The Effect of Wood Alignment on Wood Grinding – Part 2: Fines Character and Microscopic Observations

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During industrial wood grinding, logs are pressed against a rotating stone, with the logs and fibre axes parallel to the axis of the stone. For this study, 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, the amount, and the quality of the fines were measured, and a grinding mechanism is proposed. In this paper, the obtained results showed that the pulp quality was highly sensitive to the angle between the stone surface and the log, and different for fatigue-based and force-based grinding. The tests were observed using microscopic techniques and discussed in terms of fines amount and fines quality. In gentle refining, the fibre structure is loosened by fatigue before it is bent on the surface, pressure pulses produce fibrillar material, and fibres develop good bonding ability. In forced grinding, the process is "violent" and the fibre wears and is crushed immediately on the surface into small particles with low bonding ability.

Keywords: Groundwood; Grinding angle; Wood alignment; Norway spruce; Fines properties; Light microscopy; CLS

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INTRODUCTION

Mechanical pulps can be produced using specific attrition processes. Groundwood (GW), pressure groundwood (PGW), and thermomechanical pulp (TMP) all apply similar shear and compression forces on fresh wood and fibres. In grinding, a high strain rate of cyclic compressive loads heat, loosen, and fatigue the wood (Atack 1981; Lucander *et al.* 2009; Salmi *et al.* 2009), whereas shear loads free the hot fatigued fibres from the solid wood. As a result, a capable pulp is obtained. All the mechanical pulps have one significant common feature: they consist of a continuum of different kinds of particles (Brecht and Klemm 1953). These pulps contain long fibres (up to 3 mm in length), shorter fibres, and debris or fine materials of very small dimensions. In papermaking, these very small objects, characterized down to a size of only few micrometres, play an important role in the development of tensile strength and stiffness, as well as in light scattering and the forming and structure of paper web.

The parameters of the pulping process applied reflect 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 the strong correlation between the specific energy consumption and the related amount of fines in mechanical pulping. Many of the assets of fines are direct consequences of the large specific surface area. Depending on the production process, the fines can either be flaky or fibrillar. Fibrillar fines are like yarns in that they have larger specific surface area and are, therefore, favourable relative to flake and chunky fines in regards to its strength development. Furthermore, the relationship between fines and fatigue in mechanical pulping has yet to be defined.

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

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

The aspects of wood alignment have been studied in previous research (Brauns and Gavelin 1959; Alfthan 1970; Atack 1971). Recent studies on fatigue-based and force-based grinding (Saharinen *et al.* 2015) have shown the essential differences of the resulting fibre and fines characteristics, as well as their effect on strength and optical properties. In this study, the same samples investigated by Saharinen *et al.* (2015) were inspected using microscopic techniques to verify the pulp quality results obtained with different grinding angles.

EXPERIMENTAL

Laboratory grinding of special wood blocks was performed in a custom-built laboratory grinder. The grinding procedure is described more detailed elsewhere (Saharinen *et al.* 2015). For the special wood blocks, three spruce logs were cut to 34 x 34 mm blocks with various angles in relation to the axis of the logs. Each batch included 400 to 500 g of wood with a moisture content of 45%, with the same number of blocks from each log, and aberrant materials, such as branches, were excluded.

Two types of wood alignment were studied. All possible wood alignments can be represented by the radial angle α and the tangential angle β (Saharinen *et al.* 2015). The 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°.

