Designing grinding tools to control and understand fibre release in groundwood pulping

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Abstract


Mechanical pulping is a very energy demanding process in which only a fraction of the energy is used for the actual separation of wood fibres. The rest of the energy is lost, partly in damaging already separated fibres and partly as heat during viscoelastic deformation of the wood. Groundwood pulping is one of the major mechanical pulping processes. In this process, a piece of wood is pressed against a rotating grinding stone. The stone surface has traditionally been made of grinding particles fused to a vitrified matrix. Though the process is close to 200 years old, the detailed mechanisms of the interactions between the grinding particles and the wood surface are still not fully understood. The random nature of the grinding stones combined with the heterogeneous nature of wood creates a stochastic process that is difficult to study in detail. This work utilizes well-defined tools, that facilitate testing and analysis, to increase the understanding of the tool-wood-interaction. In-situ tomography experiments were performed with such well-defined tools, to study the deformations and strains induced in the wood as the tool asperities engage the wood surface. Numerical simulations were used to study the influence of asperity shape, and to show how the induced strains promote intercellular cracks and fibre separation. Several well-defined tool surfaces were designed and tested in a newly developed lab-scale grinding equipment, to study their performance in terms of energy consumption and the quality of the produced fibres. It was shown that the well-defined grinding surfaces, with asperities the same size as a fibre diameter, can be designed both to achieve drastically lower energy consumption compared with that of traditional stones and to produce long and undamaged fibres. This thesis shows that it is possible to design future tools that can help reducing the energy consumption in industrial pulping.

Keywords: Groundwood pulping, Grinding mechanisms, Diamond grinding tool, Energy efficiency

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This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


VI Heldin, M., Wiklund, U. (2019). Influence of alignment between extended tool ridges and the wood structure on the defibration mechanisms in groundwood pulping experiments. *In manuscript*

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Author’s contributions to the papers

Paper I  Part of planning. Major part of experimental work. Part of evaluation and writing.

Paper II  Part of planning, experimental work, evaluation and writing.

Paper III-VI  Major part of planning. All of experimental work. Major part of evaluation and writing.
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*Scratch testing of wood for mimicking the early stage of wood defibration*
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*Initiation of wood defibration, tribology at the fiber level*
Presented at the 16th Nordic Symposium on Tribology, 10-13 June, Aarhus, Denmark, 2014.

*A lab scale test equipment to study the defibration mechanisms in the pressure groundwood process*
Presented at the 20th International Conference on Wear of Materials, 12-16 April, Toronto, Canada, 2015.

*Designed tools for controlling the defibration mechanisms in the pressure groundwood process*
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*Micrometer compressions to facilitate controlled wear in groundwood pulping*
Presented at the 17th Nordic Symposium on Tribology, 14-17 June, Aulanko, Finland, 2016.

*Tailored grinding surfaces for groundwood pulping – influencing wear mechanisms and energy requirements*

*Influences of grinding surface alignment in groundwood pulping of Norway spruce*
Presented at the 18th Nordic Symposium on Tribology, 18-21 June, Uppsala, Sweden, 2018.

*On tool engagement in groundwood pulping – in-situ observations and numerical modelling at the microscale*
Presented at the 11th Fundamental Mechanical Pulp Research seminar, 2-4 April, Norrköping, Sweden, 2019.
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1 Introduction

Paper is a very old invention, with papyrus produced 3000 B.C. as predecessor. The first large-scale paper use has been traced to China. Texts from 105 A.D. have been found, describing a process using fibres as raw material for paper. At that time the fibres were extracted from plants and later textiles but not wood. In the 1800\textsuperscript{th} century the French naturalist René-Antoine de Réaumur suggested that wood fibres could be used to make paper, but it was only in the 1840s that the first sheet of paper containing only wood fibres was produced by Friedrich Gottlob Keller in Saxony. His invention was the grinding process in which wood is pressed onto a rotating grinding stone [1,2]. This principle is still used in pulp mills.

There has been a steady development of the pulp and paper processes during the last 2000 years and since the early industrialisation, 200 years ago, there has been a high demand for paper and paper products. During the last 15 years there has been a declining demand for many grades of print and writing paper [3] as society transitions towards using electronic media to a great extent.

The pulp and paper industry is facing large challenges moving forward, as the demand for paper and pulp products continues to change. However, not all paper grades are affected by this change, packaging and sanitary grades are still extensively used [3]. As the different paper grades have different demands on the pulp, the pulp mills must adapt their production to suit the changing market. Many mills choose to invest towards speciality products. Finding new markets for pulp is also possible, e.g. as fibre reinforcement of plastics. When trying to meet the changing demands on the fibre characteristics, both understanding and control over the defibratation mechanisms are important in order to produce the desired pulp.

There are many different pulp production processes and in this thesis the focus lies on the group of processes called groundwood pulping. These are mechanical processes originating from the invention by Keller in the 1840s. In the industrial processes, logs of wood are pressed onto large rotating grinding stones. To ease the fibre separation, this is done at elevated temperatures.

The mechanisms leading to fibre separation in the wood are interesting. The grinding process requires a huge amount of electrical power but only a fraction of the energy consumed in the grinding process is actually consumed to separate the fibres. The rest of the energy consumed in the
The grinding process is converted to heat by undesired viscoelastic deformations of the wood as well as by undesired fibre cutting or fracturing.

Even a relatively small efficiency improvement in this process would result in enormous energy savings, since the global mechanical pulp production is several million tonnes per year as each tonne consumes roughly 1500 kWh.

1.1 Aims of the thesis

This thesis investigates the mechanisms behind the fibre separation and how to design more energy-efficient grinding tool surfaces. This is performed by:

- Developing physical grinding tools, test equipment and methods of analysis that allow detailed, micro-scale, studies and evaluation of different grinding tools in terms of
  - deformation and damage mechanisms in the initial contact with wood
  - comparisons with simulations
  - defibration and energy consumption in extended grinding

Using grinding tools with well-defined surface asperities, the following questions are to be answered:

- Can more energy-efficient grinding tools be produced that reduce the consumption compared to conventional grinding stones?
- Is it possible to control the character of the fibres in the pulp?
- How does the load and temperature affect the defibration process?
- What shape should the tool asperities ideally have and how should they be distributed, in order to optimise the energy efficiency or the fibre characteristics?
2 Background

2.1 Wood
Wood is a natural inhomogeneous anisotropic biocomposite produced from trees. As this implies, the mechanical properties of wood are not easily characterised and determined as they have a natural variation and directionality. The trunk of a tree has many different parts, the bark which acts as a protective outer layer, followed by the cambium which produces the new cells that allow the tree to grow. Beneath this region is the sapwood, consisting of cells that transport water and nutrients from the roots to the leaves. In most trees this is followed by a region called the heartwood, which consists of dead, inactive cells in which there is an enrichment of extraneous chemicals called extractives. The inner core of the wood, noticed as a dark circle, is called the pith.

The annual rings are readily noticed in the cross section of a tree, see Fig. 1. The annual rings occur as a result of the differences in growth through one season. Fig. 2 show this in larger magnification.
Note that as the tree grows during a season (starting from spring to the left and growing to the right) there is no distinct transition from earlywood to latewood, but rather a gradual transition. The same is not valid between the growth seasons, as an abrupt change in cell size exists going from latewood to earlywood.

