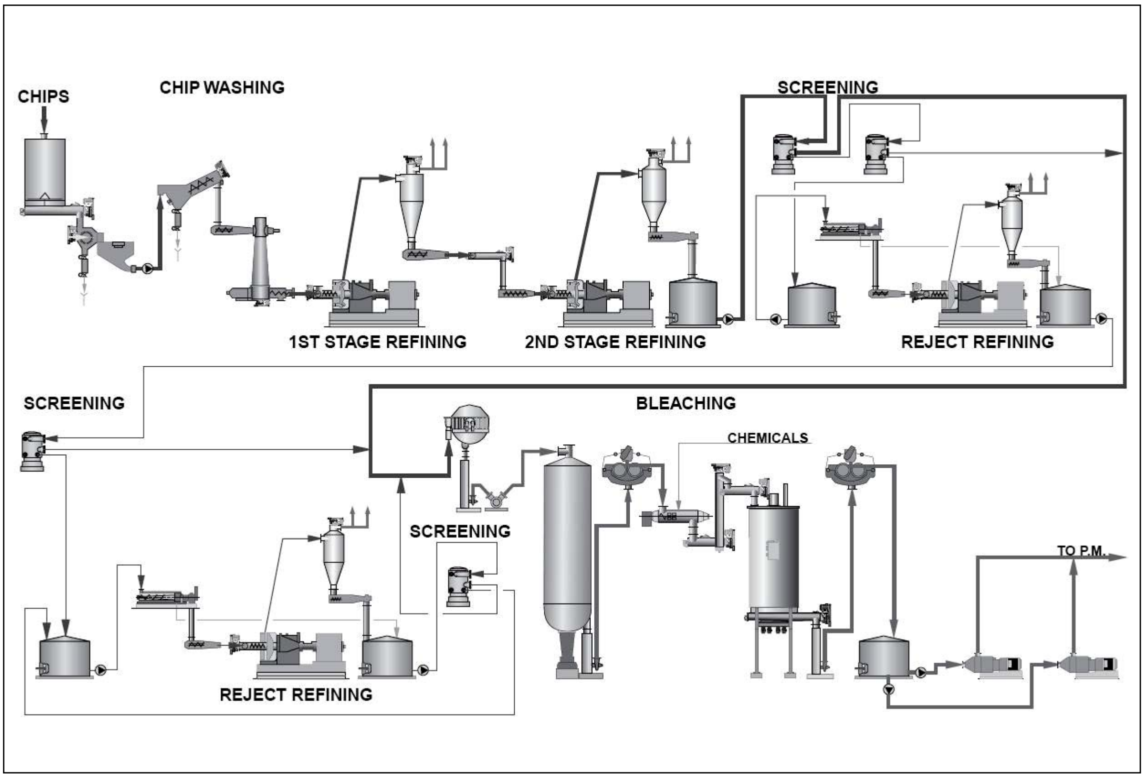

Figure 6. Flowsheet of a typical TMP plant [38].

Since the pulp quality and the energy used in the refining process are significantly influenced by the equipment and process parameters, a deeper understanding of these variables is necessary for further study of the process. In this chapter, refining mechanism and fundamental energy consumption, including process and equipment variables affecting pulp quality and energy consumption, are reviewed.

3.2 Mechanisms of thermomechanical pulp refining

In refiner-based mechanical pulping, the wood chips are fed into the narrow gaps between the rotating discs of the refiner. They are broken down into coarse fibers and developed to the required quality for papermaking, as shown in Figure 7. Generally, the pulping process can be completed in a single refiner or a two-stage refiner.

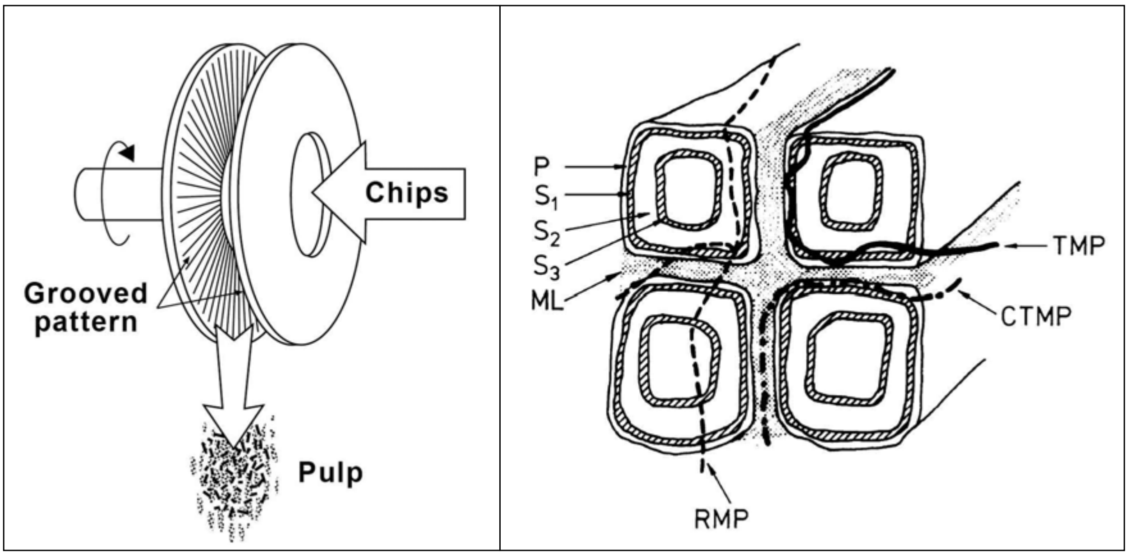

Figure 7. Principle of refiner-based mechanical pulping [38] and fracture zone of softwood in TMP refining [5].

The fundamental mechanism underlying the development of TMP fibers consists of two stages, i.e., defibration and fibrillation stages. In the defibration stage, the fibers are separated from the wood matrix. The fracture zones occur between the primary wall and secondary layer (Figure 7), which produces longer fibers. In the fibrillation stage, the coarse fibers are further developed to the desired quality, in which the outer layers are delaminated, peeled off and fibrillated to the extent necessary for papermaking [5, 37]. These refining processes consume over 90% of the total electric energy used in mechanical pulp production [5]. It has been suggested that the high energy consumption in refining is the result of inefficient work during the defibration and fibrillation stages, potentially related to the nature of the wood raw material.

The mechanical breakdown of the structure of the wood matrix in refining theoretically begins from the application of cyclic stresses to the wood matrix. The repeated viscoelastic deformation caused by cyclic stresses results in plastic deformation, which continues until the breaking point of the structure is reached. The repeated viscoelastic deformation consumes a high amount of energy without producing any development of wood fibers [5, 16, 39-41]. In addition, the friction of fibers over the refiner bars plays an important role for the energy loss. According to Sundholm [42], the friction force between the wood material and refiner bars is relatively small, resulting in the sliding of wood chips and fibers off the bars, and thus less treatment.

3.3 Control of the refining process

Refining has been characterized by two independent parameters: the amount of refining and the intensity of impact [43-45]. The amount of refining is described by the specific energy input. The intensity of impact is a measure of how harsh refining is. In low-consistency refining, the intensity is described by the specific energy per impact, e.g., specific edge load [46, 47], specific surface load [48] etc. In wood chip refining, these theories cannot be applied to control the refining process because the flows of pulp in the refiner are different. Miles and May [49-51] have introduced the intensity concept for high-consistency refining. The intensity means the rate of energy transfer into the total mass of pulp, which is calculated from the specific energy consumption and the residence time of pulp in the refining zone. The refining intensity is significantly affected by the changes in rotational speed and refining consistency [52]. Currently, there have no control systems of wood chip refining using the intensity concept. Härkönen et al. [7, 53] proposed that to apply the intensity concept for industrial uses, it requires a deeper understanding of fiber refining phenomena in a refiner plate gap. The significant phenomena, e.g., the fiber and steam flow phenomena [53, 54] and the power dissipation in the refiner plate gap [54, 55] have been studied and are being conducted to develop an industrial application.

Industrially, a common way to operate the refiners in high-consistency refining is the control of the energy input according to the target quality, e.g., the pulp freeness and the average fiber length [38, 56]. The specific energy consumption is practically manipulated by controlling the plate gap clearances. However, the other variables can also affect the energy input. Thereby, at constant specific energy consumption, various operating conditions can be created, and thus differences in pulp quality can be obtained. In a typical TMP plant with a two-stage process, the specific energy consumption in first-stage refining is controlled in the range of 0.5-1.5 MWh/t, and in second-stage refining in the range of about 1.5-2.0 MWh/t, depending on the paper grade and the raw material [38, 57, 58].

3.4 Effects of raw materials

In the production of TMP pulp, softwood species are the preferred raw material, as mentioned in Chapter 2. The structure of wood, the morphology of fibers and their chemical composition have a significant influence on the stability of the refining process, the energy consumption, and final paper quality. The quality of wood must also be good enough, including suitable wood density and moisture content, minimal decay, and a minimal content of bark and knots. The density is dependent on the wood species, maturity of wood, and the ratio of earlywood and latewood. High-density wood consisting of coarse fibers provides poorer strength properties and lower smoothness of paper, and requires more energy in refining [11, 59-64]. The moisture of wood is not critical in chip refining because it can be controlled by the washing and preheating. However, the moisture content is required to be above 30% to avoid generation of shives [11, 61]. Decayed wood lowers the brightness and strength of the paper [61]. An increase in the bark content decreases the brightness of pulp [11, 59, 61]. Knots impair the brightness and strength of paper [11, 59].

In addition to the quality of wood, the chip size distribution is also important, significantly affecting pulp quality and the refining process. Normally, chips with an average length of about 22 mm are acceptable for TMP refining. The over-size fraction normally contains a high a mount of knotwood, which disturbs feeding to the refiner, and impairs pulp quality. The over-thick fraction causes unstable refining and higher energy consumption. The pulp produced from over-thick chips normally has shorter fiber length, and lower brightness and strength properties. A high fines fraction content gives a higher shives content, shorter fiber length, lower tear strength of paper, and increased linting problem [11, 59, 61, 64].

3.5 Effects of equipment parameters

Refiners

Two main categories of industrial refiners, single- and double-disc refiners, are used in TMP refining, as shown in Figure 8. The single-disc refiner (SD) consists of a single rotating disc and a stationary stator facing the disc. The chips are normally fed into the refiner through the stator disc. Several designs of SD refiners have been developed to achieve higher production capacity and a good pulp quality, e.g., the conical disc refiner (CD) developed by the Sunds Defibrator, and the Andritz-twin refiner designed by Sprout-Waldron. The double-disc refiner (DD) has two counter-rotating discs, each driven by its own motor. The chips are fed through the spokes of one of the rotating discs into the refiner [38, 65]. The design of the refiner has an influence on the retention time of pulp in the refiner and on the orientation of fibers across the refiner bars. This affects the refining intensity [49-51], and consequently has an impact on pulp quality and the amount of energy used in the refining process. The DD refiner has higher refining intensity and produces a shorter length of fibers, but consumes less electric energy than the SD refiner [38, 66]. The CD refiner is operated at a larger gap clearance because centrifugal force transports the fibers across the bars, and it usually produces longer pulp fibers than the typical SD and the DD refiners [38, 67].

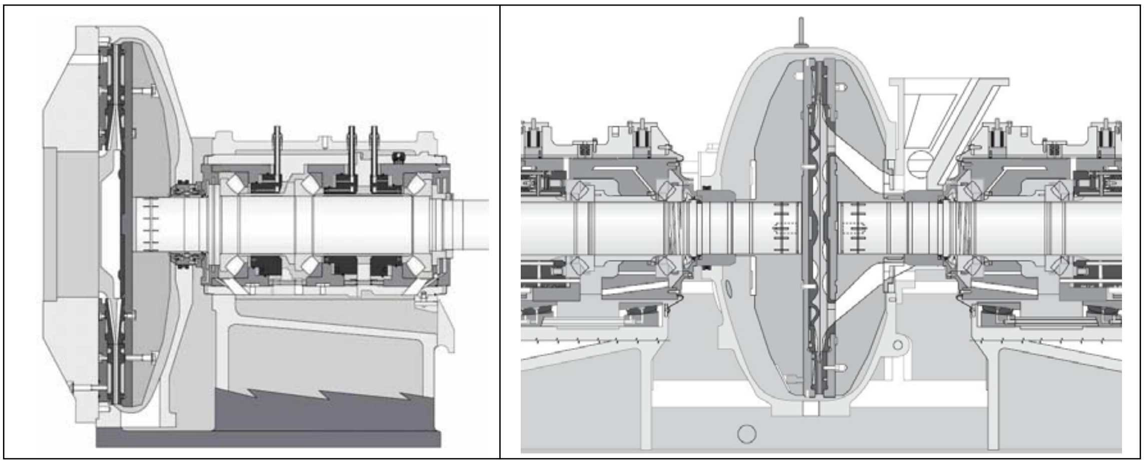

Figure 8. Single-disc refiner (left) and double-disc refiner (right) [38].