From the resulting pulps, the fines quality was determined from diluted fines slurries, separated from the original pulps in a Dynamic drainage jar (DDJ) "model KCL" (OY Keskuslaboratorio, Espoo/Finland) equipped with propeller agitation (1000 rpm) and a 200 mesh metal screen (openings 76 x 76 µm square sides). One litre of pulp suspension (5 g/L o.d.) was transferred to the DDJ. Agitation was started, and the valve was opened to the operational flow rate of 500 mL/min. Washing with deionized water was repeated in 500 mL lots until a total of 10 litres filtrate was collected. Finally, the fines suspension was concentrated by standing over night, and the supernatant clear filtrate was removed (Krogerus *et al.* 2002). The specific sedimentation volume (Marton and Robie 1969; Heikkurinen and Hattula 1993) and the amount of fibrillar fines (Luukko and Paulapuro 1999) are two important parameters when describing the fines quality. The fractional composition was determined with a Bauer-McNett apparatus (SCAN-CM 6, Lorentzen &

Wettre, Kista/Sweden) using the Tyler series: 28-mesh, 48-mesh, 100-mesh, and 200-mesh wires, and the small middle fraction $F_{100\text{-}200}$ was the mass reject on the smallest screen (200 mesh) after passing through the previous screen (100 mesh). The fines amount (fraction $F_{<200}$) was calculated as the mass difference between the sum of all reject masses obtained from the used Bauer-McNett screens and the sample feed (10 g dry). All the fractions are given as a percentage of the sample feed. The pulp fibre lengths were measured with the fibre analyser KajaaniFS300™ by Metso (now Valmet, Espoo/Finland) and given as length-weighted averages.

Microscopic methods were used to understand and verify the pulp development in grinding by its morphological features. To characterize the grinding process itself, ground surfaces of the remaining wood blocks were inspected by confocal laser scanning microscopy (LSM 710 with Axio Imager, Z2 by Carl Zeiss, Zeiss, Oberkochen, Germany). Utilizing the lignin auto-fluorescence in the wood, the laser diode 405-30 was used (with an emission wavelength of 410 to 514 nm) for all samples. Images of 848.5 x 848.5 µm were scanned with a resolution of 512 x 512 pixels, *i.e.* the pixel size was 1.66 µm. In z-direction, the resolution was between 5 and 10 µm depending on the surface roughness of the wood blocks. For image processing, the implemented software ZEN 2012 by Carl Zeiss was used. Unstained groundwood pulp samples were inspected in transmitted light using brightfield mode with the microscope (BX50, Olympus, USA) emphasizing the appearance of the fines material.

Two samples were selected for the microscopic image analysis according to their fibrillary fines content, proportion of small middle fraction $F_{100\text{-}200}$, and specific sedimentation volume for both radial grinding and tangential grinding. Additionally, the samples with both grinding directions in non-zero positions were observed. The selected pulps are marked with circles in Fig. 1.

RESULTS

Groundwood Fines Characterization

The wood alignment in grinding had a substantial effect on the quality of the generated fines. The results in Table 1 show that even a small radial angle of 5 to 10 degrees between the log and stone cause a considerable change in the fines properties.

The microscopic appearance, described in greater detail in the following, is in concordance with the proportions of Bauer-McNett fractions (Saharinen *et al.* 2015). On small radial angles, the small middle fraction $F_{100\text{-}200}$ increased at first (Fig. 1 left), then subsequently decreased as material from coarser fractions comminute to finer particles. The amount of fines increased constantly in radial grinding until the fines content of the pulp was close to 90%. This result is also in line with the literature (Brauns and Gavelin 1959; Alfthan 1970).

The effect of angles between the log and stone axis on the pulp quality was not as drastic in the tangential plane as in longitudinal grinding, possibly caused by the small radius of the grinding stone in the laboratory grinder. As the tangential angle increased, the fines fraction $F_{<200}$ increased while the small middle fraction decreased.

More information about the development of the quality of groundwood pulps affected by grinding angles can be read in part 1 of the publication by Saharinen *et al.* (2015).