![Figure 2. SEM micrograph of a thin section of Norway spruce with the smaller thick-walled latewood cells in the centre and the larger thin-walled earlywood cells to either side.](image)

The brighter rings in Fig. 1 are called earlywood, as they are produced during the early part of a growth season. The typical earlywood cell has a large cross section with a large lumen, seen as a void, and thin cell walls, see Fig. 3a.

The darker rings in Fig. 1 are called latewood, as they are produced during the late part of the growth season. The latewood cells are characterised by being smaller than those in the earlywood, having smaller lumen and thicker cell walls, see Fig. 3b.

The tree species differ in their composition and structure; usually the wood species are divided into two groups: softwoods and hardwoods.

The species used in pulping are most commonly softwoods and therefore the focus will lie on their microstructure. Softwood species are for example firs, spruces and yew. What the species have in common is that they have a simpler, more homogeneous, cell structure than the hardwoods. The largest part of softwoods consists of cells called tracheids, oriented in the growth
direction of the tree. In Figs. 2 and 3 the cells are oriented into the image plane. Tracheids are similar to hollow tubes, like straws, and can be up to 10 mm long in some species, but lengths between 1 and 5 mm are more common. Rays are smaller cells growing in the radial direction in the wood, seen as horizontal channels in Fig. 2. Rays are not as numerous as tracheids. Other less frequent features are parenchyma cells and resin canals [4,5].

Figure 3. Differences in cell size and cell wall thickness between (a) earlywood and (b) latewood.

This comparably simple microstructure makes the softwood suitable as raw material for pulping, making it possible to produce pulp with yields close to 100%, thereby utilizing the whole tree trunk.

The cells themselves are also composites, consisting chiefly of three different polymers: cellulose, lignin and hemicellulose, and to a lesser extent extractives. The cells are held together by a thin layer called the middle lamella, made mainly of lignin. The cell walls have a layered structure, with the primary wall (P) next to the middle lamella, followed by the secondary wall which is divided into three layers: the outer layer (S1), the middle layer (S2) and the inner layer (S3) of the secondary wall, where the S2 layer contributes the most to the mechanical strength of the wood [4,5].

The wood species used in the experimental work throughout this thesis was Norway spruce (Picea abies).
2.2 Pulping in general

Pulping is the process in which fibres are extracted from wood and other raw materials. Wood fibres are the cells from the tree. The pulping processes are generally divided into two different types, chemical and mechanical pulping. For both these, the wood is stripped of its bark prior to pulping.

In chemical pulping the wood is subjected to different chemicals and heated in a process called cooking, dissolving in particular lignin and liberating the fibres. This comes at a cost as the typical yield in chemical pulping is very low, less than 50%. The chemical pulp fibres are stiff and bulky after the cooking and in order to make good paper they need to be processed further. One common solution is to add a beating process, which is similar to the thermo-mechanical process described below, but for the chemical pulps it is run at a lower intensity. In this process the fibres are softened and made to collapse, which increases the possible contact area between the fibres in paper.

The mechanical processes instead separate the fibres by mechanical processing. Two types of mechanical processes are used today. The most common is the thermo-mechanical process (TMP) in which the wood is first cut into chips and then fed in between rotating refiner plates, essentially plates with radial bars on their surface. The wood chips are then crushed between the plates and separated into fibres.

The other type of mechanical pulping is the groundwood pulping processes (GWP), in which logs of wood are pressed against a rotating grinding stone. These processes are the focus of this thesis and will be explained in more detail in the following chapters.

The mechanical processes are performed at high temperatures, usually between 100 and 130 °C but even higher temperatures are employed in some processes. The mechanical processes have a high yield; up to 98% has been observed.

It can be noted that these processes are not one-step processes, but from wood to pulp the fibres can be subjected to multiple separation steps. The TMP process is usually performed in steps, where in the first step, the refiner is fed chips and the in the following steps, the refiners are fed the products from the previous steps. Between the steps the pulp is screened to extract the desired fibre fractions and the rest is fed through to the next refining step.

There are also several processes combining chemical and mechanical pulping, such as Semi-Chemical pulping or Chemi-Mechanical pulping. In these there can be a short chemical cooking step dissolving the lignin slightly followed by moderate mechanical refining, or prior to refining the chips are impregnated with chemicals. The yields from these processes are between the chemical and mechanical pulping processes, 50-90% [1,4,6].
2.3 Pulp

The pulps produced in the different processes do not have the same characteristics. The characteristics are for example: the average length of the fibres, the degree of fibrillation, the fractions of shives, fibre fragments and finer material as well as the amount of chemical constituents, particularly lignin, present in the pulp.

Chemical pulps can have different concentrations of lignin depending on the cooking process and generally have long fibres with high strength suitable for making strong paper. The chemical pulps are also bleachable to high brightness.

Pulp produced in the mechanical processes has shorter fibres than chemical pulp due to fracturing in the mechanical separation. The fibres are generally stiff and bulky, i.e. they are not collapsed, reducing the bonding ability and the strength in a paper. But stiff fibres also provide resilience to compression during the paper manufacturing. The fines, i.e. the fraction of smallest fibre fragments, benefit the mechanical pulps in two ways; they can provide bonding between fibres, increasing the strength of the paper, and they fill gaps between the fibres, making the paper surface smoother and increasing the opacity. This makes mechanical pulps suitable for production of newsprint, books and other printed grades. As the lignin and other constituents, which are removed in the chemical pulping, are still present the pulp will change colour with age and exposure to light [1,4,6].

Fibrillation, the process in which the fibre cell wall is being delaminated, can be both internal and external. The internal fibrillation is the breakage of bonds between the constituents in the cell wall, causing swelling in the cell wall and also making the fibres more flexible and conformable. The external fibrillation instead refers to the peeling of the cell wall into hair-like fragments of cellulose, still attached to the fibre. The external fibrillation can increase the mechanical strength of paper, by increasing the bonding surface between fibres [7,8].

Chemical and mechanical pulps should be regarded as different flavours of pulp, rather than competitors. In fact, it is common to mix different types of pulp to achieve a desired composition when tailoring the properties of paper products, such as reinforcing a groundwood pulp with chemical pulp to increase the mechanical strength of a paper intended for printing.

Recycled paper is another source from which pulp is made, but the number of cycles the fibres can be used is limited. For each cycle the fibres are worn slightly, and sooner or later they become too short and damaged to be usable in paper. It has been estimated that a fibre can be recycled about 7-8 times, but in practice the amount is lower, about 3-4 times. This implies that as long as there is production of paper, there will always be a need for supplying long and strong virgin fibres.
2.4 Groundwood pulping

The groundwood pulping processes are, as described previously, processes in which wood is pressed against a rotating grinding stone to separate the fibres. The first groundwood process was invented by Friedrich Gottlob Keller in the 1840s, and it has been studied extensively since.

A schematic drawing of a typical modern groundwood pulping machine can be seen in Fig. 4. In conventional grinding, a large cylindrical grinding stone is used, placed in the middle of the figure. The diameter of the grinding stone is about 1.8 m. The outer surface layer, several centimetres thick, is made from large grinding particles made of either alumina or silicon carbide, typical size is 200 µm diameter particles, which are fused to a vitrified matrix. The grinding stone is rotated by a large motor, with several MW power (corresponding to several thousand horsepower). Logs are pressed onto the rotating stone with typical feed rates of a few millimetres per second, in the schematic the wood is supplied in two pockets, one at each side of the grinding stone. The grinding stone is showered with water from nozzles placed around it. The showering is done to keep the temperature stable and to remove fibres from the grinding stone surface, preventing it from being filled with wood fibres, which otherwise would reduce the efficiency.

