The Effect of Wood Alignment on Wood Grinding – Part 1: Properties of Pulp and Fines Revealed in the Grinding Mechanism

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In industrial wood grinding, logs are pressed against a rotating stone, with the logs and fiber axis parallel to the axis of the stone. The objective of this study is to clarify how the wood alignment affects the process and pulp properties. In this research, wood blocks were fed into a laboratory grinder with various alignments in relation to the surface of the grinding stone. The effects of the alignment on the properties of the pulp and the amount and quality of fines were measured. A grinding mechanism was proposed. The results show that the pulp quality is very sensitive to the angle between the stone surface and the log. In gentle refining, the fiber structure is loosened by fatigue before it is bent on the surface; pressure pulses produce fibrillar material, and fibers develop toward having good bonding ability. In forced grinding, the process is "violent", and the fiber wears and becomes crushed immediately on the surface into small particles with low bonding ability.

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INTRODUCTION

Mechanical pulps are produced by specified attrition processes. Groundwood (GW), pressure groundwood (PGW), and thermomechanical pulp (TMP) all apply similar shear and compression forces on fresh wood and fibers. In grinding, a high strain rate of cyclic compressive loads results in heating, loosening, and fatigue of the wood (Atack 1981; Lucander *et al.* 2009; Salmi *et al.* 2009), whereas shear loads free the hot fatigued fibers from the solid wood. As a result, a pulp suitable for papermaking is obtained. All of the mechanical pulps have one significant common feature: they consist of a continuum of different kinds of particles. These pulps contain long fibers up to 3 mm, shorter fibers, and debris (or fine materials) of very small dimensions (Salminen 2014). In papermaking, these very small objects of only a few micrometers play an important role in the development of tensile strength and stiffness, as well as in light scattering and in the forming and structure of paper web.

Grinding — invented in 1843 by F.G. Keller in Germany (Lönnberg 2009) — is the oldest mechanical pulping process; and answering v. Alfthan's question (1974), it is still a viable process that produces fibers and fines with high yield and low cost compared to other mechanical pulping processes, and to chemical pulping. One unproven – yet widely accepted – hypothesis in the field of mechanical pulping is that the mechanical weakening in the fiber walls and between the fiber layers emerges during the grinding process (Atack

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1981). According to Atack's hypothesis, the grinding process exhibits two phases: the preliminary loosening and the defibration. The peeling always proceeds in strict sequence and in the same direction. The angle of peeling bisects the angle between the longitudinal axis of the fibers and the direction of the grit motion. In common transversal grinding, the angle is nominally 45° (Atack 1977).

In grinding, wood is in place, and moving abrasive grits repeatedly treat the surface of the wood in the presence of water at 60 °C to 90 °C. The process is well defined and thus well understood (Sundholm 1999; Lönnberg 2009). This thorough understanding has led to progress in energy saving, such as the development of the energy-efficient grinding surface (Björkqvist 2001). This concept features a grinding surface superposed with sinusoidal radius modulation that is hypothesized to generate additional fatigue in the wood compared to a traditional flat grinding stone.

The parameters applied in the pulping process have an impact on the fines, and hence, their properties can be used for characterizing the pulping process. The fines have, by nature, a very large specific surface area, which leads to a strong correlation between the grinding energy consumption and the related amount of fines in mechanical pulping. Many of the characteristics of fines are direct consequences of the large specific surface area. Depending on the production process, the fines can be flaky or fibrillar. Fibrillar fines are like yarn in that they have relatively large specific surface areas and are, therefore, favored over flaky and chunky fines in regards to strength development. It has yet to be defined how fines and fatigue in mechanical pulping are interrelated.

In wood grinding, logs are pressed against a rotating stone, and the log axis, as well as the longitudinal axis of the fibers, is aimed parallel to the stone axis. This is called transversal grinding, as the stone surface velocity is perpendicular to the fiber axis. The deviation from transversal grinding can be in the stone's tangential plane, out from this plane, or both simultaneously. If the fibers are aligned so that there is no angle between the fiber length and the stone tangent, then the grinding is called longitudinal.