Table 1. Quality Parameters of Groundwood Pulps (Saharinen *et al.* 2015) and Separated Fines

Radial/ Tangential alignment α / β	Fibre length	Small middle fraction $F_{100-200}$	Fines content $F_{<200}$	Specific sedimentation volume of fines	Fibrillar content of fines
°	µm	%	%	cm³/g	%
0 / 0	830	11.9	33.2	250	36
5 / 0	710	13.9	42.4	420	46
10 / 0	510	17.1	51.7	471	47
15 / 0	360	18.4	62.6	450	45
30 / 0	260	5.9	85.5	290	43
45 / 0	180	7.1	88.6	130	38
0 / 15	870	11.6	31.4	250	40
0 / 45	750	11.6	37.9	390	40
0 / 90	880	3.0	47.5	370	46
15 / 90	250	9.1	86.6	190	38
15 / -90	520	12.5	54.3	190	48

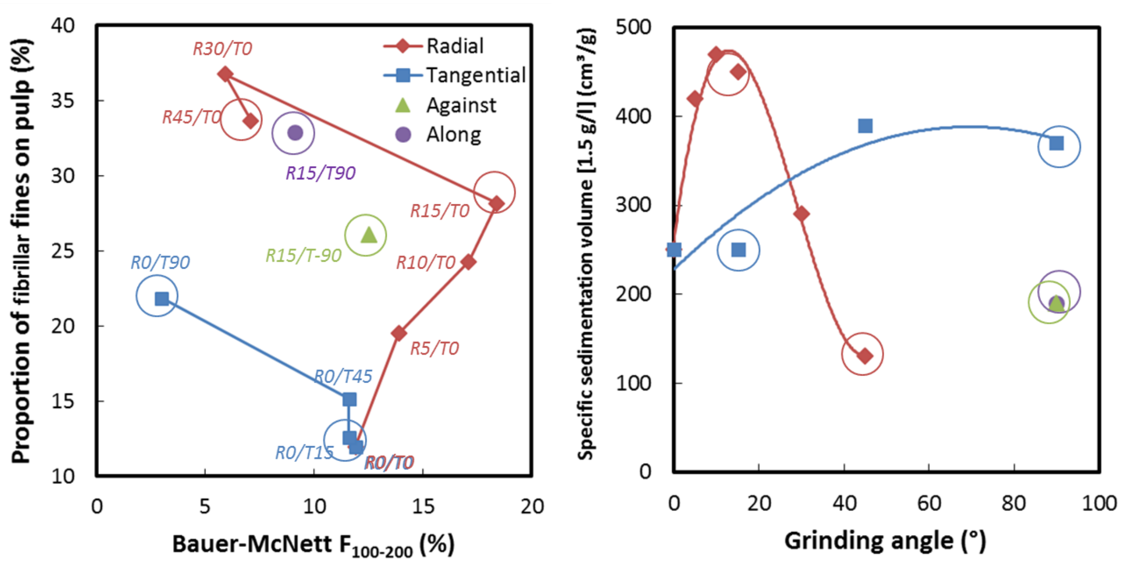

Fig. 1. Proportion of fibrillar fines *versus* short middle fraction $F_{100-200}$ (left), and specific sedimentation volume versus grinding angle (right). Circles: samples selected for microscopic inspection.

Features in Confocal Laser Scanning Microscopy

The manner in which the fibres are peeled off from the wood matrix during the grinding process could be examined by scanning the surfaces of remaining wood blocks after grinding in the confocal laser scanning microscope (Figs. 2 and 3).

Figure 2 shows the surface parts of wood blocks from radial grinding (above) and from tangential grinding (below). At a lower radial grinding angle (α = 15°, image a), fibres are pulled off around the middle lamella, and ray cells are broken. During this process, many fibres break, but an essential proportion of longer fibre parts remain in the resulting pulp. At a higher radial grinding angle (α = 45°, image b), all fibres seem to break during the grinding process, as the wood surface becomes brushed, leading to a low fibre length and a high fines proportion in the resulting pulp. At a lower tangential grinding angle (β = 15°, image c), long fibres are pulled off, creating fibre kinks and fibrillar fines. The high tangential grinding angle (β = 90°, image d) causes a high proportion of long fibril-like fines, and the fibre length is well preserved.