![Figure 4. Schematic of a Pressure Grinder. Image courtesy of Valmet Technologies, Inc.](image)

The processes are generally divided into stone groundwood pulping (SGW) and pressure groundwood pulping (PGW). SGW is performed at atmospheric pressure and lower temperatures than PGW, where grinding is performed at elevated pressures which allow for increased temperatures.
The energy requirements of this process are high, and of the energy spent during grinding, only a small portion, calculated to be less than 33%, is needed to separate the fibres and treat them, creating the desired pulp [9,10]. One of the reasons for the energy loss is viscoelastic deformation of the wood, where the energy is converted to heat [9-12]. Another is undesired fracturing of fibres, where energy is spent to create new surfaces [13,14].

2.4.1 Present understanding of basic mechanisms

Though grinding might seem like a simple process, the interactions between the wood surface and the grinding stone are complex. An illustration of the interaction between a grinding stone particle and the wood can be seen in Fig. 5. The separation and liberation of fibres are generally believed to be done in three steps. The first part is to soften the fibres and induce fatigue in the fibre structure and cause fractures between the fibres. This is accomplished by the particles in the grinding stone, as they repeatedly pass the surface fibres causing cyclic compressions and an increase in temperature. When the fibres start to separate from each other the particles will instead start peeling the fibres from the surface, often compared to combing the fibres out of the surface. The last step is to move the released fibres out of the contact. During this movement the fibres are further treated by the repeated contact between the wood and the grinding stone before they have moved completely out of the grinding zone [6]. In the following sections the present understanding of the mechanisms involved, and the influence from different process parameters on the grinding process will be described.

Figure 5. Interaction between a grinding stone particle and idealised square wood fibres.
2.4.2 Influence of temperature
Temperature greatly affects the mechanical properties of the wood, due to thermal softening. In particular the lignin and the hemicelluloses are affected by temperatures reached in the grinding process. As the lignin is the main constituent in the middle lamella, gluing the fibres together, the softening facilitates the separation of the fibres.

Moisture greatly affects the softening of the wood and at low levels of moisture, the softening temperature is higher than the temperatures reached in the grinding process [11]. Lignin has a glass transition temperature around 80 to 100 °C in water-soaked conditions, and the softening of wood is prominent between 100 and 145 °C [12,15].

There are two main contributions to the temperature during grinding, one is the temperature of the surrounding atmosphere and the shower water, the second is the heat generated in the contact between the wood and the grinding stone. The frictional heat generated in the contact is generated from the adhesion between the wood and the grinding stone surface, and from internal losses in the wood during deformation [16]. The generated heat is localised to the surface of the wood and the grinding stone. Less than 1 mm of the outer surface experience a significant increase in temperature [17,18].

By elevating the pressure in the grinding chamber, either with pressurized air or steam, the temperature of the shower water can be raised above 100 °C. This increase will affect the temperature in the grinding zone and the softening of the wood. At higher temperatures, the production rate is increased and the energy consumption is reduced [19,20]. However, the need for elevated pressure counteracts these improvements as elevated pressure has been shown to have a negative impact on the production rate and lead to an increased energy consumption [19,22-24]. Even so, pulps produced at elevated pressures and temperatures have been shown to have enhanced properties compared to those produced at lower temperatures [20-24].

2.4.3 Stress-Strain behaviour
The total energy consumption of the defibration is closely related to the energy lost in the grinding zone which in turn depends on the deformation and damage processes taking place there. Studies on the mechanical response of the wood to an applied stress can thus provide useful information on these processes.

The stress-strain behaviour of spruce is dependent on the strain rate as well as the moisture of the wood. At low strain rates, the wood is compliant, and the stresses are low, but at higher strain rates the wood gives a stiffer response resulting in higher stresses. The difference is large between dry and moist wood, where dry wood is stiffer and requires higher stresses to reach the same strains as moist wood [25]. The dependence of the stresses on the
strain rate decreases with increasing temperature, and at temperatures of 80-100 °C there is almost no dependence [26]. The stress-strain behaviour is also affected by previous treatments, e.g. successive compression pulses require less force than the first, which is related to the fatigue of the wood. But in order to continue to increase the fatigue, the amplitude of the strain pulses must also increase [10,26].

Inducing fatigue in the wood structure reduces the energy requirements for the subsequent peeling. The fatigue of wood due to cycled strains has been shown to occur in a layer of cells, often close to the surface [27,28]. It has been shown that the wood has different susceptibility to fatigue depending on the loading direction in relation to the orientation of the annual rings [29]. Wood that had been subjected to a fatigue pre-treatment required less energy during grinding compared with non-fatigued samples when producing pulp with similar properties [30,31].

During grinding, the fatigue in the wood surface arises from compression as the particles in the grinding stone move over the surface. Depending on the topography of the surface, these compression pulses will affect the surface differently. Model experiments, using steel grinding wheels with cylindrical ridges as surface pattern, showed different mechanisms depending on the radius of the cylinders. If the radius of the ridges were larger than 100 µm the strains spread in the wood surface, reducing the intensity of the pulses and thereby made the tool incapable of separating fibres from the wood. Ridges with a 100 µm radius were able to separate fibres as the strain pulses were more localized [32].

The grinding stones are sharpened regularly to remove inefficient grinding particles from the surface and to maintain the desired surface profile. Fig. 6 shows an example of such a surface profile having a sinusoidal shape. The surface shape is produced using a sharpening tool called a burr, and commonly a spiral burr with ridges at 28° angle from the axis is used. This will produce ridges in the grinding surface at that angle, see Fig. 7.

Simulations of the surface profile implied that a wave shape can reduce the energy consumption [33], and a 20% reduction of the specific energy consumption has been shown in practice with potential for even further reduction [34-36]. Creating grooves, larger than the normal surface profile, at regular interval around the circumference of a grinding stone has been suggested to have the potential to reduce the energy consumption, if the number of grooves were small [37].

The surface profile can also affect the pulp characteristics, and a grinding stone serrated along the direction of the axis has been shown to produce a pulp almost completely made of fines [38].
2.4.4 Grinding stone particles

Apart from the larger surface profile in the grinding stone, the particles are also influencing the mechanisms of the defibration process. Looking at the interactions of single particles with the wood, the deformations in the wood is related to the size of the particle. A large particle produces less localised strains in the wood moving across the surface and requires less energy, due to a smaller permanently deformed area, compared to a smaller particle which creates higher local strains and a larger permanent deformation [39].

How the fibres are oriented in the wood surface relative to a particle moving over the surface affects the mechanisms of the contact. If the rake angle is high, fibres with orientations close to the grinding particles direction of motion have been shown to have an increased risk of being pulled out in bundles instead of separated. Moreover, fibres oriented perpendicular to the direction of motion would experience gentle ploughing at a low rake angle, but an increased tendency for fibre cutting as the rake angle was increased [40].