These aspects of wood alignment have been studied earlier, too. Brauns and Gavelin (1959) found that freeness decreased very sharply as the angle between the wood and the stone tangent and the energy consumption increased. Accordingly, the wood angle has neither an effect on pulp strength nor on the energy consumption if the pulp is ground to the same freeness level. Alfthan (1970) studied the effect of the wood angle in the tangential plane of the grinding stone and out of this plane. Alfthan found that longitudinal grinding increases the long fiber fraction and fines fraction while the amount of middle fractions decreased. Fiber peeling is an essential feature of grinding (Atack 1971).

Today, there are three common routes of energy saving in mechanical pulping: pre-treatments, maximized intensity, and fractionation. Pre-treatment can be either mechanical, thermal, or chemical. In extreme defibration intensity, wood and fibers are subjected to fierce forces in order to sway the balance between beneficial and fruitless work. Finally, systematic pulp fractionation and a combination of fractions ease the optimization of discordant target in pulp properties.

Grinding is still the most energy efficient method for mechanical pulp production. Grinding should be developed to meet the challenges of today. Firstly, it can produce surface layer material for board and paper grades. In foam forming, a thin and pure layer of fines could be attached on the surface of bulky base material. Secondly, composites will benefit from new kinds of lignin-rich high-aspect ratio materials. Finally, all good raw material for nano- or micro-fibrillated cellulose or similar materials are interesting. In this study wood blocks were fed into a laboratory grinder with various alignments to find out

how the wood alignments effect on grinding process and quality of pulp. There is particular interest in the amount and quality of fines and required energy to produce pulps with high fines content. The variation in pulp properties due to the natural variation in wood is excluded in this study.

EXPERIMENTAL

Blocks with a cross-section of 34 x 34 mm^2 were cut from three spruce logs. The blocks were cut with various angles in relation of the axis of the logs. Each batch, 400 to 500 g of wood (*Picea abies,* thinning from southern Finland) with a moisture content of 55%, included the same number of blocks from each log. Aberrant material such as branches was excluded. The stone diameter of the custom-built laboratory grinder was 300 mm, with a grinding area of 35x35 mm^2 and chute length of 200 mm. The peripheral speed of the stone was 15 m/s, and the stone type was Norton A601-N5VG. The shower water temperature was between 60 and 68 °C, and the wood feeding rate was kept constant at 0.5 mm/s.

Two types of wood alignment were studied. In principal, all possible wood alignments could have been represented by the radial angle α and the tangential angle β. The angle between the longitudinal axis of the wood fiber and the grinding stone axis in the plane of the grinding stone radius is called the radial angle α (Fig. 1, left). The radial angle is always between 0° and 90°, as the alignments of the other three quadrants are similar to the first one. The tangential angle β is the angle between the wood fibers and the stone axis in the plane of the stone surface tangent that is perpendicular to the stone surface (Fig. 1, right). The tangential angle is always between 0° and 90°. However, if both angles α and β are simultaneously non-zero, the rotational symmetry is lower and different situations are found for both angles in the range from -90° to 90°. Transversal grinding was used as reference, having both the radial angle α and the tangential angle $\beta = 0°$.
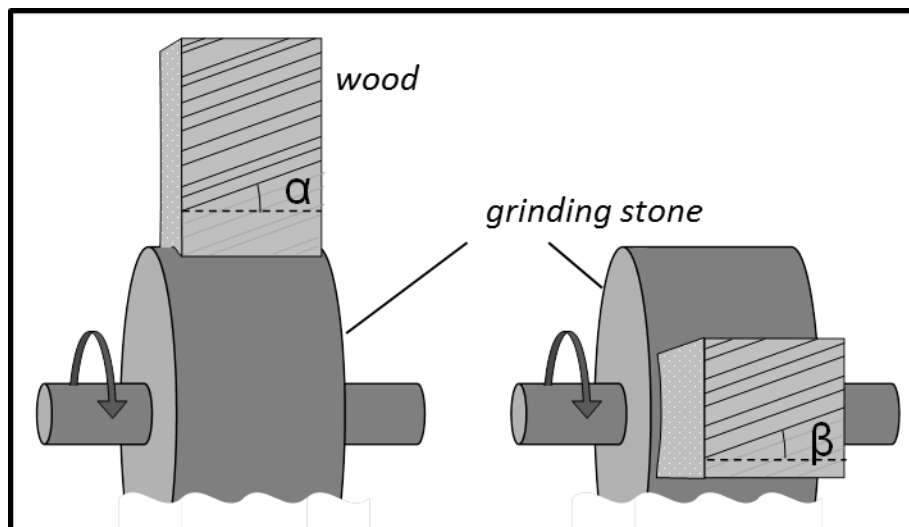

Fig. 1. Alignment of wood in grinding trials. The radial angle α is the angle in the radial plane between the grinding stone axis and the fiber longitudinal axis. The tangential angle β is the angle in the tangential plane between the grinding stone axis and the fiber longitudinal axis. The longitudinal axes of the fibers are denoted by dark lines, whereas the wood annual rings are not shown at all.