Refiner segments

The segments of refiners are vital in defibering and fibrillating fibers. Its pattern has a major influence on the dissipation of energy to the wood matrix and pulp fibers. The segments have a direct impact on pulp quality and energy consumption in refining. Basically, the refiner segments are divided into three active zones, i.e., the inlet, intermediate and refining zones, as shown in Figure 9. The inlet zone consists of breaker bars. The intermediate zone comprises wide bars and grooves. The refining zone consists of more densely spaced bars with narrower bars and grooves [38, 68].

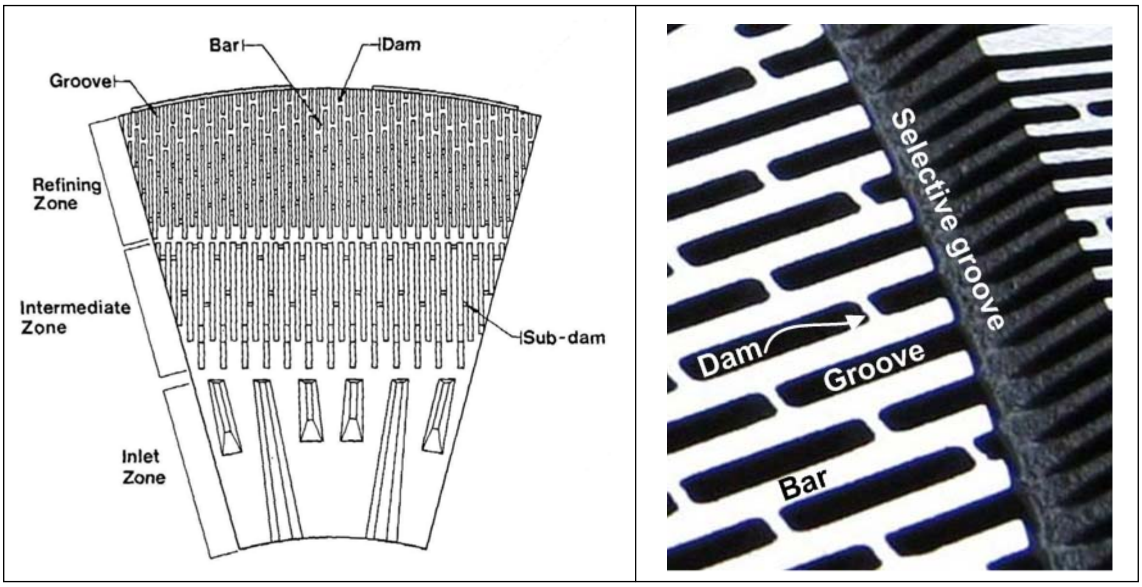

Figure 9. View of refiner segments for mechanical pulping (left) [68] and component of segments (right).

There are several designs of refiner segments, principally depending on the paper grades to be produced, the type of refiner, the position of the refiner in the pulping line and the control strategy of the paper machine. The basic design parameters for refiner segments are the width of bars and grooves, the height and angle of bars, the design and number of dams, the design of selective grooves and the taper (Figure 9). These parameters relate to the volume in the plate gap, the transportation of pulp, steam removal and refining intensity [38].

A high open volume between the plates, designed with a high bar or a wide groove with a narrow bar, allows greater steam removal and increased refining intensity, resulting in reduced energy consumption. A lower open volume, designed with a low bar height or a wide bar with a narrow groove, increases the use of energy. A too low open volume reduces the removal of steam, resulting in unstable refiner operation [8, 38]. The bar angle and dams influence the flow of pulp and steam, the residence time of pulp in the refiner, and the force applied to the pulp. Decreasing the pulp residence time allows more energy to be transferred to fibers, thus reducing the energy consumption. A selective groove on the rotor side is used to remove steam, allowing the use of segments with wider bars, narrow grooves and more dams. This can improve pulp quality without causing runability problems [8, 38]. The taper of the segment is used to compensate for possible bending of the rotating disc and to improve the feeding of chips [8, 38].

3.6 Effects of process parameters

Preheating of wood chips

Preheating of chips has been found to have a certain effect on the energy consumption in refining and on pulp quality [69, 70]. Increasing the preheating temperature and steaming time increases the energy consumption [70] and has a negative impact on pulp brightness [71]. However, it necessary to heat up the chips to avoid breaking of fibers and production of shives in the feeding and breaker bar zones. Preheating of chips is optional. Typically, preheating is performed at about 105-122 °C, and the retention time is about 1-3 min [38].

Refining consistency

The refining consistency in the plate gap is difficult to measure. Generally, it is measured at the blow line. The consistency has a significant influence on the flow and rheological property of fibers, the refining intensity, and resulting pulp quality. Theoretically, the concept of refining consistency is unclear because the moisture affects pulp quality in two opposite directions. A higher moisture content makes the wood chips and fibers less brittle producing longer pulp fibers. Contradictorily, pulp with a higher moisture content allows a faster pulp flow and shorter residence time in the plate gap. This increases the refining intensity, resulting in the shortening of fibers [38]. In practice, pulp of very high consistency flows slowly through the refiner, causing pulp burning [38]. Decreasing the consistency 50% to 38% increases refining intensity and consequently reduces energy consumption [52, 72]. The KCL reported that the optimal outlet consistency for a single stage TMP is in the range of 24-34% [38].

Refining temperature

Refining temperature generally means the steam temperature measured in the refiner housing. The refining temperature has an influence on the energy consumption in refining and on the optical and mechanical properties of pulp. Refining at a relatively high temperature has been found to give better strength properties, while causing higher energy consumption and lower light scattering of pulp [38, 69, 73, 74]. Typically, TMP refining is performed at relatively high temperature and pressure, usually at about 143-158 °C and about 300-500 kPa [38]. In some special processes, such as the thermopulp process, the temperature is kept at about 160-170 °C and refining pressure at about 600-700 kPa [75].

Refiner speed

The rotating speed of refiner dices directly impacts refining intensity, development of pulp quality, and energy consumption. Increased refiner speed causes lower energy consumption, shorter fiber length, lower tear strength and higher light scattering [51, 52, 76-78]. In normal mill conditions both single- and double-disc refiners are operated at a speed of 1500 rpm. In special processes, such as the RTS process, the refiner speed can be up to 2400 rpm [38, 76].

Production rate

A change in the production rate affects the energy consumption and pulp quality. In practice, an increase in the production rate has been found to have less effect on the gap clearance between the plates, whereas it increases the volume fraction of pulp fibers and chips in the refiner. This causes intensive refining action [79, 80]. Increasing the production rate results in faster development of pulp fibers at a given freeness, and allows lower energy consumption. However, at the same time, this produces a shorter length of fibers, a higher shives content and lower strength properties of the resulting paper [38, 79, 80].

4. LABORATORY TESTING OF GRIT APPLICATION

4.1 Introduction

Laboratory testing of grit application to TMP refining was carried out to gain a better understanding of the underlying mechanism in the development of wood fibers, which involves a combination of disruption and refining of fibers. In this study, the main aims were to examine the change in the cell wall structure of high-freeness TMP pulp fibers and their critical properties when pretreated by an abrasive material, to study how to break down the fiber cell wall efficiently, and to evaluate the potential for reducing the energy consumption.

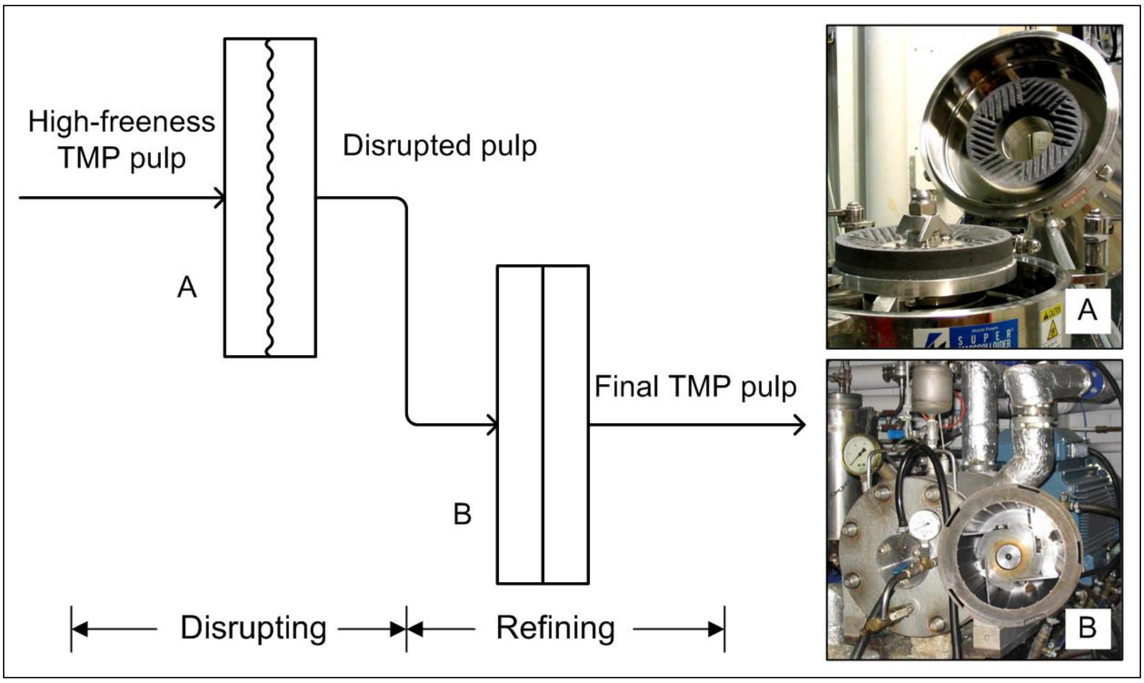

Figure 10. Experimental schematic of the treatment of high-freeness TMP with a combination of disruption and refining using an ultra-fine friction grinder (A), and a wing defibrator (B).

The raw materials were high-freeness TMP pulps, i.e., first-stage and reject TMP pulps made from Norway spruce (*Picea abies L. Karst.*). The treatment of high-freeness TMP pulps consisted of two stages, as shown in Figure 10. In the first stage, the pulp fibers were pretreated with an abrasive material to various levels of pulp freeness to examine the changes in fiber structure. In the second stage, the pretreated pulps were further refined under TMP refining conditions to evaluate the required energy, and to examine their pulp- and papermaking properties.

The grit treatment was performed using an ultra-fine friction grinder [81, 82]. The refining of disrupted pulps was carried out using a wing defibrator [83]. Pulp fibers and laboratory sheets were tested according to SCAN and ISO standards. Fiber length and coarseness were measured with a Kajaani FiberLab apparatus according to TAPPI standards. The strength of wet fibers was determined based on derivation of the breaking stress of wet paper strips at a zero span and the number of fibers bearing the load (Chapter 2). The flexibility of the long-fiber fraction was analyzed based on the hydrodynamic method [84]. The disruption of the fiber wall structure was measured based on the micropore volume in the cell wall and degree of fibrillation of fractionated fibers (R30). The micropore volume was measured using a differential scanning calorimeter based on the thermoporosimetry method with an isothermal step melting technique [85]. External fibrillation and the splitting of long fibers were analyzed with an image analysis method developed by KCL [86]. More information on this study is presented in Papers III and IV.

4.2 Grit application

The grit treatment on TMP pulp fibers was carried out using an ultra-fine friction grinder (Figure 10). The pulp slurry feed was kept at a low consistency of 4% and circulated through the grinder in several passes to achieve the target freeness. At the beginning of the study, the key process parameters of the grinder were analyzed to optimize the treatment so as to achieve fast disruption of pulp fibers, while minimizing fiber shortening. The intensity of treatment, rotational speed and grit size of the grinding stone were taken into account [Paper III].