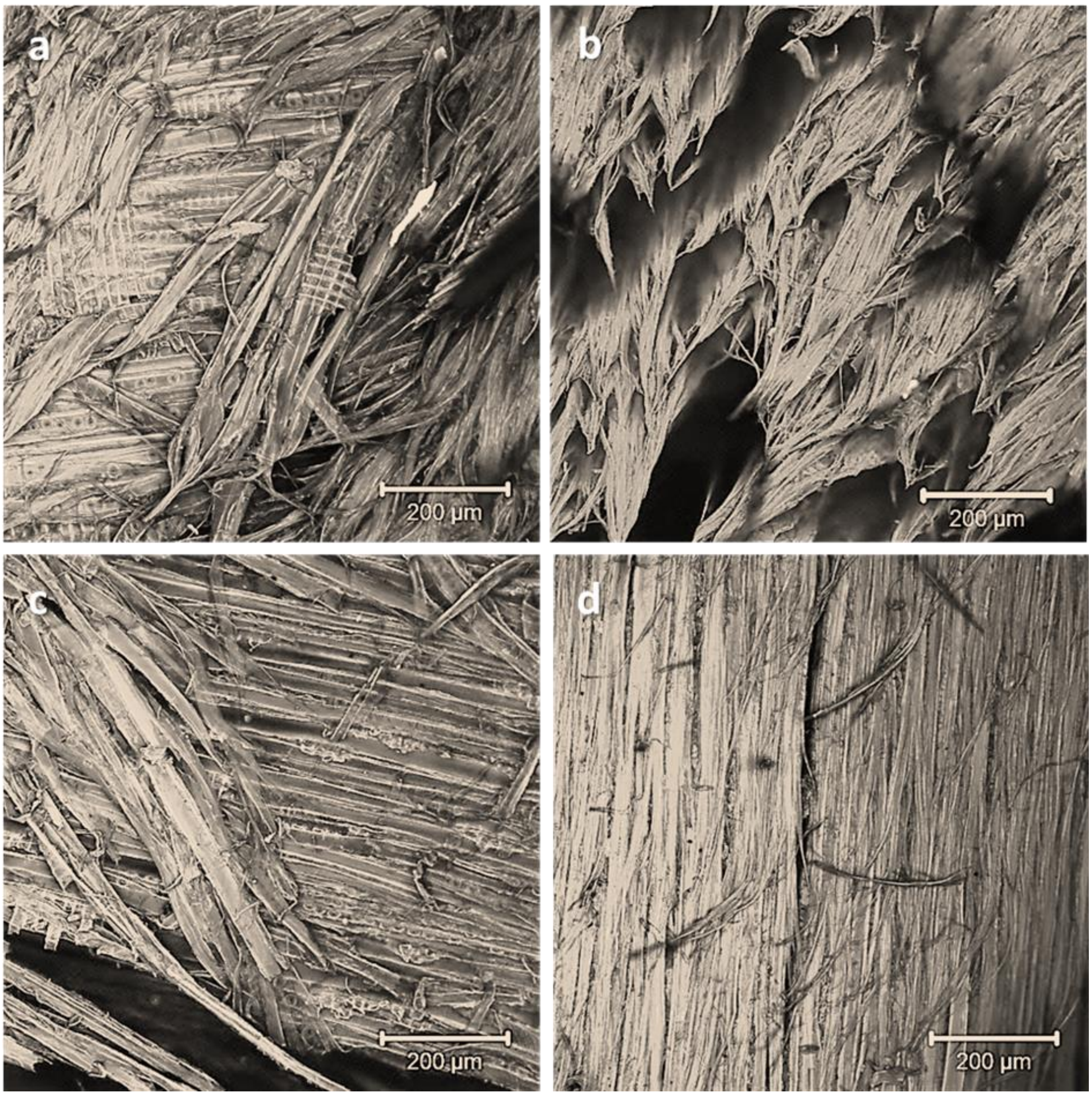

Fig. 2. Ground surfaces of wood blocks in confocal scanning laser microscope. Above: Radial grinding (tangential grinding angle β = 0°) - image a: radial grinding angle α = 15°, image b: radial grinding angle α = 45°). Below: Tangential grinding (radial grinding angle α = 0°) – image c: tangential grinding angle β = 15°, image d: tangential grinding angle β = 90°.