Grinding trials were performed for six radial angles α: 0°, 5°, 10°, 15°, 30°, and 45°. In the radial alignment series, the tangential angle β was set to 0°. In the series of varied tangential angle β (0°, 15°, 45°, and 90°), the radial alignment was kept constant at 0°. The resulting pulps were characterized by specific energy consumption, fractional composition, and fiber length. To obtain optical and strength properties, laboratory handouts were made according to EN ISO 5269-1 (with recirculated fines). The tensile strength was measured according to ISO 5270 and EN ISO 1924-2, and the light-scattering coefficient was determined according to ISO 9416.

The fractional composition was determined with a Bauer-McNett apparatus by Lorentzen & Wettre, Kista/Sweden (SCAN-CM 6) using the Tyler series: 28-mesh, 48-mesh, 100-mesh, and 200-mesh wires. The pulp fiber lengths were measured using the fiber analyzer KajaaniFS300™ by Metso (now Valmet; Finland) and given as length-weighted averages. The packing character of the fines in the wet state was determined by measuring the specific sedimentation volume (Marton and Robie 1969; Heikkurinen and Hattula 1993).

Macroscopic wood surfaces after grinding were captured by photography using the macro tool with the nearest possible distance to the samples. In order to analyze changes in terms of specific surface area in the grinding zone, layers from never-dried wood blocks were separated using a microtome RM 2055 with autocut unit by Leica, Wetzlar, Germany, equipped with a metal knife. Two different layers were cut, one from the surface up to 300 µm, and the other from a depth of 600 to 900 µm. The microtome cuttings were solvent-exchanged to acetone in a continuous extracting vessel. The wood cuttings in acetone were then critical point-dried with CO_2 in the Baltec CPD 030 apparatus by Leica, Wetzlar, Germany. The specific surface area of the wood cuttings was determined by the BET-method (Brunauer *et al.* 1938) based on the physical adsorption of nitrogen molecules (ISO 9277) of the critical point-dried samples. The BET-analysis was performed with the surface area analyzer Tri Star by Micromeritics (USA).

RESULTS

Groundwood Pulp Characterization

The wood alignment in grinding had a substantial effect on energy consumption and pulp quality. This is in line with earlier studies (Brauns and Gavelin 1959; Alfthan 1970). The results in Table 1 show that even a small radial angle of five to ten degrees between log and stone can cause a considerable change in pulp properties.

The changes in the fractional composition of the pulps are shown in Fig. 2. With small and increasing radial grinding angles, the proportion of the long fibers (McNett fraction $F_{>28}$) decreased, while the other fiber fractions remained constant (Fig. 2, left). A further increase of the radial grinding angle caused the proportion of the fraction F_{28-48} to decrease. This was then followed by the decrease of F_{48-100}, and finally by the decrease in fraction $F_{100-200}$. The amount of fines increased constantly with increased radial grinding angle until the fines content of the pulp was close to 90%. This result is in line with the literature (Brauns and Gavelin 1959; Alfthan 1970).

The effect of grinding angles on the pulp composition in the tangential plane was not as drastic as in the radial grinding (Fig. 2, right). With increasing tangential angle, the long fiber fraction $F_{>28}$ and the fraction of fines $F_{<200}$ increased, while middle fractions became diminished.