It was found that to achieve efficient disruption of pulp fibers, with minimal shortening and weakening of pulp fibers before fibrillation, the disruption of high-freeness TMP pulp should be performed using a grinding stone with a grit diameter of 297-420 μm. The grinder should be operated at a high rotational speed of 1500 rpm and controlled to ensure a low intensity of treatment, approximately at the contact point of the stones. The testing results are shown in Figure 11, 12 and Paper III.

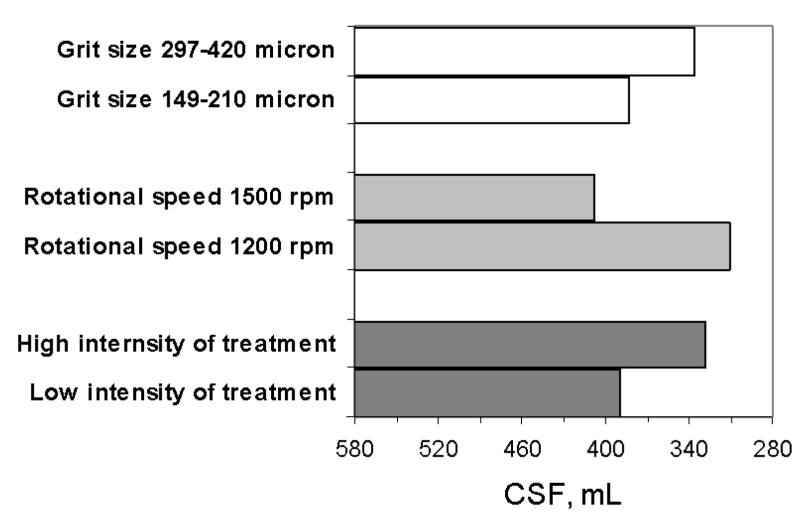

Figure 11. Average main effects [87] of disrupting intensity, rotational speed and grit size of grinding stone on pulp freeness. The raw material was first-stage TMP pulp with a freeness of 580 mL.

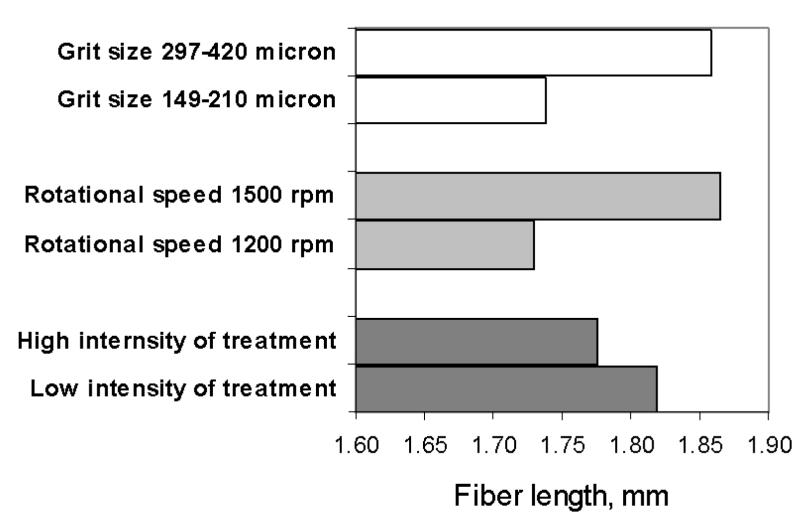

Figure 12. Average main effects [87] of disrupting intensity, rotational speed and grit size of a grinding stone on length-weighted fiber length. The raw material was first-stage TMP pulp with a fiber length of 1.96 mm.

The effects of the grit application on the properties of fibers are presented in Table 1, Papers III and IV. The treatment causes disruption of the wall structure, opening of the outer layers and peeling-off of the cell wall. When using reject TMP as a raw material, fiber length, fiber coarseness and wet fiber strength were clearly reduced [Paper IV]. However, in the treatment of first-stage TMP pulp performed in the freeness range of 580 mL to 360 mL, the average length of the whole pulp fibers did not change and the strength properties of the long-fiber fraction were not severely degraded. Figure 13 shows the surface morphology of the long-fiber fraction of first-stage TMP observed with a scanning electron microscope.

Table 1. Effects of grit treatment on first-stage TMP analyzed using the long-fiber fraction, R30. The degrees of treatment were targeted at 10, 15, and 20% of the total refining energy [Paper III].

Percentage of disrupting energy		0 %	10 %	15%	20%
Freeness*	(mL)	580	480	420	360
Fiber length*	(mm)	1.96	1.96	2.03	2.02
Pore volume	(mL/g)	0.65	0.65	0.66	0.68
Non fibrillated fibers	(%)	22	28	24	15
Fiber splitting	(%)	17	15	14	21
Fiber coarseness	(mg/m)	0.635	0.356	0.390	0.408
Fiber strength	(mN)	279	161	160	193

* Whole pulp

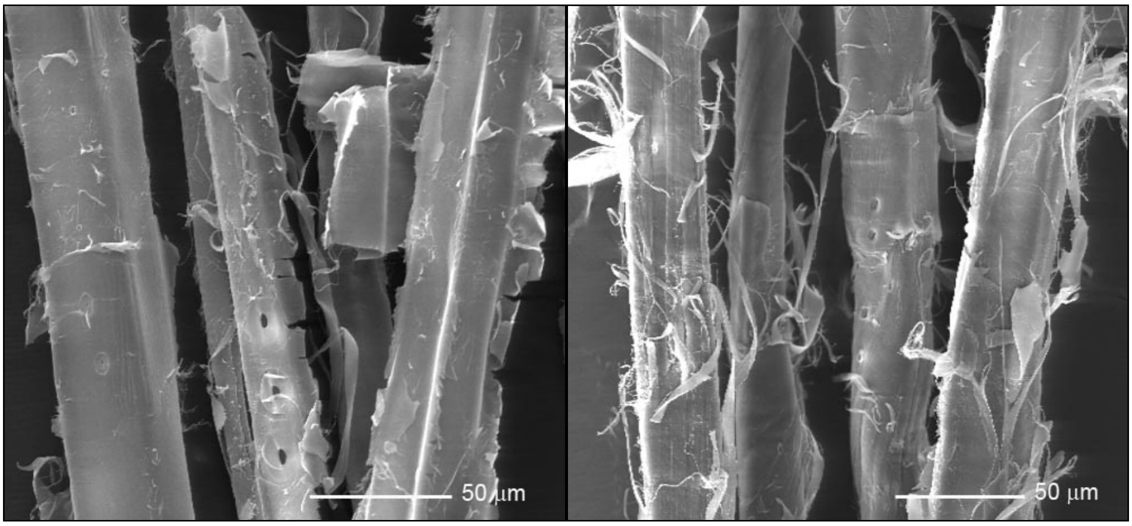

Figure 13. First-stage TMP fibers with a CSF of 580 mL (left) and disrupted pulp using a grit material with a CSF of 360 mL (right).

4.3 Refining of disrupted pulp

The refining of disrupted pulps was carried out using a wing defibrator operated under typical TMP refining conditions. The feed pulps were controlled at a consistency of 23% and a dry weight of 150 g. The peripheral speed of the defibrator was set to 750 rpm. The pulps were refined at a temperature of 130 °C without preheating and under various specific energy consumptions from 1 to 5 MWh/t. Based on the research hypothesis, disrupting and opening of the wall structure of fibers affect the development of fibers in subsequent refining. In principle, the potential for reduced energy consumption can be calculated from the differences in the slope of the trend-line of pulp freeness in the refining process, as presented in Paper IV. In addition, the energy used for disrupting and refining refiners can be taken into account in evaluating the energy reduction, as presented in Paper III.

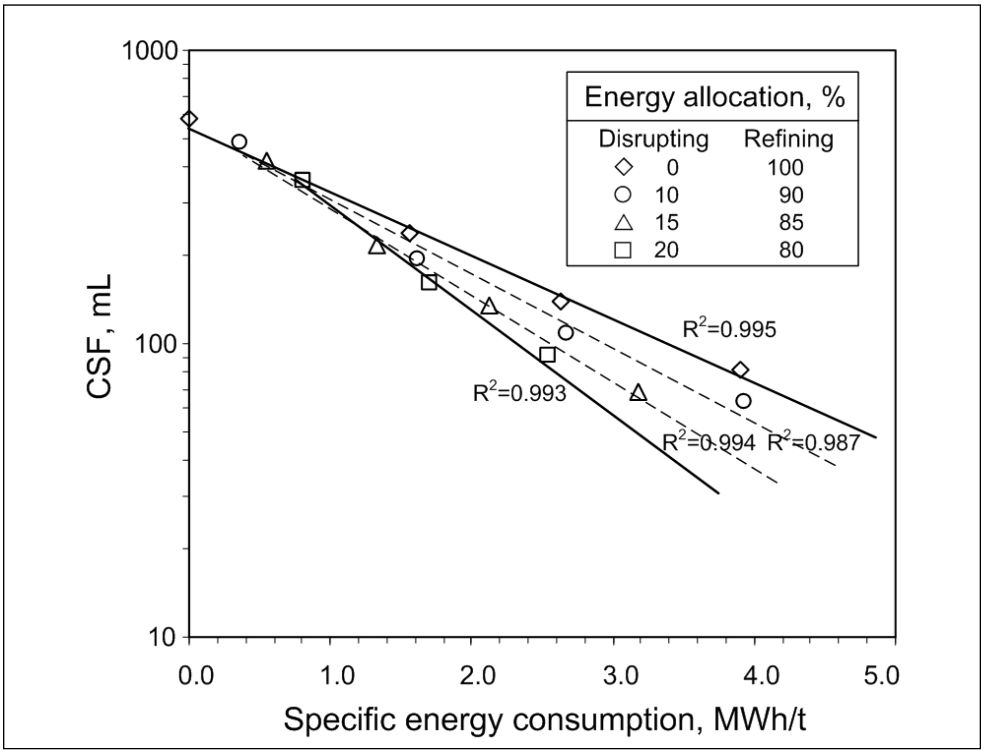

Figure 14. Freeness development as a function of specific energy consumption in the treatment of first-stage TMP, including disruption and refining.

According to the results presented in Papers III and IV, the disrupted pulp developed faster during subsequent refining, while energy consumption was reduced (Figure 14). Increased disruption of high-freeness pulp allows a greater reduction in energy consumption in subsequent refining. A high degree of disruption may cause severe shortening of fibers in refining [Paper IV], limiting the allowable degree of disruption. According to the experimental results, the pulps can be disrupted to reduce the energy consumption by up to 30% without a significant loss of pulp quality [Paper III, IV].

4.4 Pulp and paper properties

At a given pulp freeness, the disrupted pulps show a higher pore volume, indicating more loosening and disruption of the fiber wall structure. Increasing the degree of disruption of pulp fibers results in a greater disintegration of the fiber wall structure in further refining. However, the disrupted pulps have somewhat shorter fiber length than non-disrupted pulp, as shown in Figure 15.

The laboratory sheets were prepared with the whole pulp and white water circulation for testing papermaking properties. There were no significant differences in tensile strength (Figure 16) and light scattering coefficient [Papers III, IV] between disrupted and non-disrupted pulp at a given level of pulp freeness. The tear strength of disrupted pulp was somewhat lower than that of non-disrupted pulp. However, at a freeness below 100 mL, there were no significant differences in tear strength, as shown in Figure 16 [Papers III and IV].

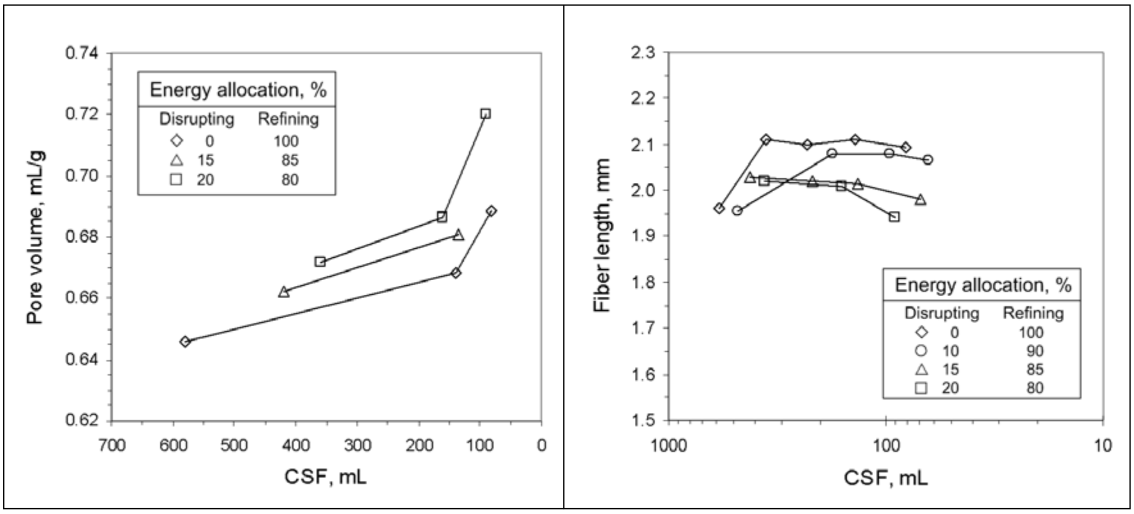

Figure 15. Micropore volume of fiber cell walls (left) and fiber length (right) as a function of pulp freeness. The raw material was first-stage TMP pretreated using grit material to various degrees of freeness and further refined to the target freeness.