Studies of the initial interactions with a grinding surface have shown that the defibration mechanisms found during industrial grinding are already
present after the passage of a few particles, raising the question whether fatigue is a necessity or not [41]. The amount of particles present at the surface of a grinding stone will affect the grinding process. Fewer particles present have been shown to reduce the energy consumption, but also decrease the fibre length, compared to a conventional grinding stone [21]. Larger particles in the grinding stone increased the energy consumption, produced longer fibres and also produced a larger number of shives [22]. Mixing particles of different sizes have shown the same tendency, the energy consumption increases with the average size of the particles together with an increase in fibre length [22-24].

The conditioning of the particles influences both the energy consumption during grinding and the characteristics of the produced pulp. Sharp particles produced pulps containing shorter fibres, as the particles cut the fibres before they were fully separated from the wood surface. Conditioned particles, having a rounder profile, produced longer fibres that had a higher degree of fibrillation, but also a larger fraction of fines [42]. The energy consumption, at a constant production rate, has been shown to be smaller with sharp particles than with conditioned particles [42-48]. Rounder particles required a higher load to achieve the same production rate as sharper particles [45,46], which is likely related to the contact situation between the particles and the wood. The penetration depth is reduced with a rounder particle and conditioning also reduces the relative height difference between adjacent particles [42,43,48], increasing the likelihood that the load is shared between more particles.

Nearly all previous work in the area has been on grinding using conventional grinding stones, i.e. particles fused to a vitrified matrix, where the relative position between particles is stochastic both laterally and vertically at the surface. Recently a method to position particles on a surface has been developed, removing the stochastic behaviour, showing benefits during grinding [47,49].

2.4.5 Influence of load

To initiate the defibration, the intensity in the interaction between the particles and the wood must reach a certain threshold. Varying the load with which the wood is pressed onto the grinding stone reveal that at low loads the production rate is low, but upon reaching a certain load the production rate increases rapidly [19,50].

This is likely related to the deformation tendencies at different loads, leading to deeper penetration [16], together with the temperature rise in the wood as more energy is put into the contact [15,17]. Applying more load after passing the threshold reduced the energy consumption per produced tonne pulp, and increased the average fibre length when using a conventional grinding stone [20].
2.4.6 Grinding stone velocity
Wood is a viscoelastic material and depending on the applied strain rate, the mechanical response will be different, as previously described in section 2.4.3. The wood structure behaves stiffer at high strain rates than at low. The grinding stones peripheral velocity will therefore affect the mechanics as the particles come in contact and move through the wood. The friction force during grinding has shown to be higher at higher velocities [44,51], raising the temperatures in the grinding zone [17] and increased the production rate. The total energy consumption has been shown to increase slightly with increasing stone velocity [22-24].

2.4.7 Wood variation and alignment
The anisotropy in wood influences the grinding process as well. Different species of wood have different microstructure leading to different mechanical strength, density, fibre properties etc. and the defibration process must be adapted accordingly [52].

Even within a species the heterogeneity in the wood structure changes the interactions during grinding, such as the difference between sapwood and heartwood. The heartwood has slightly shorter, thin-walled fibres and the moisture content is lower than in the sapwood. Pressurized grinding has shown to have a positive impact on the fibres produced from heartwood [20].

The differences in fibre diameter and cell wall thickness through the wood also play important roles during grinding. The orientation of the annual rings was shown to have an impact on the macroscopic mechanical properties of the wood and the fibres susceptibility to fatigue [29]. The relative orientation of the fibres compared to the grinding stone surface affect the defibration mechanisms, and by extension the properties of the produced pulp. In experiments where the wood logs were cut at different angles relative to the grain and thereafter ground, different mechanisms were observed depending on fibre orientation. Small changes in fibre orientation in the radial plane, even by only 10°, changed the mechanisms and the produced fibres were drastically shorter and the amount of fines increased, where a change in orientation in the surface plane did not produce any significant changes [53,54].
3 Contributions

In the following chapter a summary of my contributions to the research on groundwood pulping is presented. A large part of the work included in this thesis is the development of experimental equipment and evaluation methods aimed at investigating the contact mechanics (*Paper I* and *II*) and a lab scale grinding equipment (*Paper III*). The lab scale equipment is then applied to investigate the influence of load, surface pattern and alignment using well-defined tools for groundwood pulping (*Paper IV, V* and *VI*).

3.1 Materials

3.1.1 Wood

Throughout this thesis the wood used came from Norway spruce, the most common species used in Swedish pulp mills. In *Paper I* and *II* the wood was dried prior to the experiments and in *Paper III-VI* the wood was kept fresh in a freezer and only thawed prior to being used.

3.1.2 Well-defined grinding surfaces

One of the aims in this thesis is to investigate if the grinding process could be improved by using tools with well-defined tool surfaces, compared to the stochastic surfaces of conventional grinding stones. A manufacturing process for well-defined surfaces have recently been employed in grinding as described previously [47,49], but that process use similar grinding particles as the conventional stones. As the particles have shapes close to a sphere, the contact is restricted to a near point contact.

Grinding surfaces without that constraint have been produced for grinding of other materials [55] and the same process has been used to create tools with elongated asperities for embossing metals [56]. The method allows control of the position and size of the asperities down to the micrometre level.

Employing this type of grinding surface when grinding wood could create new possibilities to design the contact to suit the wood structure. This could give new possibilities for more controlled defibration, with the potential of reducing the energy consumption and improving the pulp properties.
The grinding surfaces produced for the work in this thesis followed a procedure similar to that used by Gåhlin and Pettersson [55,56].

The grinding surfaces consisted of structured diamond films attached to a supporting plate able to carry the mechanical loads. In Paper II a grinding surface was glued to a plastic backing to be used in the tomograph, and three other surfaces were soldered to steel plates and used in the grinding experiments, Fig. 8, as was done with the grinding surfaces used in Paper III-VI, Fig. 9.

To produce the diamond tools, a negative tool master was created in a silicon wafer, Fig. 10b, on which the diamond was deposited using hot filament chemical vapor deposition (HF-CVD) [57]. The silicon master was made by first growing an oxide layer on top of a <100> silicon wafer in a furnace. Then a pattern of the desired grinding surfaces was created in AutoCAD and using this, a chromium lithography mask was produced, Fig. 10a. Photoresist was spun onto the silicon oxide surface and light was shone through the lithography mask to weaken the photoresist in the exposed areas. The weakened photoresist was then removed and revealed the oxide, which was subsequently etched using a buffered hydrofluoric acid solution. After the oxide etching, the photoresist was removed from the wafer, leaving an oxide mask on top of the silicon wafer. The silicon was wet etched using a potassium hydroxide (KOH) solution, which etches the silicon crystal planes in the <100> directions faster than in the <111> directions. Having aligned the desired pattern in the correct direction, grooves with a triangular cross section were produced. The slope of the sidewalls in the grooves was 54.7° because of the anisotropic etching, resulting in a bottom angle of 70.6° in the grooves, Fig. 11.

After the diamond film, approximately 10 µm thick, was deposited on the silicon master, binding layers of first titanium and then nickel was sputtered on top of the film. This allowed the diamond to be soldered to e.g. a steel plate. Lastly, the silicon master was etched using a KOH solution, revealing the grinding surface. The revealed diamond now had a surface with the geometries replicated from the master, including e.g. the 70.6° top angle of the diamond asperities. An outline of the process is found in Fig. 11.

The grinding tools used were all 5 mm wide and 5 mm high and the thickness of the steel plate was 1 mm.