Table 1. Specific Energy Consumptions, Pulp and Handsheet Properties, and Characteristics of Fines (Specific Sedimentation Volume) for the Investigated Groundwood Pulps

Radial/ Tangential alignment α / β	Specific energy consumption	Fiber length	Fines content $F_{<200}$	Specific sedimentation volume of fines	Light scattering coeff. (sdv)**	Tensile index (sdv)**
°	MWh/t	µm	%	cm³/g	m²/kg	Nm/g
0 / 0	1.23	830	33.2	250	77.1 (0.8)	41.7 (1.3)
5 / 0	1.89	710	42.4	420	81.7 (1.0)	49.6 (4.1)
10 / 0	2.11	510	51.7	471	85.8 (1.7)	46.9 (5.6)
15 / 0	2.59	360	62.6	450	83.3 (1.9)	49.0 (4.4)
30 / 0	3.01	260	85.5	290	*)	*)
45 / 0	3.38	180	88.6	130	*)	*)
0 / 15	1.23	870	31.4	250	74.8 (0.8)	40.8 (1.8)
0 / 45	1.51	750	37.9	390	80.0 (0.6)	40.6 (3.9)
0 / 90	1.84	880	47.5	370	79.1 (1.7)	42.8 (3.9)

*The handsheets attached to the blotting board so that they could not be detached after drying.
**sdv = standard deviation in brackets; light scattering 5 and tensile index 10 measurements per experimental point
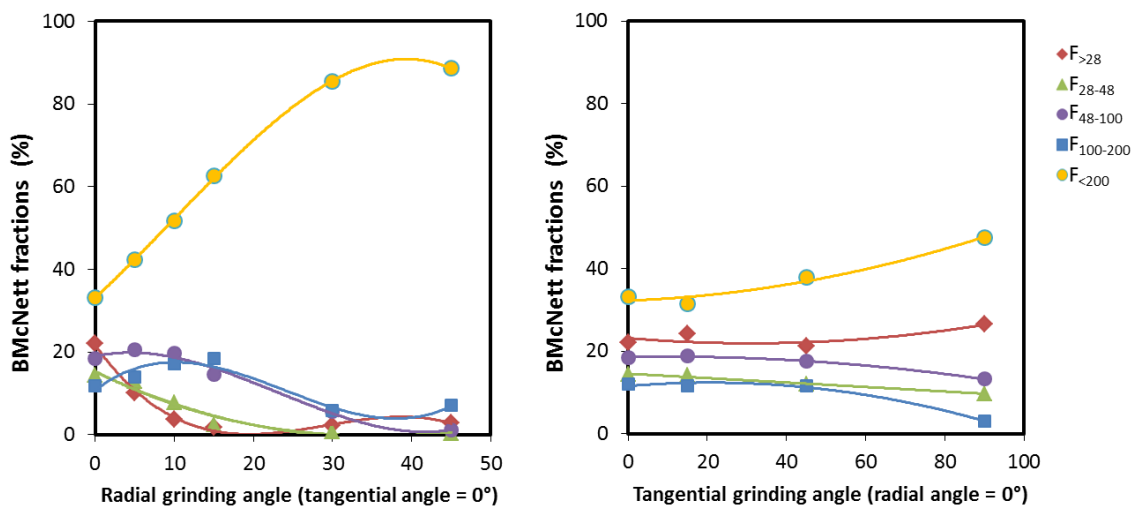

Fig. 2. The percentage of McNett fractions shown as a function of radial alignment between fiber and stone (left), and as a function of tangential alignment between fiber and stone (right).

With respect to fiber lengths (Fig. 3 left), a small change in radial grinding angle caused a drastic decrease in the average fiber length, while in tangential grinding, the average fiber length remained steady even when the pulp composition changed.

The specific sedimentation volume of the fines increased to a marked degree with radial grinding angles α up to 15° (Fig. 3, right). This development of the character of fines might be regarded as evidence of an improved bonding potential, which could be confirmed conclusively by the tensile index and the light-scattering coefficient (Sirviö and Nurminen