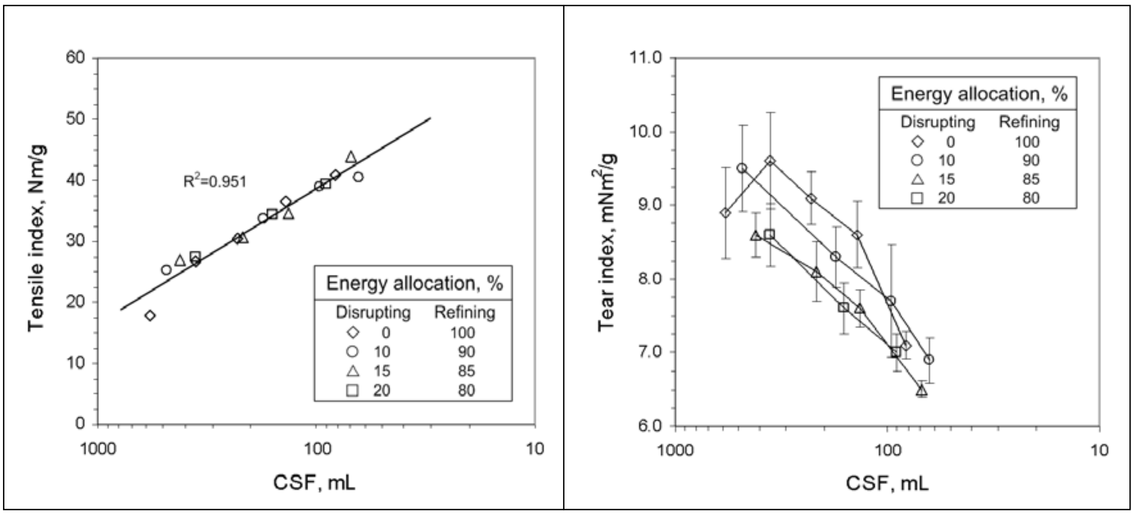

Figure 16. Tensile strength (left) and tear resistance (right) as a function of pulp freeness. The raw material was first-stage TMP pretreated using grit material to various degrees of freeness and further refined to the target freeness.

4.5 Summary

Grit treatment on high-freeness TMP with low intensity of treatment, high rotational speed and grit diameter of 297-420 μm are favorable for disrupting the pulp with minimal shortening and weakening of fibers. The disrupted pulp developed faster during subsequent refining, while energy consumption was reduced. However, a very high degree of treatment with grit material caused weakening and shortening of fibers, resulting in a possible drop in the tear strength of laboratory sheets.

The grits can be applied between the first and the second stages of TMP refining. According to the experiment with the first-stage TMP presented in Paper III, the pulps can be disrupted to reduce the energy consumption by up to 30% without a significant loss of quality.

5. SIMULATION OF GRIT APPLICATION

5.1 Introduction

In this study, a finite element analysis was conducted to gain a deeper understanding of the mechanical breakdown of the softwood fiber structure under grit treatment, taking into account the nature of the wood raw material and the TMP refining conditions. The analysis was carried out to provide a basis for further modifying the abrasive refiner segments and to optimize the conditions of the TMP refining process [Paper V].

The modeling of the softwood fiber cell wall and simulation of the fatigue behavior of softwood fibers were carried out using a finite element method with the ABACUS program. The model fiber was built from the elementary microfibrils winding around the cell axis and using the lignin as a binder. The fatigue simulation was performed under typical TMP refining conditions. The energy was directed to the model fiber through the grit material proposed to be applied on the surface of refiner segments [Chapter 6, Papers VI and VII].

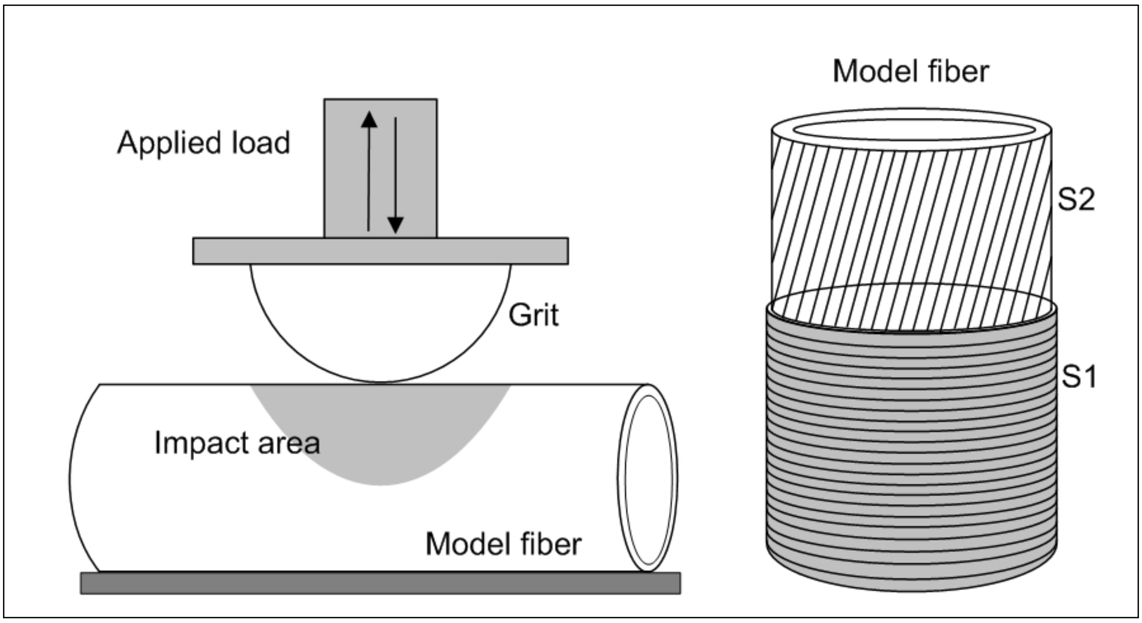

Figure 17. Model fiber and schematic of fatigue simulation under the cyclic load applied on the model fiber through the grit material [Paper V].

The structure of the cell wall was built from elementary microfibrils, proposed to have a cylindrical shape and varying orientation, embedded in a homogeneous and isotropic lignin. The constant data used for constructing the model fiber are summarized and presented in Paper V. The fiber was formed in a circular cylinder with a diameter of about 30 µm, approximately in the range of softwood tracheids. The length of a model fiber was about 2 mm. The cell wall was proposed to comprise S1 and S2 layers. The S1 layer was composed of circular microfibrils, while the S2 layer consisted of a helical orientation of microfibrils with the angle of 15°, as shown in Figure 17. The effect of the chemical composition of each layer on its mechanical properties was neglected. After the modeling, the elastic moduli of the model fiber and its S1 and S2 layers were analyzed [Paper V].

The fatigue of the softwood fiber cell wall was dynamically simulated based on the ABAQUS/Explicit code [88]. The Kelvin-Voigt viscoelastic model [89] and coupled thermal-stress analysis [88] were employed for the simulation. The amplitude of cyclic load applied to the model fibers was estimated according to experimental measurements along the radius of refiner segments [90]. The frequencies of impacts were generated by the simulation program. The data used for simulation are presented in Paper V. The cyclic stress was directed to the model fiber through hemispherical grits assumed to be applied on the surface of refiner segments [Chapter 6]. The grit size was 500 µm, approximately in the range of number 46 pulpstone grits used in groundwood mills [91]. The fatigue was assumed to take place across the model fiber (Figure 17). The relative changes in the elastic modulus affected by heat generation were based on shock wave measurement [92]. The local temperature rise due to the adiabatic heating was automatically calculated from the inelastic energy based on the simulation program, which assumed that no energy was lost in the fatigue simulation. The fatigue of the cell wall was applied for approximately 2 seconds according to the retention time of the pulp in the refiner [5]. The hysteresis response of the fiber cell wall and the changes in elastic modulus were examined.

5.2 Mechanical properties of fiber cell wall

Figure 18 shows the model fiber and its response to the applied load simulated using the ABAQUS program. Table 2 shows the elastic modulus of fiber cell walls calculated from the stress and strain curve at the middle point of each layer. The longitudinal elastic modulus of the model fiber and S2 layer were about 68-73 GN/m^2, while that of the S1 layer was about 25 GN/m^2. The transverse elastic moduli of the model fiber, and S1 and S2 layers were about 25-30 GN/m^2 [Paper V].

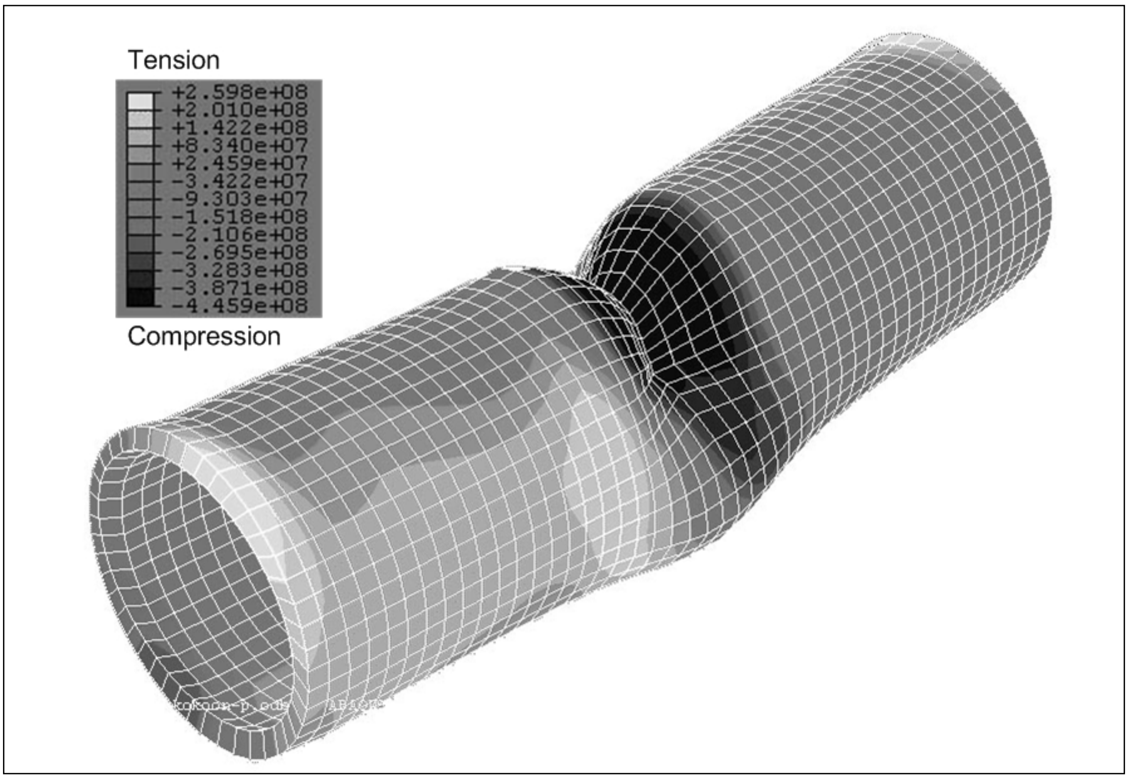

Figure 18. Local stress distribution in the wall structure under the compression load in the radius direction of the model fiber.

Table 2. Elastic modulus of the model softwood fibers calculated from the stress-strain curve.