Figure 8. Grinding surfaces used in Paper II. Small pyramids used in tomography and grinding (a), larger pyramids (b) and truncated pyramids (c) used in grinding.
Figure 9. Grinding surface with long ridges across the tool, used in Paper IV and V, seen from above (a) and in cross section (b). Grinding surface used in Paper V with ridges sparsely placed (c,d). Grinding surface used in Paper IV and V with ridges densely placed (e,f) and the grinding surface used in Paper VI with truncated ridges across the tool width (g,h).

Figure 10. Chromium lithography mask (a) and a negative silicon master with grooves (b), prepared for diamond deposition.
3.1.3 Grinding stone specimen

For comparison with the well-defined grinding tools, a piece of a conventional grinding stone was obtained from a Swedish pulp mill. A piece of the stone was cut into the same size as the other grinding surfaces, Fig. 12, and used in the grinding experiments in *Paper V.*

*Figure 11.* Outline of the grinding surface production method. Starting from a silicon wafer (1), a mask with the desired pattern is created (2). The wafer is anisotropically etched in KOH (3) and the mask is removed (4). A diamond film is deposited onto the wafer (5) and binding layers of titanium and nickel are sputtered on top of the diamond film (6). The diamond film together with the wafer is attached to a backing (7) and the silicon wafer is removed by etching, revealing the grinding surface (8).

*Figure 12.* Grinding stone specimen overview (a) and view of the grinding surface (b).
3.2 Experimental method

3.2.1 Single asperity scratching

Scratching was employed as a method to investigate the initial and repeated interaction between single asperities and the wood in *Paper I*. A CSM Revetest scratching equipment was used, Fig. 13, together with three different diamond styli. The styli used all had sphero-conical shape with a cone angle of 120° and different radii, exemplified in Fig. 14.

To resemble the temperatures of industrial grinding, the scratching equipment was modified and equipped with a heated water bath. This allowed the wood specimen to be submerged in water, heated or non-heated, during the scratching. The heated tests were compared to tests performed in 20 °C to investigate the influence of the thermal softening.

*Figure 13*. CSM Revetest scratching equipment.

*Figure 14*. Diamond stylus used in scratching experiments.
3.2.2 Computed tomography

Computed tomography was used extensively in the work presented in this thesis. In Paper I a benchtop X-ray micro computed tomography (µCT) equipment, Bruker Skyscan 1172, was used to investigate the strain behaviour as an indenter penetrated the wood.

In Paper II the computed tomography was performed at the Swiss Light Source synchrotron facility at Paul Scherrer Institute in Villigen, Switzerland. The benefits of the synchrotron radiation is that it has a smaller angular spread than the lab scale equipment, improving the quality of the images and the reconstructions. The beam intensity is also much higher, reducing the time to run the experiments and allow scanning of thicker samples.

3.2.2.1 In-situ indentation and one-stroke grinding in computed tomography

To study the deformations in the wood as grinding tools engage during grinding, computed tomography which images the wood cells was used. The movement between scans was managed by a compression stage capable of holding an upper and lower sample.

For the indentation experiment in Paper I, the upper tool was a metal needle with a 200 µm radius spherical tip indenting vertically in a piece of dry wood.

In the experiments in Paper II, a simple setup was 3D-printed in a polymer (PLA). The upper part held a well-defined grinding surface in a lateral orientation and the lower part held the wood specimen with the surface also in a lateral orientation. As the upper and lower parts were pressed together, the upper holder’s wedge-like geometry forced the tool to engage the wood. Fig. 15a show the parts separated and Fig. 15b in contact, note that the compression stage is not shown in these images. The grinding surface shown in Fig. 8a was used in this experiment.

![Figure 15. The setup used in the experiments for the engaging of the well-defined tool surfaces. Showing the parts separated (a) and in contact (b).](image-url)
Images were obtained of the wood before and after contact with indenting tools. Image correlation was used to analyse the deformations and strains induced by the tool contact.

In *Paper I*, sections from the reconstructed volumes of the wood was selected; one section before and one section after the indenter penetrated the wood. These sections were compared and analysed using a 2D digital image correlation (DIC) algorithm [58].

In *Paper II*, a digital volume correlation (DVC) algorithm was employed [59]. From the reconstructed volumes, a sub-volume was selected and the correlation was made by comparing the same sub-volume just before and after the tool engaged the wood.

### 3.2.2.2 Grinding track measurements using tomography

In *Paper III-VI* the benchtop equipment, used in *Paper I*, was used to measure the amount of fibres removed during grinding. This approach offered the benefit of being able to measure the amount even though partly removed fibres were present in the grinding tracks. This would not have been possible using most other techniques, limited to analysing what is in the line of sight.

### 3.2.3 Simplified grinding tests

In *Paper II*, a simplified grinding experiment was performed to correlate the simulated strains to mechanisms observed in the contact between the tool and the wood during repeated unidirectional grinding, see Fig. 16. Three different grinding tool surfaces were tested; one with pyramids with sharp tips placed across the surface in a square pattern, one with a small truncated area on the top of the pyramids and one with a large truncated area, see Fig. 8.

Each test used a flat wood sample, placed in a heated water bath.

*Figure 16. Sketch of the setup used in the simplified grinding experiments.*
3.2.4 Asperity contact simulation

Finite Element modelling was performed to understand the contact between the wood and the grinding stone asperities and the impact of different asperity shapes. The simulations were performed to illustrate both the process where asperities move into contact (indentation) and indentation followed by a movement across the wood surface.

The modelling was performed in Abaqus FEA (2015) using a simplified wood model. The wood model consisted of fibres, equal in size and shape, placed in a regular pattern. Each fibre was modelled as the union of the cell wall layers, $S_1$, $S_2$ and $S_3$, and between the cells were a compound middle lamella, consisting of the primary wall and the middle lamella, see Fig. 17. The constituents were simulated as a linearly elastic, anisotropic continuum, i.e. the wood fibres were modelled to have different properties across and along their length.

The tips used in the models were a tip with small radius, a tip with large radius and a truncated tip, see Fig. 18.

The indentation was modelled by moving the tips in contact and then half a cell into the wood, simulating strain distributions in the wood under relatively large deformations.

The lateral motion was simulated by first moving the tips to a shallow depth in the wood, and then moving them one cell diameter across the cells. This simulated the variations in stress and strain occurring during grinding.

![Figure 17. Indenter in position before the start of a simulation. Shown as a section through the middle of the contact due to symmetry constraints.](image1)

![Figure 18. Indenter geometries, tip with small radius (a), tip with large radius (b) and truncated tip (c).](image2)
3.2.5 Lab scale grinding

A lab scale equipment was developed to run tests to simulate grinding at temperatures and humidities relevant in industrial grinding, *Paper III*, Fig. 19. For this the equipment was based on a pressure chamber, in which water was heated to reach the desired temperature. As steam was generated from the heated water, the pressure in the chamber increased and temperatures above 100 °C could be achieved. The chamber was designed to tolerate pressures up to 7 bar, which gives a maximum achievable temperature of about 170 °C. The highest temperature used in the work in this thesis was 110 °C.

Inside the chamber a setup similar to a miniature lathe was placed. The lathe was connected to a motor on the outside of the chamber supplying the rotation. A cylindrical piece of wood was used in all the tests in *Paper III-VI*. This was beneficial as the grinding tools used could be small, about 5×5 mm², making them easier to produce. Another benefit was that during the rotation all orientations of the annual rings were tested in one experiment, though this possibility was not exploited in the present work.