2004) (Table 1). Sheet properties from the samples that had the highest fines content could not be measured, because those hand sheets attached to the blotting board. Therefore data from light scattering and tensile index are limited. Available results showed that the specific sedimentation volume of fines and fines content correlated well with light scattering. Although the tensile index increased, the light scattering stayed at a high level. With radial angles α exceeding 15°, the pulp consisted mainly of fines (86 to 87%), which were of non-fibrillar shape, and the specific sedimentation volume dropped to 130 cm³/g at $\alpha = 45$°. In the tangential direction, the specific sedimentation volume was the highest at a grinding angle $\beta = 45$°, and it remained at a high level up to a grinding angle $\beta = 90$°.
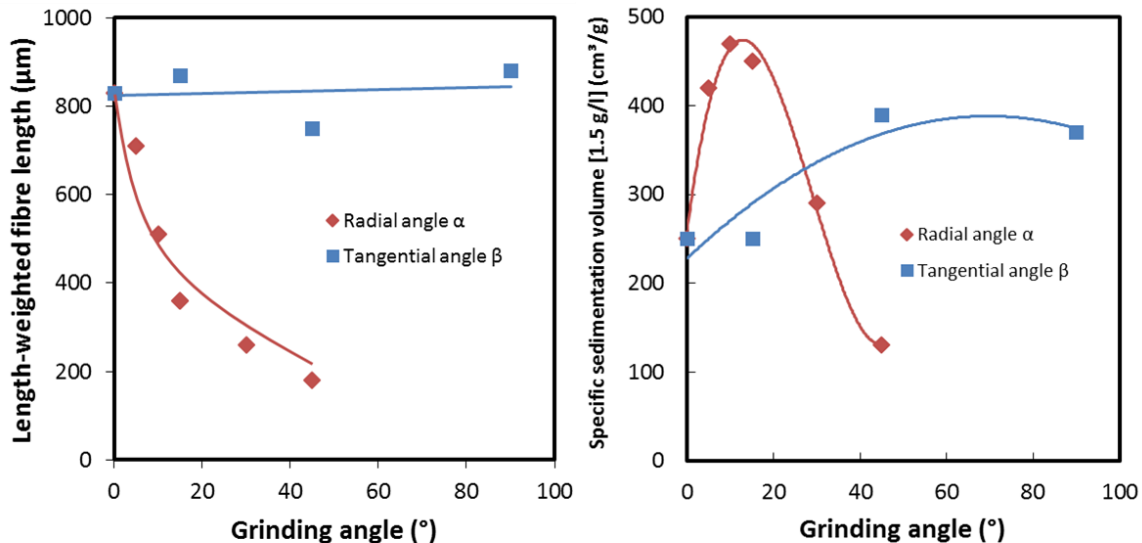

Fig. 3. The length-weighted average fiber length of pulp (left) and the specific sedimentation volume of fines (right) *versus* the radial and tangential grinding angles

As shown in Fig. 4, the fines content and the specific energy consumption in grinding followed each other, but the surface area of the particles (measured as specific sedimentation volume) was not so straightforward.
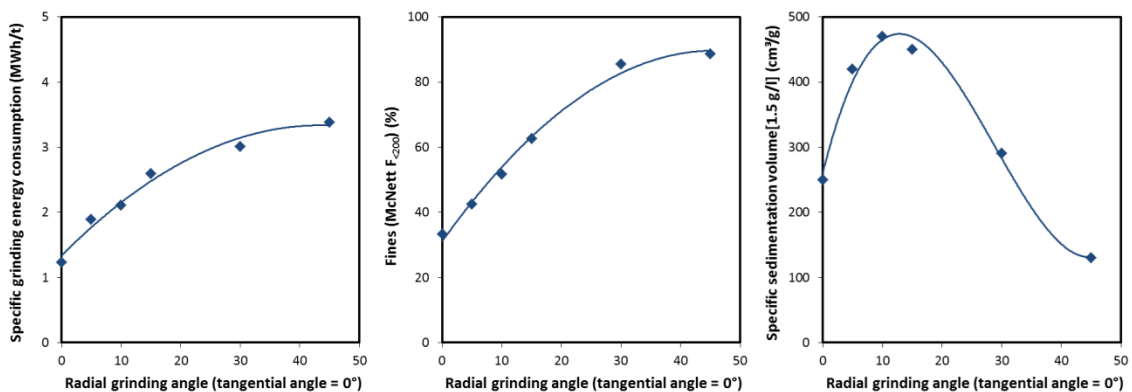

Fig. 4. Specific grinding energy consumption (left), amount of fines (center), and quality of fines in terms of specific sedimentation volume (right) in grinding *versus* radial alignment between wood block and grinding stone

To gain a greater insight into how and where defibrillation occurs in a wood block, the BET-specific surfaces area were measured in different depths of the wood block, taken from interrupted grinding and from the pulp. Wood blocks were ground at a zero angle in the radial and in the tangential direction, which corresponds to traditional grinding. The changes in the BET-specific surface area inside the wood block indicated that the loosening of the wood structure started close to the wood surface. At a depth of 0.6 to 0.9 mm, BET-specific surfaces areas had the same values as deeper surfaces, but in the range of depth of 0 to 0.3 mm, a clear increase was detected. The specific surface area of the untreated wood was 0.08 m^2/g. At a depth of 0 to 0.3 mm, it was 0.2 to 0.3 m^2/g, and for the groundwood pulp, it was 10 to 13 m^2/g.