Elements	Longitudinal elastic modulus	Transverse elastic modulus
S1 layer	24.80 GN/m^2	24.69 GN/m^2
S2 layer	73.04 GN/m^2	30.22 GN/m^2
Fiber	68.78 GN/m^2	29.76 GN/m^2

5.3 Fatigue behavior under grit application

In the fatigue simulation, the hysteresis loops of the model cell wall under the cyclic compression were used to calculate the changes in elastic modulus and examine the fatigue behavior of the fiber cell wall (Figure 19). The reduction of the elastic modulus was proposed to indicate the potential for breaking down the fiber wall structure in the refining process.

The dynamic changes in the modulus of the S1 and S2 layers under various frequencies of applied cyclic load are shown in Figure 20. The elastic modulus of the model fiber was significantly affected by the frequency of impacts. Based on the ABAQUS program, when increasing the impact frequency of the grits applied on the model fiber from 25 to 100 cycles/second, the calculated instantaneous elastic modulus of the wall structure was found to be higher by about 10-15 GN/m^2. This clearly shows that the fiber cell wall becomes stiffer at higher impact frequency. However, this condition allowed fast reduction of cell wall strength, indicating that efficient breakdown of the wall structure could be achieved. In addition, the impact frequency was found to play a more important role in the reduction of the elastic modulus, where the fatigue was applied under a lower amplitude of applied load.

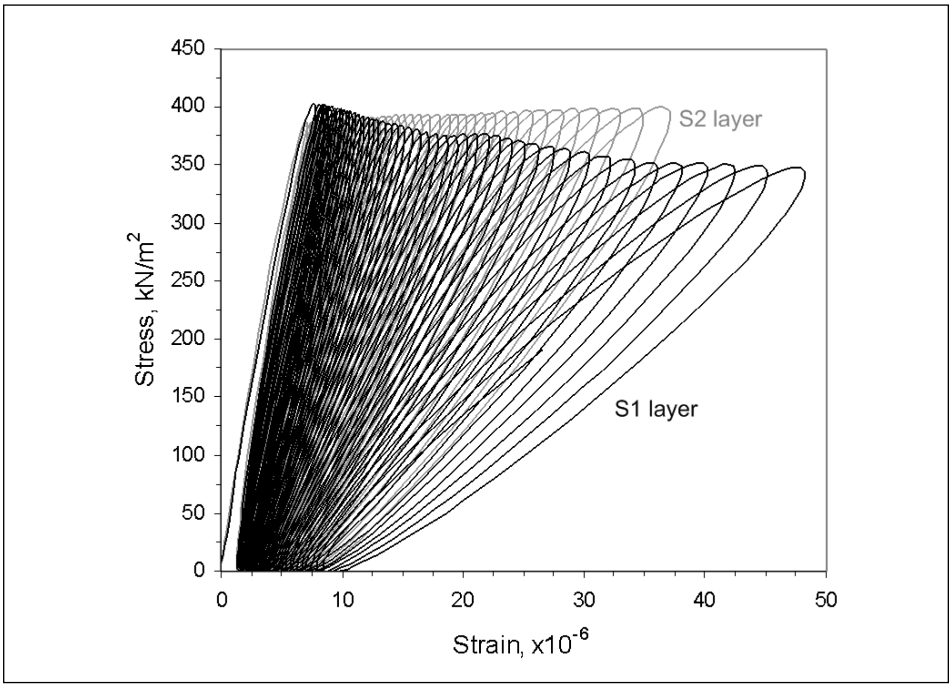

Figure 19. Hysteresis loops of the S1 and S2 layers under a cyclic compression of 150 kN/m^2 and an impact frequency of 25 cycles/second.

The effects of the amplitudes of applied loads on the changes in the modulus of the cell wall treated by the grit are shown in Figure 21. The applied loads were simulated at 50, 100 and 150 kN/m^2 along the radius of segments. There were clear differences in the effect of the grit treatment between the inner zone and outer zone of refiner segments on the fatigue of the cell wall. The inner zone of segments with the applied load of 50 kN/m^2 yielded a significantly lower reduction of the modulus in comparison to the outer zone with the applied load of 150 kN/m^2. However, when the fatigue was simulated at a higher frequency of impact there were smaller differences in the effect of the grit treatment in the segment zone.

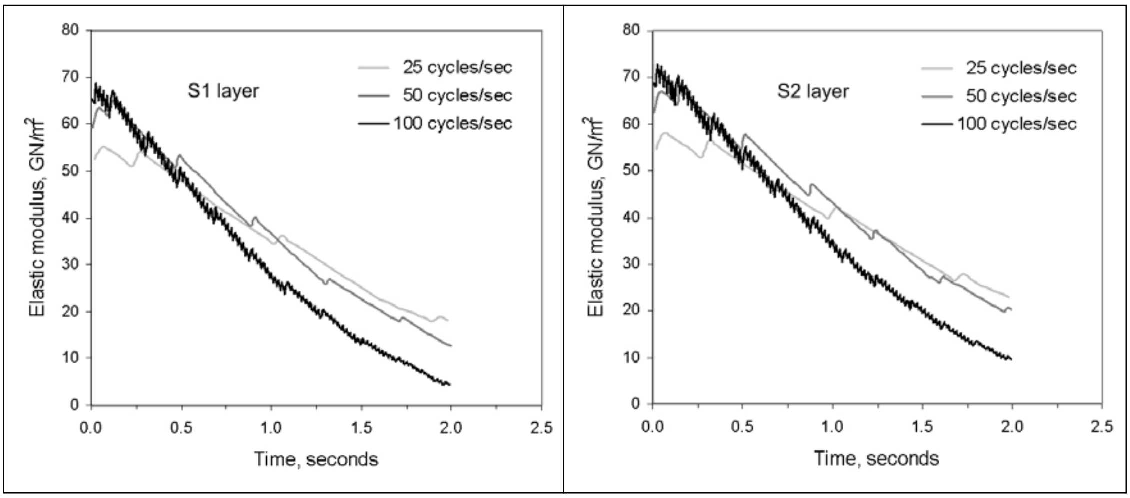

Figure 20. Dynamic transverse elastic modulus of S1 and S2 layers during fatigue simulation under a compression of 100 kN/m^2 and various impact frequencies.

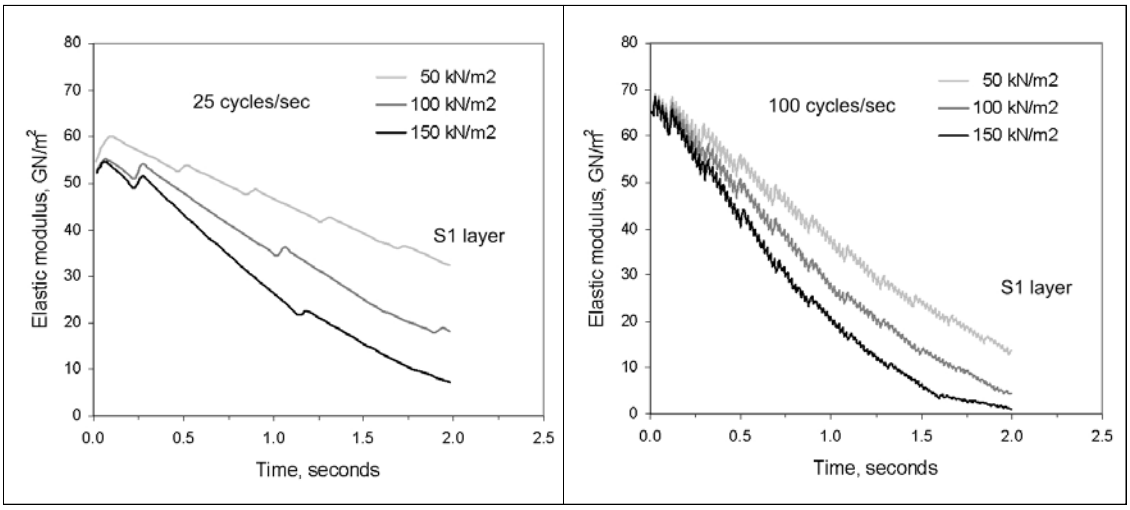

Figure 21. Dynamic transverse elastic modulus of S1 layer during fatigue simulation under various levels of applied compression. Impact frequencies were controlled at 25 cycles/second (left) and 100 cycles/second (right).

5.4 Summary

Based on the simulated results, the inner S2 layer dominantly controls the mechanical properties of wood fibers. This implies that the breakdown of the S1 layer and partly the S2 layers can be achieved with less negative impact on the strength properties of the pulp fibers. In the simulation of grit treatment, an increase in the applied load and impact frequency has a positive impact on the reduction of the elastic modulus of the fiber cell wall, indicating improved potential for disrupting the wall structure. An increase in impact frequency increases the elastic modulus of the cell wall at the beginning of the forces applied on the model fiber, but allows faster reduction of the modulus under fatigue. When a lower force was applied to the model fibers, a higher impact frequency was required to improve the potential for mechanical breakdown of the fiber cell wall.

6. INDUSTRIAL APPLICATION OF GRITS IN THERMOMECHANICAL PULPING

6.1 Introduction

According to laboratory work and the simulation presented in Chapter 4 and 5, it is possible to increase the disruption of pulp fibers and reduce the energy consumption in TMP refining by using grit treatment. In this chapter, a practical application of grit treatment for industrial use is presented. The research consisted of a modification of refiner segments and trials at pilot scale. The modification of segment having grits on their surfaces was carried out using laser coating technology [93]. The gritting process was carried out in cooperation between the Helsinki University of Technology, Tampere University of Technology and Metso Paper. LE-segments (RG4202) [8] manufactured by Metso Paper were used as the base segments. The experiments consisted of two trials, i.e., analyzing the process parameters of the refiner performed with grit segments [Paper VI] and evaluating the potential for reducing energy consumption [Paper VII]. The trials were performed in the pilot TMP plant at the Finnish Pulp and Paper Research Institute (KCL).

6.2 Reinventing grit segments

Grit materials are the small particles made from aluminum oxide and silicon carbide used in the manufacture of the groundwood pulpstones for surface sharpening [91]. In this research, the grits are the hemispherically composite materials consisting of the small grits and the holder formed on the surface of refiner segments. The design of the grits on the segments is shown in Figure 22. The gritting was made at the inner zone of the segments. This zone has a steeper taper, allowing a proper gap clearance between the rotor and stator sides to prevent contact between the grits. The grits were placed in the middle of each bar in a radial direction arranged in a zigzag pattern to allow more grits to be added. The grits were made from self-fluxing tungsten-carbide powder (diameter of 44-88 μm) and Ni-base alloy powder, which were laser-cladded onto the surfaces of the segment bars. The grit was shaped as a flat hemisphere, with a diameter of 500 μm and a height of 300 μm. The distance between adjacent grits is 300 μm.

The gritting process on the surface of segments, which was performed using a computer-controlled robot, is shown in Figure 23. The cladding materials were sprayed with a carrier gas into a laser beam targeted to the cladding position. When the cladding materials absorbed the energy, they were melted and attached on the base segments. The surface of the base segment at the attachment point was also melted by the laser beam, thus enabling a very strong adhesion. The grit segment with the LE segment base is shown in Figure 24.

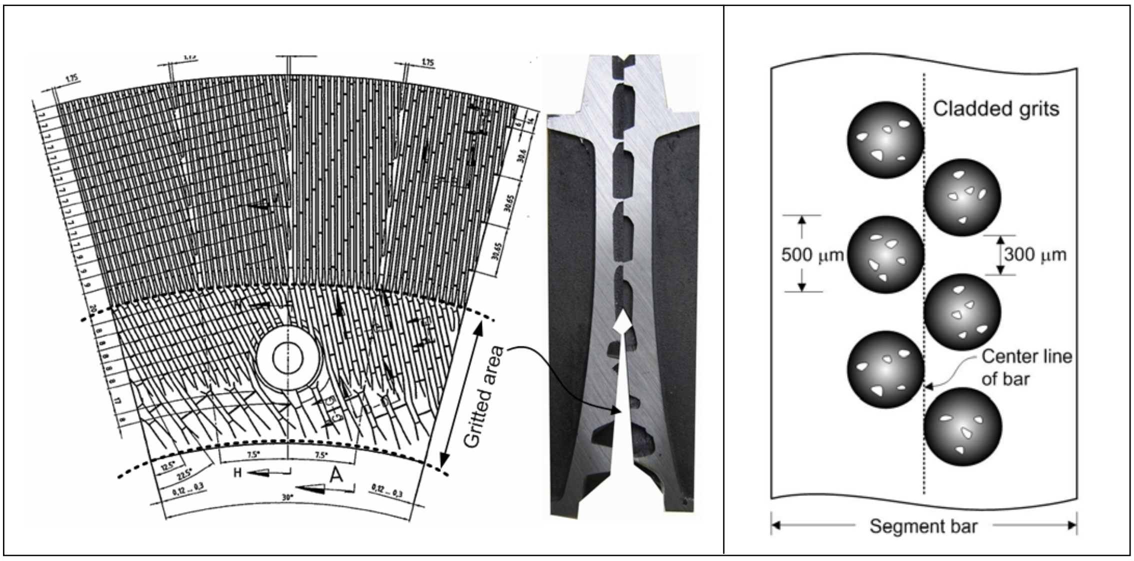

Figure 22. Gritted area of base segments (left) and configuration of the grits on the bars of base segments (right).