The grinding surfaces was held and pressed against the wood by a spring-loaded holder. The holder was equipped with two sets of strain gauges in Wheatstone bridge configurations, measuring the applied normal force and the resulting tangential force during grinding. A schematic of this setup is seen in Fig. 20.

As heat and humidity is disruptive for electric circuits, care was taken to protect all wires and the strain gauges inside the chamber. Even though this was done, a deviation in the force measurements was noticed when the chamber was heated, and steam pressure was building up. To compensate this, measures were taken when analysing the recorded data, described in detail in *Paper III*.

*Figure 19*. The equipment used in the grinding experiments in *Paper III-VI*, from the outside (a) and looking closer on the wood and the grinding tool (b).
3.2.6 Scanning Electron Microscopy (SEM)

SEM was used to investigate the grinding mechanisms present at the surface of the tracks after grinding and to qualitatively assess the fibres removed during grinding.

A wood and diamond are poor electrical conductors and mostly consists of carbon with low atom mass, special considerations must be taken when using SEM. The poor conduction can lead to surface charging, electrons from the beam become trapped and interfere with the image generation. To reduce this, the beam current can be reduced. This has the effect that the number of electrons detected is lower, which also have the negative effect that the brightness of the acquired images is reduced. Another method is to coat the samples with a conducting coating, and in the works included in this thesis a gold/palladium coating was sputtered on top of the samples.

An appropriate acceleration voltage should also be selected. Depending on the voltage and the atoms in the irradiated material, the beam will penetrate to a certain depth. Higher voltages and lower atom weight allow the beam to penetrate further. As wood is mostly carbon, with low atom weight, a low acceleration voltage should be selected if the surface is to be analysed. There is a balance to take into consideration as lower voltage will also make the beam harder to focus and reducing the magnification possible with good focus.

3.2.7 Optical profiling

An optical profiler using Coherence Scanning Interferometry (CSI) was used in order to map the topography of the surface of the grinding stone specimen used in Paper V.
3.3 Grinding energy calculations

Several estimations of the energy consumed in the grinding experiments were performed to compare the efficiency of the different grinding tools under different grinding conditions, Paper III-VI. The calculations are based on the assumption of a constant rate of fibre separation and removal from the wood surface. With that assumption we can say that the work of separating and removing fibres is equal to the work that is performed by the grinding surface.

Work, $W$, is defined as

$$W = F \times s$$

where $F$ is the force acting on a point moving it the path length $s$.

In Paper III-VI the path length is the length the grinding surface has travelled around the circumference of the cylindrical wood specimens. The work of the tools can be written as

$$W = F_T \times r \omega t$$

where $F_T$ is the tangential force on the tool, $r$ is the radius of the specimen, $\omega$ is the angular velocity and $t$ is the test time.

As we are interested in the efficiency of which the tools separate the fibres from the wood, we must include the volume of separated fibres, $V$:

$$V = A \times 2\pi r$$

where $A$ is the cross section area of the grinding track.

The specific energy per volume, $E_V$, consumed during a test is given by

$$E_V = \frac{W}{V} = \frac{F_T \times \omega rt}{A \times 2\pi r}$$

And assuming a wood density of $\rho$, a mass specific energy consumption, $E_m$, can be calculated

$$E_m = \frac{F_T \times \omega rt}{A \times 2\pi r \times \rho}$$

In Paper III-VI, the specific energy consumption is calculated from cross section areas measured at one position along the grinding tracks in the wood. As the fibre separation is affected by different orientations of the annual rings in the wood the cross section areas will also vary along the circumference or the wood specimen. Therefore the energy calculations should not be taken as absolute values and compared to those derived in other types of experiments, but rather as a comparison between the different tools in the test series.
3.4 Initial interaction between wood and indenting asperities

To develop more efficient grinding tools, knowledge of the interactions between the tool surface and the wood is crucial. Fatigue in wood has been studied, but what about the peeling? And how does it relate to the interactions between the asperities and the wood? Combining finite element modelling, in-situ tomography experiments and simple model experiments this is investigated in Paper I and II, to add to the understanding of the contact situation.

In Paper I, indentation of a wood surface was imaged using computed tomography to study the strains developed during the initial contact between an asperity and a wood structure. By correlating the images, the strains inside the wood were estimated and found to be very different from strains in a regular dense material, idealised as a continuum, Fig. 21 and 22.

The image correlation revealed that the highest strains were located deeper in the wood than would have been anticipated with continuum mechanics, whereas the total affected zone was smaller. This indicates that the strains in the wood are localised in a region around the indenting asperity.

The addition of motion studied in the scratching experiments showed that the asperity radius greatly affected the results, Fig. 23 and 24. At low temperature and using a stylus with a small radius, the scratching cut the fibres before any greater separation could be achieved. The other extreme,
where a hot wood specimen was scratched with a stylus with a large radius, little to no evidence of separation or fracture of the fibres in the surface was found. This correlates well with the literature as sharp grinding stone particles are known to cut fibres before full separation and conditioned, duller particles do not separate the fibres as easily, and an increase in the applied normal load is required to achieve defibration. The effect of the temperature is also evident, as the fibres were more readily separated when the temperature was increased.

Figure 23. Scratching of heated wood by styli with different tip radii; 50 µm (a), 200 µm (b) and 500 µm (c).

Figure 24. Scratching of room temperature wood by styli with different tip radii; 50 µm (a), 200 µm (b) and 500 µm (c).

The stress and strain behaviour was also investigated for surfaces with multiple asperities by finite element modelling of tips with different radii. Modelling indentation into a structure, Fig. 25, showed that the strains were less localised when the tip radius was larger. This is the same as in the scratching experiment where high local strains cut the fibres. If the strains are distributed in too large volume they will only lead to viscoelastic deformations and no permanent changes in the wood.

The estimated deformations and strains from the tomography experiment in Paper II confirm the behaviour seen in the finite element model with the smallest tip radius. The tomography images show that deformation is limited to a few wood cells around the tips, i.e. the deformation is very local, Fig. 26. The geometry of the asperities used is extreme in the respect that these are small and very sharp. This makes them even more likely to cut the fibres than the sharpest stylus used in the scratching experiments. It should also be noted that in the tomography experiments the wood specimens were dry. Dry wood have different mechanical properties compared to moist wood, and the strains will therefore have a different distribution. The trends are still
believed to be the same for dry as for moist wood, where an increase in size of the asperity would spread the strains further into the wood.

Figure 25. Finite element modelling of indentation by tips with (a) small radius, (b) large radius and (c) truncated tips.

Figure 26. DVC data from an experiment where a grinding surface engage and moves in a wood surface, imaged in synchrotron computed tomography showing (a) vertical deformation of the DVC volume, (b) a selected sub-volume around one tool asperity and (c) the 1st principal strain in that volume. The asperity movement is indicated by the arrow in (b).
3.5 Influence of grinding tool surface design

In total, eight different diamond grinding tool designs have been evaluated in the work included in this thesis. In Paper II, three different surfaces with pyramid asperities were investigated, Fig. 8, using a simplified grinding experiment. The primary interest was to investigate the influence of the asperity geometry on the defibration mechanisms in the contact between the wood and the grinding tool. The wear tracks in the wood caused by the different tools, Fig. 27, displayed different mechanisms depending on the tool used. The tools with the small and large pyramids were shown to be too sharp and cut the fibres without removing them from the wood surface. The tool with the largest, truncated pyramids showed a different behaviour. At the start of the contact, as the tools only were partly in contact with the wood, the asperities cut the fibres in a similar manner to the other two tools. As the tool came in full contact, however, the mechanisms changed to instead separating and removing the fibres. This, together with finite element simulations (section 3.2.4), imply that in order to get fibre separation, rather than cutting and fracturing, the tool asperities must not be too small. As shown, a small tool asperity would localise the stresses and potentially reach the fracture strength of the fibre walls and cut the fibres.