The increase of the BET-specific surface area close to the wood surface was in line with previous observations, in which wood fatigue was detected by thermoporosimetry and ultrasonic methods (Salmi *et al.* 2011). Most new surfaces were created during the final separation of fibers, or after. Therefore, significant extra grinding after the fiber is separated from the wood matrix is unlikely, because the length of grinding area of the laboratory grinder was only 35 mm.

Grinding Phenomena

According to Ilvessalo-Pfäffli (1995), the typical mean length of a Norway spruce fiber is 3.4 mm, ranging from 1.1 to 6.0 mm, with a mean width of 31 µm ranging from 21 to 40 µm. Using simplified arguments, the ratio between these dimensions means that on alignments larger than 0.57°, the length of the wood fiber limits the length of the resulting pulp fiber. Moreover, all pulp fibers are shorter than 500 µm, if the alignment between the fiber longitudinal axis and the stone axis is 3.4°. This simple algebra, assuming fiber liberation without any peeling (Atack 1971), emphasizes the significance of the alignment in grinding (Fig. 5). Figure 3 shows that this concept fits well with the results now achieved.
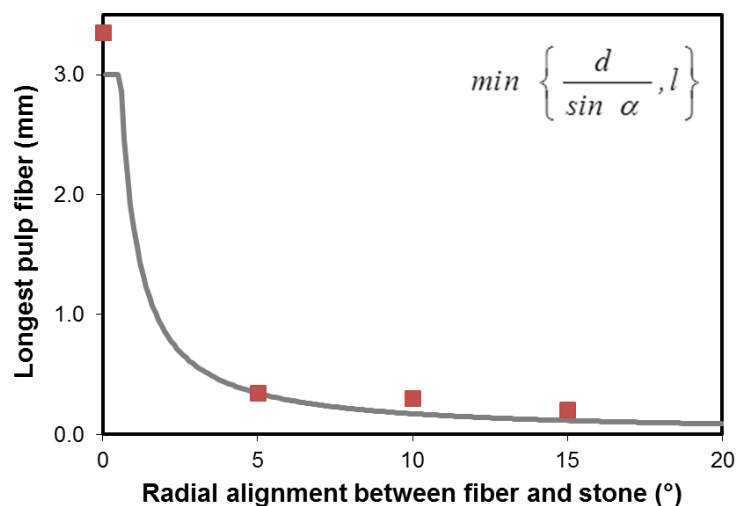

Fig. 5. The median of pulp fibers as a function of *α*, the radial alignment between fiber and grinding stone (gray line), according to Atack (1971). The corresponding arithmetic mean fiber length results from trials are shown in red (*d* = fiber width, *l* = fiber length).