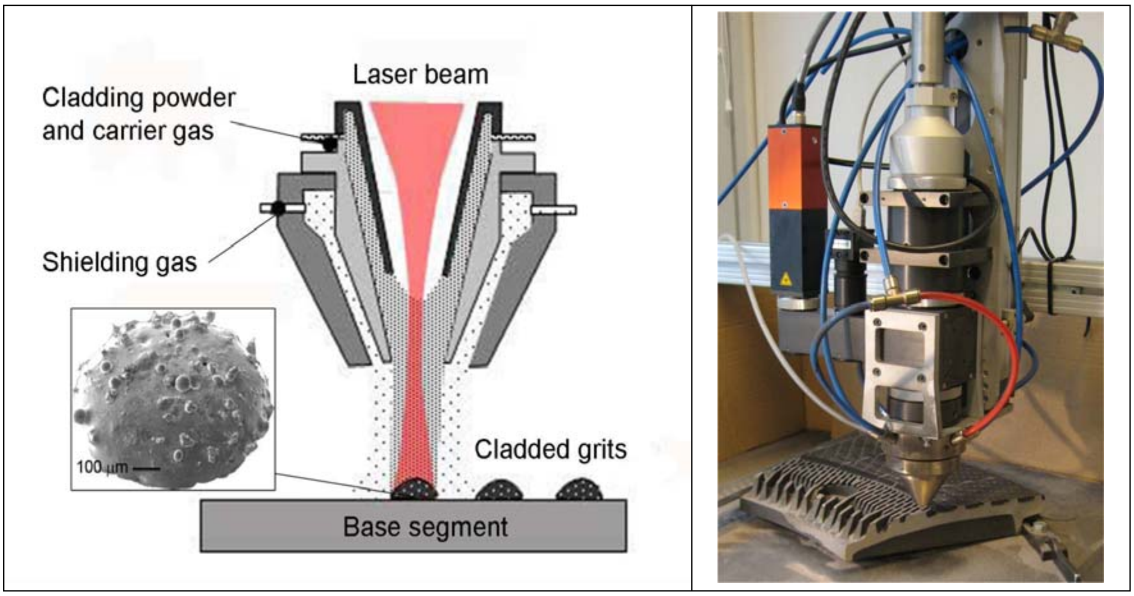

Figure 23. Laser cladding process (left) and equipment specially constructed for the gritting process (right).

6.3 Raw material

The raw material was fresh chips made from Norway spruce *(Picea abies L. Karst.)*. The average basic density of the chips was 358 kg/m^3. Their dry solids content was 51.1%. The chip size distribution was analyzed according to SCAN-CM 40:01. The accept fraction was 82.7% of the total dry weight, the coarse fraction 14% and the fine fraction 3.3%. The length-weighted fiber length of macerated fibers was 2.54 mm.

6.4 Process conditions of grit segments

According to the hypothesis, the grit segments were proposed to be applied in the first stage of refining where the key process parameters were optimized. The trial with grit segments was performed on a Sunds Defibrator RGP44 single-disc refiner. The grit segments were mounted on the first-stage refiner, both on the rotor and stator sides. The key process parameters of the first-stage refiner, i.e., peripheral speed, refining pressure and specific energy consumption, were optimized. The peripheral speed was tested at 1200, 1500 and 2400 rpm. The refining pressure was 100, 300 and 500 kPa, corresponding to a saturated steam temperature 120, 143, 150 °C, respectively. The specific energy input was controlled incrementally from 0.8 to 1.5 MWh/t. The chip feed was preheated under a pressure of 150 kPa with a steaming time of 45 seconds. The pulp was discharged at a consistency of 30%.

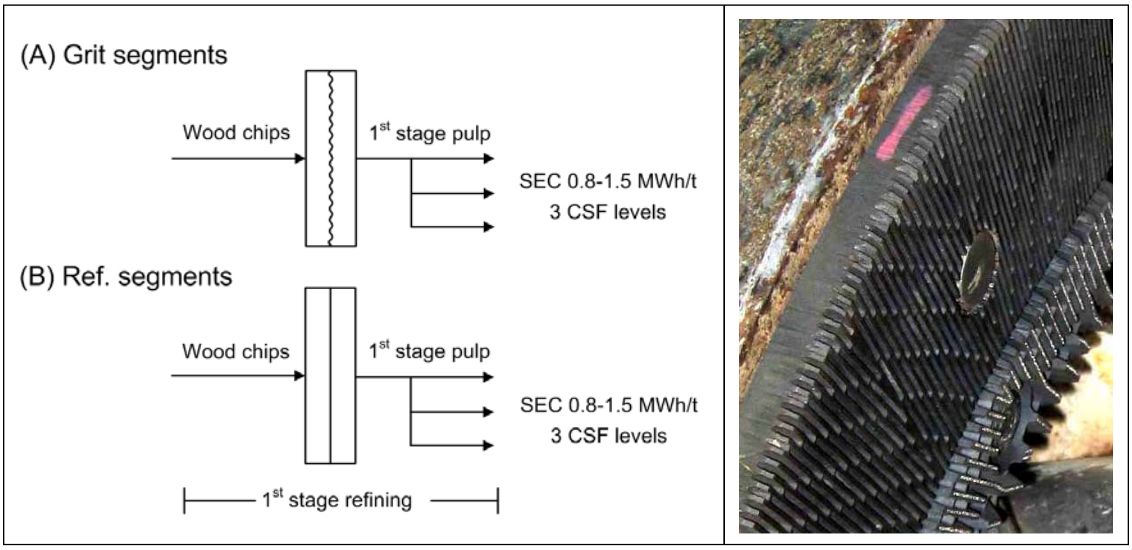

Figure 24. Experimental schematic of refining trials with grit and reference segments in the first-stage TMP refining (left). Grit segment-LE segment base (right).

At high rotational speed the grit segments were found to produce fast development of freeness, while resulting in a shorter fiber length and causing a faster drop in fiber length at an energy input above 1.3 MWh/t (Figure 25). At a high rotational speed of 2400 rpm the refiner equipped with grit segments produced pulp with a higher degree of disrupted fibers than the refiner with the reference segments, which is indicated by the flexibility of fibers and the pore volume of cell the wall, as shown in Figure 26 [Paper VI].

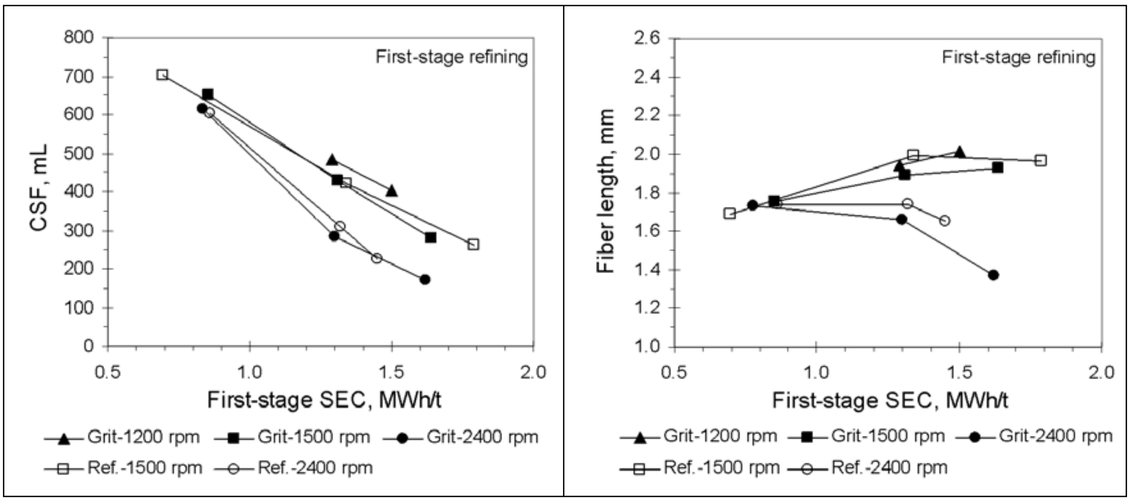

Figure 25. Development of pulp freeness (left) and length-weighted fiber length (right) as a function of specific energy consumption in first-stage refining.

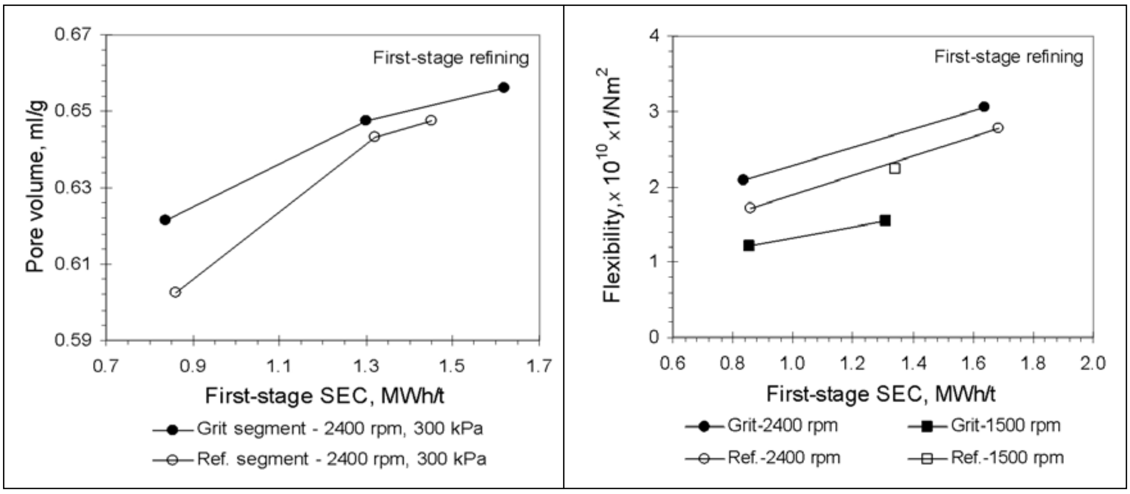

Figure 26. Pore volume of fiber cell walls (left) and fiber flexibility (right) as a function of specific energy consumption in first-stage refining (left).

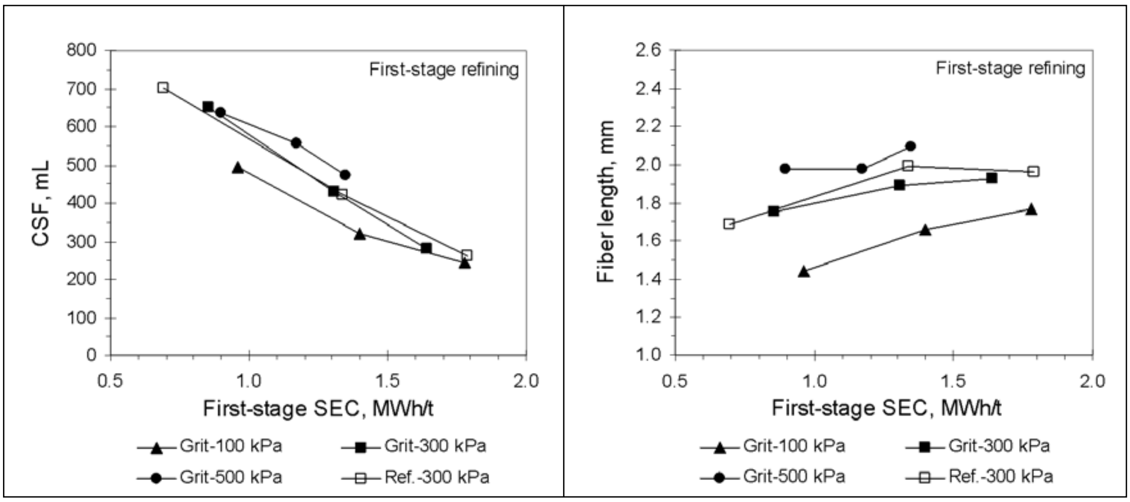

Figure 27. Development of pulp freeness (left) and length-weighted fiber length (right) as a function of specific energy consumption in first-stage refining. The refiner was equipped with grit and reference segments and controlled under various levels of refining pressures.