Figure 27. Grinding tracks in the wood after simple grinding experiments with three different diamond tools; one with small pyramid asperities (a), one with larger pyramid asperities (b) and one with large truncated pyramid asperities (c).
In *Paper III-VI* the tool surfaces did not have a pyramid shape; instead the asperities were elongated, like ridges, providing a line contact with the wood rather than the point contact of the pyramids and the particles in a conventional grinding stone.

To summarize, the five surfaces used in *Paper III-VI* were:

- A surface with short asperity ridges, placed close to each other and with a small overlap between rows (S\textsubscript{Dense}). Used in *Paper IV* and *V*.
- A surface with longer ridges, set sparsely over the surface (S\textsubscript{Sparse}). Used in *Paper V*.
- A surface with sharp ridges across the full width of the tool (S\textsubscript{Long}). Used in *Paper III* and *V*.
- A surface with truncated ridges across the full width of the tool (S\textsubscript{Trunc}). Used in *Paper VI*.
- A piece of a conventional grinding stone. Used in *Paper V*.

Images of the surfaces are found in Figs. 9 and 12.

In *Paper V* three of the diamond surfaces were compared with a conventional grinding stone, at three different temperatures. For all four surfaces the specific energy consumption was reduced when the temperature was increased, Fig. 28. At the lowest temperature, 70 °C; the grinding stone performed better than any of the diamond surfaces. When the temperature was increased to 110 °C two of the diamond surfaces were instead the most energy efficient.

Comparing the surfaces at 90 °C, and adding the surface used in *Paper VI*, the most energy efficient surface was S\textsubscript{Sparse} followed by S\textsubscript{Trunc}. It is believed to be related to the contact between the asperities and the wood surface. Both these tools have lower fractions of their surfaces covered by ridges than S\textsubscript{Long} and S\textsubscript{Dense}. At a given load, this means that the asperities of S\textsubscript{Sparse} and S\textsubscript{Trunc} will penetrate further into the wood, allowing easier removal of fibres. The grinding surface actually penetrate furthest into the wood of all the tools at any given load, but the load is carried by a few grinding particles rather than being distributed evenly across the surface. This leads to an increased risk of fracturing the fibres, due to the local stresses from a point load, and less fibre removal.
Figure 28. Average specific energy consumption for the grinding tools evaluated in Paper V. The grinding tool used in Paper VI is added for comparison.

The grinding tool surface also affects the characteristics of the released fibres. The fibres separated by the diamond tools showed a clear dependence on temperature. The experiments run at 70 °C mainly produced smaller fragments and fractured fibres whereas at 110 °C the released fibres were longer and fewer short fibre fragments were found, Fig. 29. The same dependence on temperature was not found when using the grinding stone. The fibres were longer than those produced by the diamond tools at 70 °C and raising the temperature to 110 °C only increased the average length of the fibres slightly, Fig. 30.

The characteristics of the fibres should be related to the mechanisms present during defibration. At low temperature the diamond tools only penetrate the surface slightly, leading to localised strains in the top layer of wood cells at the surface. The strains will then fracture the fibres and remove small fragments rather than separate longer sections. At higher temperature the tool asperities move deeper into the surface as the wood softens, leading to more efficient separation of the fibres. The softening also increases the flexibility of the fibres, reducing the risk of fracturing them before they are fully separated from the wood. For the grinding stone, the load is carried by a few protruding grinding particles making it able to penetrate further into the wood than the diamond tools, even at low temperature. By increasing the temperature the grinding stone penetrates deeper into the surface, but the contact is still limited to a few points.
To summarise, the asperity geometry and density of asperities in the grinding tool surface clearly affect the grinding, both the energy efficiency and the character of the produced fibres. At high temperature the diamond grinding tools had lower specific grinding energy and produced long fibres, but at low temperature the grinding stone was more efficient and produced better fibres.

Figure 29. Examples of fibres produced during grinding with S\textsubscript{Dense} at 70 °C (a) and 110 °C (b).

Figure 30. Examples of fibres produced during grinding with the grinding stone at 70 °C (a) and 110 °C (b).
3.6 Influence of load on a well-defined grinding surface

To get a better understanding of how grinding with well-defined grinding tools was influenced by different process parameters, the effect of load and temperature was studied in Paper IV.

The grinding surface with a dense distribution of shorter ridges, S_{Dense}, was tested at three different loads and three temperatures. The penetration depth of the grinding tool asperities is affected by both the load and the temperature. Increasing either the load or the temperature, or both, will allow the asperities to penetrate deeper into the wood. The specific energy consumption was high at either low load or low temperature and decreased as the temperature or load was increased. The lowest energy consumption was observed at both high load and high temperature, Fig. 31.

![Figure 31. Specific grinding energy at three different applied loads and three different temperatures when using the well-designed grinding surface S_{Dense}.](image)

The characteristics of the released fibres were also different for the different parameters. At low load and low temperature, only small, fragmented fibres were produced. When applying a higher load or at a higher temperature the produced fibres were longer. The longest fibres, with only a low fraction of smaller fragments, were produced using a combination of high load and high temperature, Fig. 32.
These results also point towards the existence of a grinding efficiency threshold. At a certain process temperature, the load must be high enough to enable defibration. If that is not reached, the fibre separation is slow and mostly smaller fragments of fibres are removed from the wood.
3.7 Influence of the alignment between tool features and fibre orientation

As the fibre structure in the wood is anisotropic, the position and orientation of the grinding tool asperities will influence the contact with an individual fibre. With conventional grinding stones the contact is limited to point contacts and the interactions will occur at random positions along a fibre until it has been separated from the wood surface. A well-defined grinding surface, on the other hand, can be designed to interact with a fibre in a more controlled manner. In Paper VI this was investigated by using a diamond tool surface with truncated ridges across the full width of the tool, $S_{\text{Trunc}}$. The tangential angle between the ridges and the fibres in the plane of the tool surface, $\alpha$, is varied from being parallel up to 45°. Another angle also proved to be important during grinding, the radial angle $\beta$, being the angle between the ridges and the fibres in the plane defined by the ridges and the radius of the wood cylinder, visualised in Fig. 33. The angle $\beta$ was not controlled in the experiments but was measured afterwards.

![Diagram](image)

*Figure 33.* Sketch of the alignment of the grinding tool surface relative to the wood surface and the wood fibre orientation viewed from the top (a) and in cross section across the grinding track (b).

The specific grinding energy did not change much if looking at the effect of the angles $\alpha$ and $\beta$ individually, Fig. 34. There is some scatter, but that is mainly due to natural variations in the wood. However, the combination of the angles had more of an influence, Fig. 34. The energy consumption was
doubled with both high $\alpha$ and $\beta$ angles compared to the other combinations. It should be noticed that a ‘high’ angle $\beta$ is still below 10°, whereas a high angle $\alpha$ is 45°.