In conventional grinding, where fibers are parallel to the grinding stone axis, fibers are separated from wood one fiber layer at time (Atack 1971), see Fig. 6.
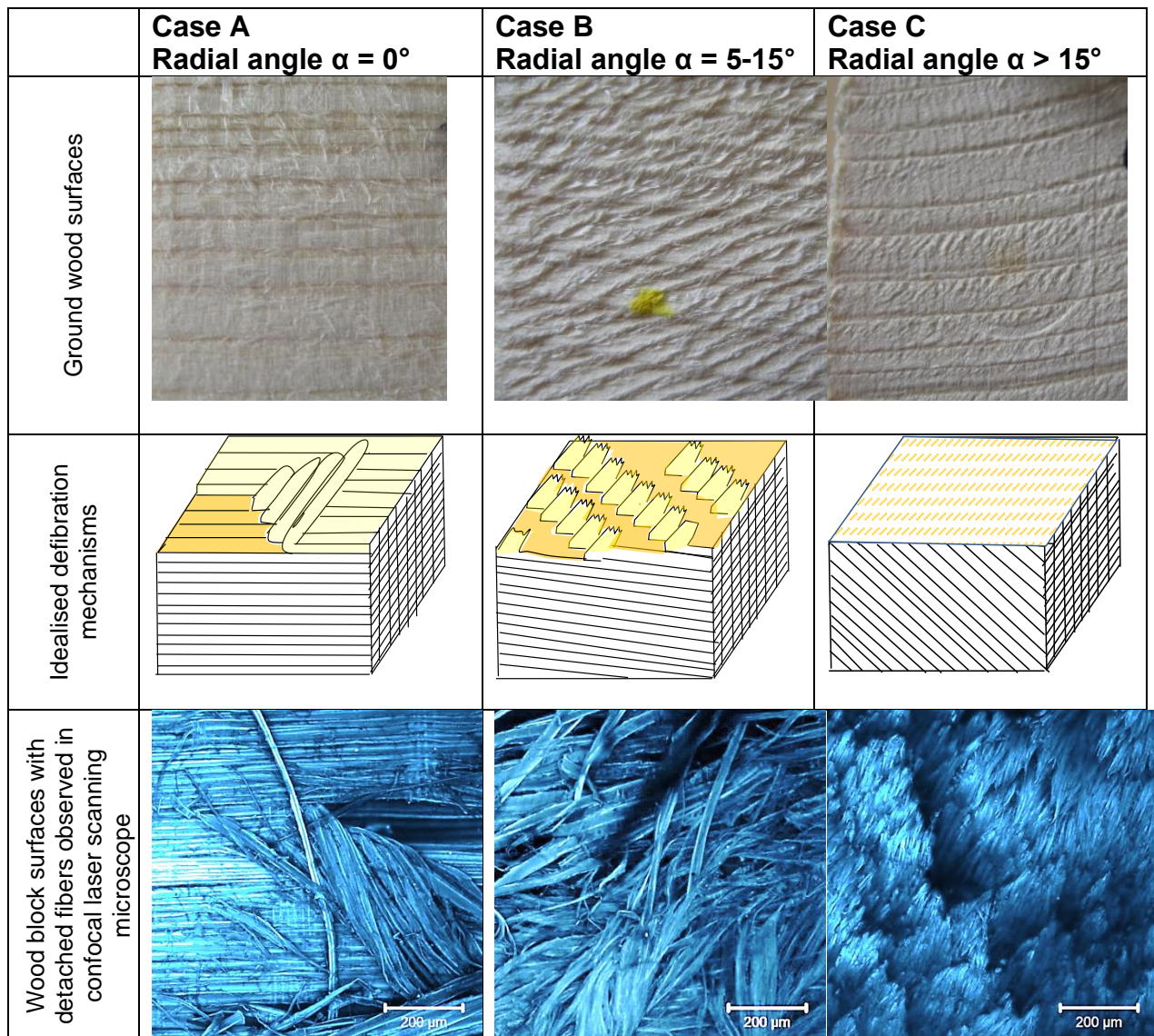
	Case A Radial angle α = 0°	Case B Radial angle α = 5-15°	Case C Radial angle α > 15°
Ground wood surfaces			
Idealised defibration mechanisms			
Wood block surfaces with detached fibers observed in confocal laser scanning microscope			

Fig. 6. Ground wood surfaces (above), ideal defibration mechanisms (center), and fiber detachment from wood blocks (below) for different radial grinding angles: Reference grinding (radial angle *α* = 0°, Case A), small radial angles (*α* = 5 -15°, Case B), and bigger radial angles (*α* >15°, Case C).

It is evident that pressure pulses generated heat and fatigue in fiber layers close to the surface. This caused softening of the lignin in the middle lamella, and fibers peeled out easily from the wood matrix. Fibers and fiber bundles bent over the wood matrix in the rotating direction of the grinding stone. The pressure was then applied intensively to the protruding fibers and the fiber matrix underneath. Therefore, the matrix below the partly released fibers was heated more than the surrounding area. This enabled continuous fiber peeling without intensive shortening of fibers (Fig. 6, Case A).