Figure 27 shows the effect of refining pressure on the development of pulp freeness and fiber length. Refining at a lower pressure was found to produce faster development of freeness. At the typical refining pressure of 300 kPa, there were no distinct differences in the development of pulp freeness and fiber length between the grit and reference segments [Paper VI].

According to the results, to increase the disruption and opening of fiber cell walls while maintaining fiber length, the first-stage refiner should be operated at a high rotational speed of 2400 rpm and a pressure of 300 kPa, while the specific energy consumption should be kept in the range 0.8-1.3 MWh/t [Paper VI].

6.5 Effect of grit segments on the refiner operation

According to the trials, a Sunds Defibrator RGP44 single-disc refiner equipped with grit segments can be loaded up to a specific energy consumption of 1.8 MWh/t and a production rate of 550 kg/h, which is equal to that of the reference segments. There was no grit contact between the rotor and stator during zero-position calibration and refining. At rotational speeds of 1500 and 2400 rpm, the plate equipped with grit segments required a wider gap to maintain the desired level of specific energy. However, at an energy consumption above 1.5 MWh/t, there were no differences. In addition, when comparing the gap clearances at a given pulp freeness, it was found that the grit segments have a wider gap to produce pulp at the desired freeness level, as shown in Figure 28.

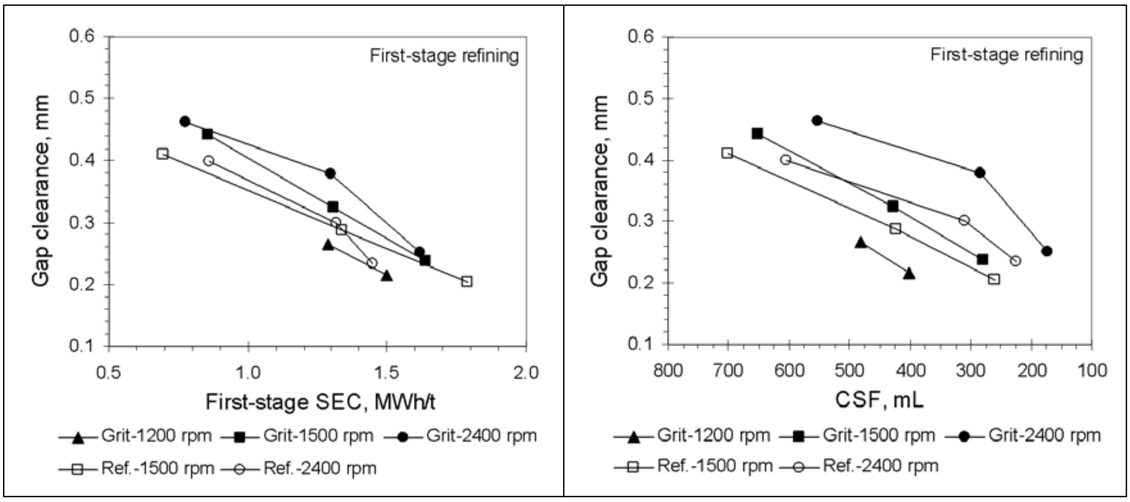

Figure 28. Plate clearance of first-stage refiner equipped with grit and reference segments operated under various levels of rotational speeds as a function of specific energy consumption (left) and pulp freeness (right).

6.6 Potential for reducing energy consumption

To evaluate the potential for reducing energy consumption, the refining was carried out with a two-stage refining process using a Sunds Defibrator RGP44 refiner. An experimental schematic and the operating conditions in TMP refining with a combination of grit and reference segments are presented in Figure 29 and Paper VII.

In first-stage refining, the refiner was equipped with grit segments on both the rotor and stator sides and the refining was performed under optimized conditions (Chapter 6.4) and typical mill conditions. In optimized conditions, the refiner was operated at a rotational speed of 2400 rpm, a refining pressure of 300 kPa and a total specific energy consumption between 0.8 and 1.3 MWh/t. In normal mill conditions, the rotational speed was 1500 rpm. The refining pressure and specific energy consumption were similar to the optimized conditions. The raw material was fresh chips made from Norway spruce *(Picea abies L. Karst.)*. The chip feed was preheated under a pressure of 150 kPa with a steaming time of 45 seconds. The pulp was discharged at a consistency of 30%.

The second-stage refining was carried out with reference segments, LE-segment (RG 4202), and controlled to maintain constant conditions. The refiner was operated at speed of 1500 rpm. The refining pressure was 300 kPa. The total specific energy was raised in equal increments from 1 to 3 MWh/t. The consistency of the discharged pulp was controlled at 30%. Pulp samples were taken for testing fiber and paper properties. The potential for reducing the energy consumption was evaluated at a given pulp freeness.

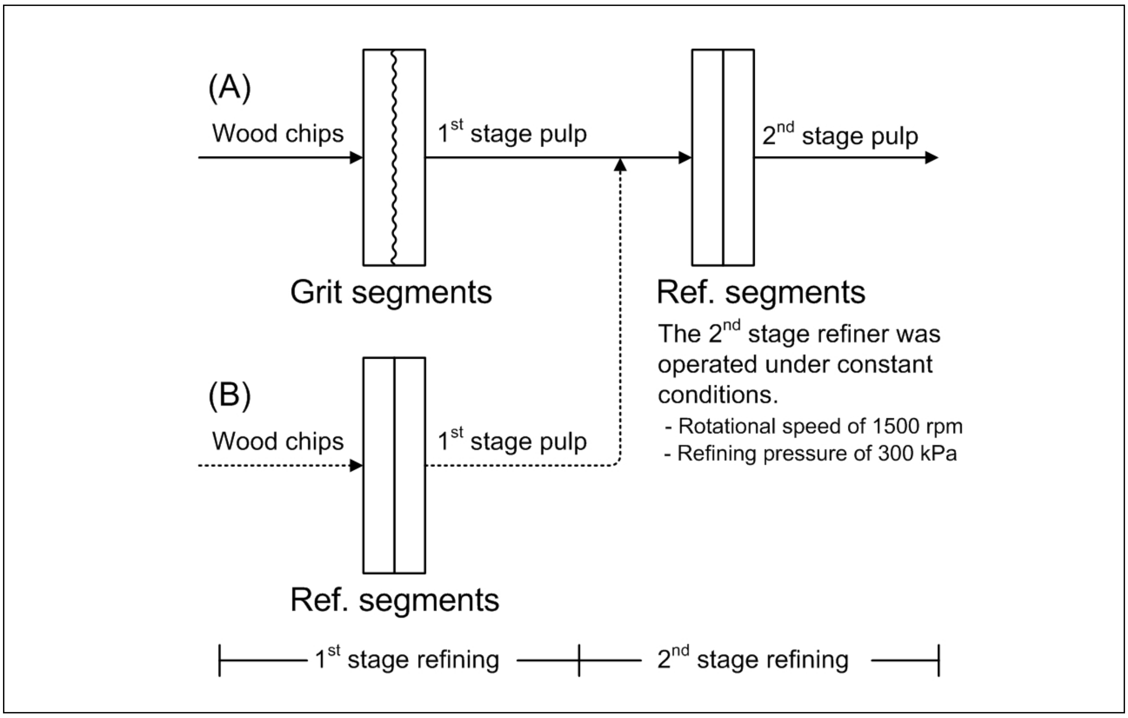

Figure 29. Experimental schematic of TMP refining trials with grit segments (A) and reference segments (B).

The results showed that in optimized conditions the first-stage pulp refined with grit segments at a rotational speed of 2400 rpm reached its target freeness faster in second-stage refining, while requiring less energy, as shown in Figure 30. The potential for reducing the energy consumption was calculated at a CSF of 50 mL, which is generally used for SC or LWC paper [94, 95]. It was found that the energy used in refining can be reduced by at least 10% compared to refining with the reference segments. In normal mill conditions, the first-stage refiner was operated at a rotational speed of 1500 rpm. The results showed that there were no differences in total energy consumption in developing the pulp to a certain level of freeness.

Figure 31 shows that when using grit segments, both increasing the rotational speed from 1500 to 2400 rpm and increasing the energy input from 0.8 to 1.3 MWh/t promote the development of pulp freeness in second-stage refining. However, the rotational speed has a greater effect on the energy reduction when refining with grit segments.

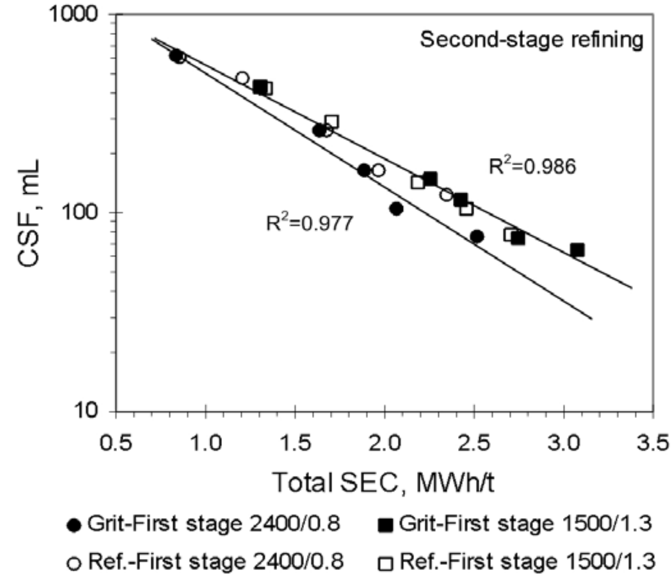

Figure 30. Development of pulp freeness in second-stage refining as a function of total specific energy consumption.

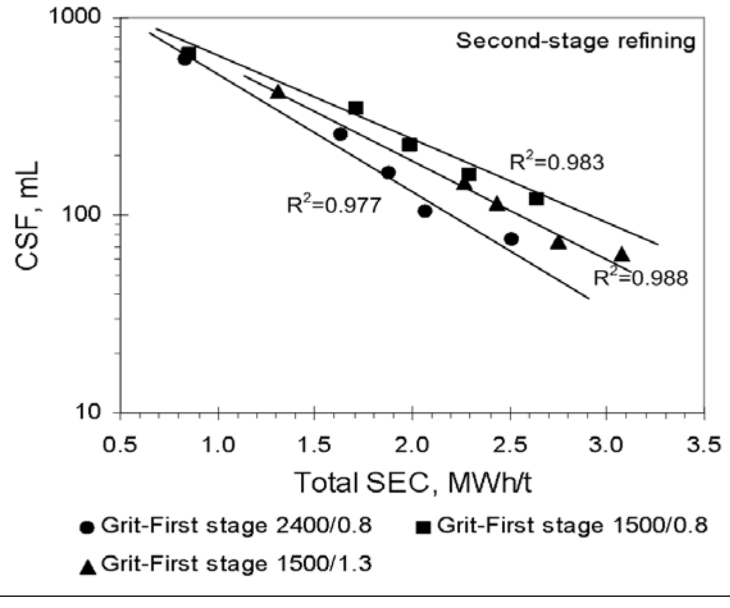

Figure 31. Development of pulp freeness in second-stage refining as a function of total specific energy consumption. Comparison between grit segments in refining performed at various operating conditions in the first stage.

6.7 Pulp and paper properties

The fiber length and shives content at a given pulp freeness are shown in Figure 32. The fiber length and shives content are not affected by the segments but they are dependent on the operating conditions. When the speed was increased from 1500 rpm to 2400 rpm, the fiber length was reduced by about 0.2 mm and the shives content increased by about 1%, when examined at a CSF of 50 ml. Figure 33 shows the degree of disruption of the fiber cell wall indicated by the pore volume in its structure, and the strength of wet fibers in second-stage refining. At a rotational speed of 2400 rpm, grit segments produced a higher pore volume in fiber cell walls in second-stage refining than the reference segments. Under these operating conditions, there were no distinct differences in fiber strength properties between the segments in relation to the degree of refining. This indicates that the grit segments produce more broken fiber cell walls, but do not weaken or cause severe shortening of pulp fibers.