**Figure 34.** The specific grinding energy of four selected tests, with different alignment angles $\alpha$ and $\beta$.

The mechanisms of fibre separation were also affected by the different alignment angles. The micrographs of the grinding track surface, Fig. 35, show that even at high angles of $\alpha$ the fibres were readily removed and not leaving many damaged fibres still attached to the surface. Changing $\alpha$ only gave slight differences of the mechanisms present in the wear tracks. With a high angle $\alpha$ and a higher angle $\beta$, short, partly separated, fibres were present at the surface.

**Figure 35.** SEM micrographs of grinding tracks after grinding with high angle $\alpha$ together with low $\beta$ (a) and high $\beta$ (b).
The differences can be attributed to how the fibres are separated. At a low $\alpha$ and low $\beta$ the whole fibres are aligned to the surface, and as they become separated they are easily removed. However, if $\beta$ increases, the whole fibres are no longer at the surface. When the parts present at the surface become separated they cannot be removed easily, as the other ends of the fibres are still held firmly inside the wood, which would be the case regardless of what grinding surface is used. For both high $\alpha$ and $\beta$ the effect on fibre separation depends on their relative direction. For example, using Fig. 33 as a guide, if $\beta$ is positive as in the figure, the right side of the fibres are at the surface. Together with a negative $\alpha$, the right side of the fibres will be pushed slightly to the left, assisting the separation and peeling of the fibres. If $\alpha$ instead is positive as in the figure, the tool will pull the fibres to the right, promoting cutting. The $\alpha$ angle can be readily controlled, but in the case of the present study, $\beta$ was not controlled. This is also the case for industrial grinding, but natural variations in the wood will still occur and influence the defibration mechanisms.
4 Conclusions and outlook

The overall aim of this thesis was to increase the knowledge on how the surface of the grinding tools used in the groundwood pulping processes interacts with the wood. With this follows the possibility to create more energy efficient grinding surfaces and to tailor the surface to produce a pulp with desired fibre characteristics.

The main conclusions from the work in this thesis:

- The new types of well-defined grinding tools developed proved capable of separating fibres at lower energy consumption than the conventional grinding stones.
- The new tools can be designed to produce pulp with different characteristics, e.g. promoting long and undamaged fibres.
- Asperities with a size matching the wood fibre diameter are fully capable of defibration.
- The new tools are especially efficient above the lignin softening temperature.
- As for conventional tools, the well-defined grinding tools require loads above a minimum threshold to engage the wood properly and to yield efficient fibre separation.
- Finite element models showed how tensile strains, promoting crack initiation and fibre separation, develop in the wood as asperities move over the surface.
- Asperities with elongated shapes result in line contacts rather than point contacts with the wood, which reduces fibre damage and fibre cutting.
- The alignment of the tool asperity pattern relative to the wood structure was found to be of relatively low importance for the defibration.
- The equipment and methods developed and used during the present work proved invaluable for investigating both the initial contact between tools and wood and the detailed mechanisms occurring during grinding.

The present work has yielded new insights into the mechanisms of mechanical defibration and demonstrated some really interesting possibilities of improving the groundwood pulping process, increasing the energy
efficiency, by using well-defined, improved grinding surface shapes. However, this initial research has only touched upon the enormous range of possible grinding surface geometries. So far, the surfaces used have only been selected first examples to investigate the behaviour, and no optimisation has been attempted.

To move on to optimising the grinding surfaces, more knowledge is still needed. One example is understanding the influence of the speed of the interaction between the grinding asperities and the wood, which has been shown to have an effect in industrial grinding. Will the influence be different for a well-defined tool surfaces? Likely, the ranking between the surfaces is the same, while the relative differences will change.

The diamond grinding surfaces presented here each has had a single type of asperities, while combining different types of asperities would give additional opportunities to tailor the characteristics of the produced fibres. To just mention a single example of the myriad of possibilities: A combination of gentle ridges designed to separate the fibres, followed by sharper pyramids can be used to produce fibres of a desired length.
5. Svensk sammanfattning


De mekaniska massaframställningsprocesserna kräver väldigt mycket energi, nära den energi som krävs för att framställa motsvarande vikt stål. När man har uppskattat hur mycket av den tillförda energin som faktiskt behövs för att separera fibrerna i träet, har man kommit fram till att mindre än en tredjedel går till den faktiska separationen av fibrer medan den resterande delen omvandlas till värme när träet knådas av slipstenen.

Fortfarande är det inte helt utrett vad som händer när en träyta kommer i kontakt med en ojämn yta, så som ett sliphjul. Trots att stor kunskap finns om hur olika processparametrar påverkar den framställda pappersmassan är detaljerna kring separationsmekanismerna ännu inte helt klarlagda.

En svårighet som man möter är att trä är ett material som det finns stora variationer i. Cellerna i träet kan jämföras med sugröra, och om man sätter ihop tillräckligt många så får man ved. Men det är också så att cellernas storlek, tillsammans med tjockleken på cellväggen, varierar beroende på när på året de bildats, se Figur 37.

En annan svårighet är att man använder slipstenar som består av slipkorn, ihoppackade och fastgjutna i en glasmatris. Det innebär att det är slumpmässigt hur de sitter spridda över ytan och hur mycket de sticker ut, se Figur 38, vilket gör att interaktionen mellan slipkornen i stenen och ytan hos träet är minst sagt slumpmässig. Det är först på 2010-talet som man har börjat tillverka slipstenar i vars yta man noggrant positionerat enskilda slipkorn för att få en mer väldefinierad yta.

Genom åren har mycket forskning gjorts på olika delar av de mekaniska massaprocesseerna, och idag finns mycket kunskap om hur träet ändras vid olika förhållanden, som till exempel temperatur. Lignin, en beståndsdel i trä
som bland annat sitter som ett lim mellan cellerna, blir mjukt vid temperaturer runt 100 °C och därför blir det lättare att separera fibrerna om det samtidigt är varmt.

Det här arbetet syftar till att fördjupa förståelsen av interaktionerna mellan träet och verktyg av olika slag som tränger in i träytan. För att göra detta har en kombination av olika analysetekniker använts tillsammans med nya väldefinierade slipytor som möjliggör detaljerade studier, ett exempel visas i Figur 38. Dessa har provats i olika utrustningar, bland annat en utrustning som tagits fram specifikt för att kunna utvärdera prestandan hos de väldefinierade ytorna vid slipning i förhållanden som efterliknar dem i massaindustrin.

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I slipexperiment visades att ett väldefinierat slipverktyg kunde sänka energiåtgången drastiskt, jämfört med ett konventionellt slipverktyg, om processen sker vid 110 °C, men vid en lägre temperatur var slipstenen mer effektiv, se Figur 39.

Genom att välja en annan diamantstruktur kunde slipningen istället påverkas till att frilägga längre, mindre skadade fibrer, se Figur 40.

Tillsammans visar detta på stora möjligheter att anpassa nya slipverktygs ytstruktur med potential att sänka energiförbrukningen och anpassa den producerade pappersmassan.
Figur 39. Energiåtgången vid slipning med diamantverktyget i Figur 38, jämfört med en slipsten, vid tre olika temperaturer.

Figur 40. Frilagda fibrer efter slipning vid 110 °C med ett diamantverktyg.
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Bibliography


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