The grinding process changes drastically when there is a radial angle between the grinding stone and the longitudinal fiber direction. Fiber peeling is partly prevented because one end of the fiber is deep in the wood matrix. Cases B and C illustrate this situation. A fiber cannot be separated before the process is applied to the attached end of

the fiber. With small angles (5° to 15°, Case B), the free tail of the fiber can bend in the rotational direction. The maximum length of the free tail is probably determined by the radial angle; the higher the angle, the shorter the longest possible tail. In order to keep the feeding rate constant, the feeding pressure must be increased with an increased radial angle. This causes more pressure to act on free tails and more fatigue on the layer closest to the surface, resulting in short but highly fibrillated fibers and high-quality fines. When the radial angle exceeds 15°, the free tails are very short, or there are no tails at all (Fig. 6, Case C). The highest modulus of elasticity of a fiber occurs in the direction of the fiber axis. When the angle increases, the pressure is increasingly applied to the fiber axis and the amplitude of repeated compressions decreases, with the consequence that structure loosening by fatigue decreases. Fibers are crushed or fatigued due to cycling straining more than refined as soon as they reach the surface. Almost all wood material becomes fines, but of lower quality than in normal grinding (the feeding speed is the same for all cases).

The mechanism can be seen very clearly already from the noticeably symmetrical profile of the released fibers on the ground surface of the wood blocks (Fig. 6, above). However, with higher magnification, the release of fibers from the conventionally ground samples show this mechanism (Fig. 6, center, Case A).

Evidently, the main development of fiber properties such as inner and outer fibrillation, as well as of the amount and properties of fines, occurs on the wood surface just before the fiber is released from the wood matrix. The fiber is then at a favorable position for the mechanical treatment when it is bent on the wood surface (Fig. 6, Case A). This is assumed to resemble the situation in the refiner plate gap during TMP refining. On that surface, fibers are refined to their final properties.

This refining phase can either be fatigue-based or force-based. In the fatigue-based defibration phase, the structure of the fiber is loosened by cyclic compressions (*i.e.* fatigue) before it is bent onto the surface. Pressure pulses produce fibrillar material, and the fibers develop towards a good bonding ability. In force-based grinding, this process is harsh and the fiber wears and crushes immediately on the surface into small particles with low bonding ability. The proportion of fibrils produced in force-based refining is smaller than in the case of fatigue-based refining (case C in Fig 6).

CONCLUSIONS

1. The pulp composition and fines quality in grinding can be controlled by the wood alignment angle against the stone surface. Radial refining with small angles (5-15°, case B in Fig 6) leads to fatigue-based refining, in which the fiber structure is loosened by cyclical straining and fatigue before the fibers are bent onto the surface. Pressure pulses produce fibrillar fines and fibers of good bonding ability. When the angle increases, the fibers are worn and crushed immediately on the surface into small particles with low bonding ability.

2. Grinding was found to be extremely sensitive to the radial angle between wood and the grinding stone. If this angle differs from zero, the process starts to require more energy, producing shorter fibers and more fines. With radial angles higher than 30°, almost pure fines are produced. The radial angle largely determines the fiber length and the quality of fines.

3. The change of the tangential grinding angle does not have an effect as drastic as the change in the radial angle. An angle of 90° in a tangential direction produces a higher amounts of fines and of long fiber fraction, compared to transversal grinding.

4. The results emphasize actions that occur just on the surface of the wood when fibers are partly liberated from the wood matrix. In this alignment, individual fibers are unshielded from forces generated by the grinding stone. Most of the new surface is created during precisely this phase.

5. The results indicate that grinding can be force-based or fatigue-based. In force-based grinding, the production is done by forced feeding, and the free tails of the fibers are worn and crushed immediately on the wood surface into small particles with low bonding ability. The resulting groundwood pulp consists of short fibers with low-quality fines. In the fatigue-based grinding, the free tails of the fibers go through similar actions as fibers in a refiner, and the product consists of higher fibrillar content. Evidently, force-based and fatigue-based features are present simultaneously in the typical grinding process, and the quality of the produced groundwood pulp is determined according to the dominating feature.

6. In this research only one wood sample was studied. Sample to sample variation is large in wood, just like in any natural material. This may restrict the generality of the results. Secondly, only one grinding stone surface was studied, and grinding is very sensitive to possible microscopic imperfections in the stone surface. Other grinding stone surfaces may thus result in different results. However, we believe that the trends in pulp properties and energy consumption caused by a varying grinding angle have high generality.

7. A detailed microscopic analysis of the wood surfaces and the corresponding pulps has already been published in part 2 of this study (Heinemann *et al.* 2016).We expect that other studies on this subject will be published soon.

8. Similar deliberate wood alignment is used in "fines stone" surface design (Saharinen *et al.* 2016). This new stone grinds wood logs almost completely to fines.

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