The effect of segment types and operating conditions on tensile strength is shown in Figure 34. The tensile strength of the final pulp was found to increase when the first-stage refining was performed with grit segments using a rotational speed of 2400 rpm and a SEC of 0.8 MWh/t, and when using a rotational speed of 1500 rpm and a SEC of 1.3 MWh/t. This shows that the grit segments can produce pulp to the desired level of tensile strength with lower energy consumption. However, when compared at a given freeness, there were no differences in tensile strength between the pulps produced with different segments and under different operating conditions.

Figure 35 shows tear strength and light scattering of laboratory sheets. The tear strength was less affected by the segment type. It was somewhat lower under the operating condition at high rotational speed of 2400 rpm. However, at a CSF below 100 mL, there were no distinct differences. The light scattering coefficient was not affected when using different segments between the grit and reference segments and different operating conditions.

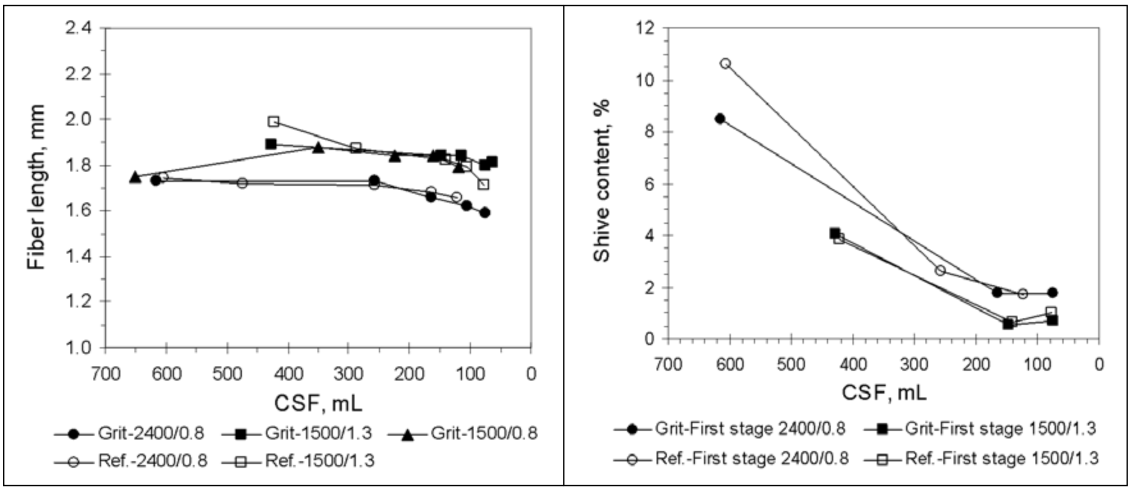

Figure 32. Fiber length (left) and shives content (right) as a function of pulp freeness.

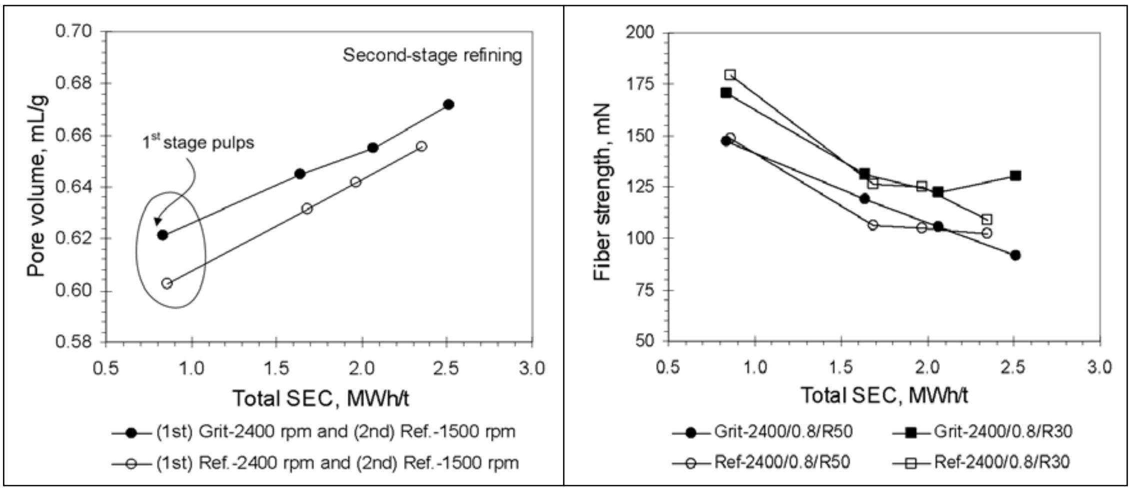

Figure 33. Pore volume (left) and strength of wet fibers (right) as a function of total specific energy consumption.

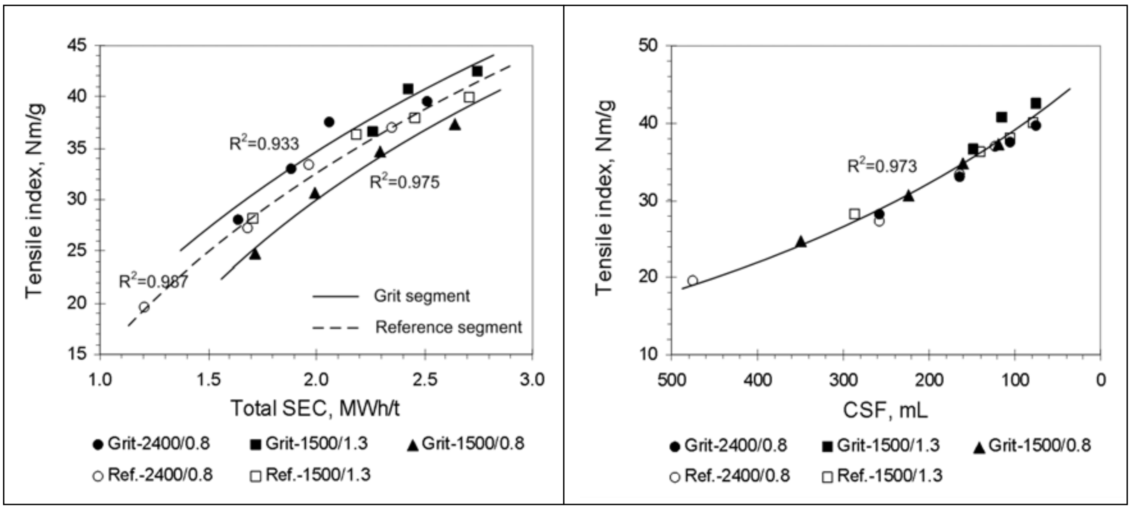

Figure 34. Tensile strength of laboratory sheets as a function of total specific energy consumption (left) and pulp freeness (right).

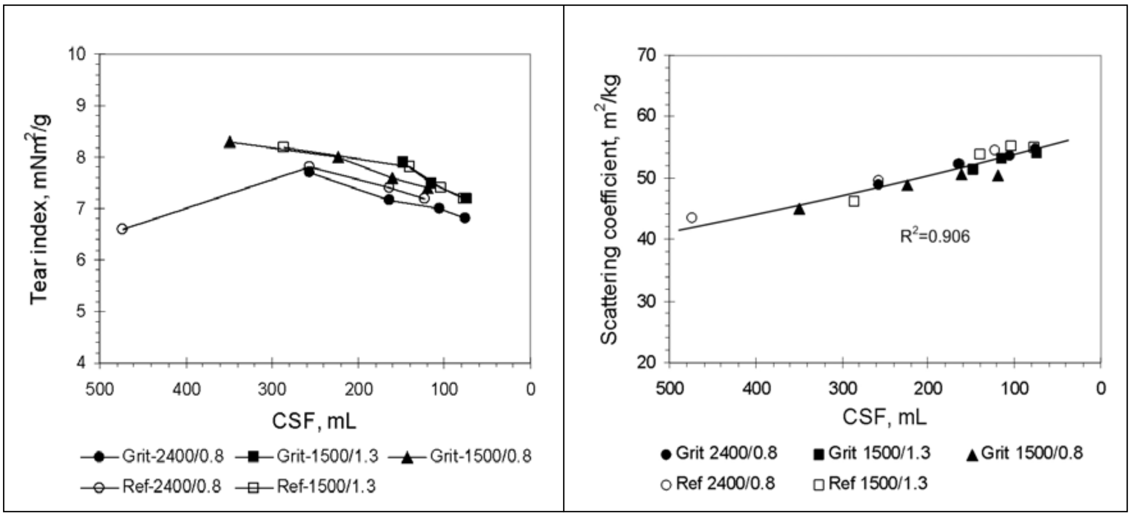

Figure 35. Tear strength (left) and light scattering coefficient (right) of laboratory sheets as a function of pulp freeness.

6.8 Summary

Gritting on refiner segments can be made by using laser cladding technology. Grit segments can disrupt fiber cell walls efficiently and allow a lower energy consumption, depending on the operating conditions. The application of grit segments in first-stage TMP refining at high rotational speed, followed by treatment with base segments operated under normal mill conditions, can reduce the energy consumption by at least 10%, with minimal negative impacts on pulp and paper properties.

7. CONCLUSIONS

The aim of this research was to develop a mechanical pulping process which consumes less electrical energy, while producing good-quality pulp. The research was carried out based on the hypothesis that increasing the disruption and opening of the fiber wall structure during the defibration stage by applying grit material would promote the development of pulp fibers in the fibrillation stage and thus reduce energy consumption. In this study, the focus was on the application of grit treatment to TMP refining and the reinvention of refiner segments with grits on their surfaces to enhance breaking of the fiber cell wall. The study comprises tests at laboratory scale and development of an application for industrial, including trials at pilot scale.

In the laboratory study, the grit application was tested in low-consistency grinding. High-freeness TMP pulps were used as a raw material. The pulps were pretreated by the grit material and further refined at a typical TMP process. The results showed that the grit application causes disruption of the wall structure, opening of the outer layers and peeling-off of the cell wall. An efficient disruption of high-freeness TMP pulps, with minimal shortening and weakening of fibers, should be performed using a grinding stone with a grit diameter of 297-420 μm, and operated at a high rotational speed and a low intensity of treatment. The disrupted pulp developed faster during subsequent refining, while energy consumption was reduced. In tests with reject TMP pulp, the pretreatment with grit material caused weakening and shortening of fibers, resulting in a drop in tear strength. Experiments using first-stage TMP pulp as raw material showed that the pulp fibers can be disrupted to reduce the energy consumption by up to 30% without a significant loss of quality.

In developing a practical application, reinvention of refiner segments having the grits on the surfaces and the pilot trial of girt segments were carried out. The gritting process was carried out using a laser-cladding method. The grit segments were tested on the first-stage refiner operated under TMP conditions. The results showed smooth operation of the refiner without any adverse effects on the motor load and pulp feeding system. When operated at a higher rotational speed of 2400 rpm, the refiner performed well with the grit segments, producing higher disruption of the fiber cell wall than refining with the reference segments. The strength of long fibers was found not to be affected by grit segments. However, the grit segments, operated at a high rotational speed and an energy input above 1.3 MWh/t, produced shorter fibers and caused a faster drop in fiber length. To increase the disruption and open the fiber cell walls and maintain the fiber length, the first-stage refiner equipped with the grit segments should be operated at a high rotational speed of 2400 rpm and a pressure of 300 kPa, and the specific energy consumption should be kept in the range 0.8-1.3 MWh/t.

The application of grit segments in first-stage TMP refining at high rotational speed, followed by treatment with reference segments performed under normal mill conditions, can reduce the total energy consumption by at least 10% with minimal negative impacts on pulp and paper properties. A reduction in energy consumption appears to be possible at high rotational speed, but great care should be taken to minimize the shortening of fibers and the lowering in tear strength.

Recommendations for future work

According to the findings of this work, the performance of the grit segments in breaking down the fiber cell wall is significantly influenced by the dimensions of the grits, the operating conditions of the refiner and the positioning of the grits along the radius of the segment. The grit segments, for example, the grit geometry and the positioning of the grits, including optimization of the refining process, should be developed further. Moreover, mill-scale trials with the grit segments over a longer operating period should be performed to evaluate their service life and suitability for industrial use.

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ISBN (printed) 978-951-22-9750-4
ISSN (printed) 1797-4496
ISBN (PDF) 978-951-22-9751-1
ISSN (PDF) 1797-5093
Yliopistopaino, Helsinki 2009