Figure 3 shows the effect of grinding direction on wood blocks with a high tangential grinding angle β of 90°, and a radial grinding angle α of 15°. For the reference sample, the radial angle α was 0°.

When the grinding occurred along the fibre orientation (tangential grinding angle β=90°), fibres and length-cut fibre parts (macrofibrils) were brushed off and bent (image c in Fig. 3). Many fibres were broken at their weak kink points, resulting in a high proportion of fibrillar fines. Fibres with preserved length were often twisted as well. Large flakes of peeled-off outer fibre wall also contained pit areas found in the fines; hence, many of the fines are also thick and heavy. Subsequently, a low specific sedimentation volume was measured (Table 1).

Grinding against the fibre direction (tangential angle β = -90°) caused the greatest damage observed from all grinding trials (image b in Fig. 3). This is visible on the wood block surfaces to the naked eye. Big fibre bundles were broken out, creating a high number of shives. The fibres were already deformed in the wood matrix before they were liberated during the grinding process, and surface peeling seemed to occur resulting in a huge proportion of "crill".

Fig. 3. Ground surfaces of wood blocks, observed through a confocal scanning laser microscope. Image a: Reference (radial grinding angle α = 0°, tangential grinding angle β = 90°), image b: grinding direction against the fibre direction (radial grinding angle α = 15°, tangential grinding angle β = -90°), image c: grinding direction along the fibre direction (radial grinding angle α = 15°, tangential grinding angle β = 90°).

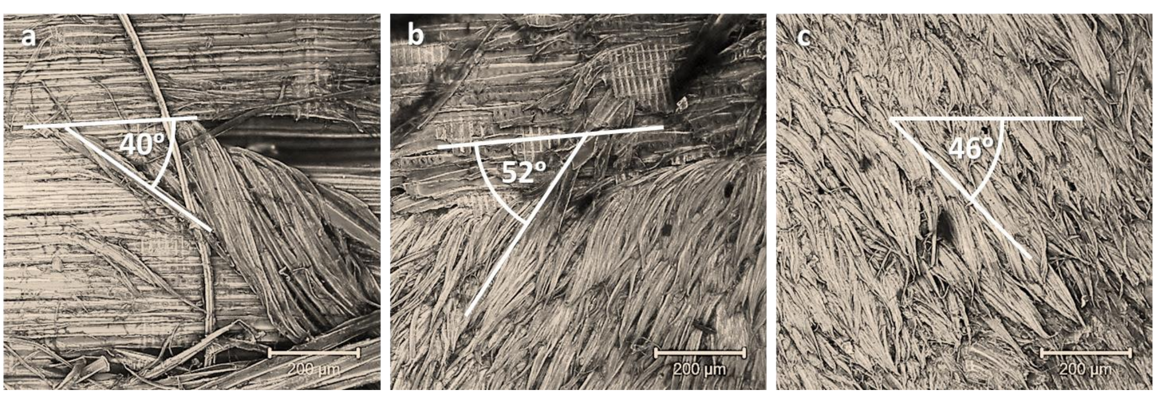

Fig. 4. Surfaces of radially ground wood blocks, observed by a confocal scanning laser microscope, indicating the peeling angle for fibres combed off the wood matrix. Image a: radial grinding angle α = 0°, image b: α = 15°, image c: α = 30°. Tangential grinding angle β was always 0°.

The wood log alignment in radial grinding has no effect on the angle by which the fibres are combed off from the wood matrix. This so-called peeling angle was calculated from images captures by confocal scanning microscopy. The average angle calculated from the images in Fig. 4 was 46°, which is in concordance with Atack's presumption of 45° (Atack 1977).

Features in Light Microscopy

Figures 5 and 6 show the respective groundwood pulps using transmitted light microscopy and emphasizing the fines' character.

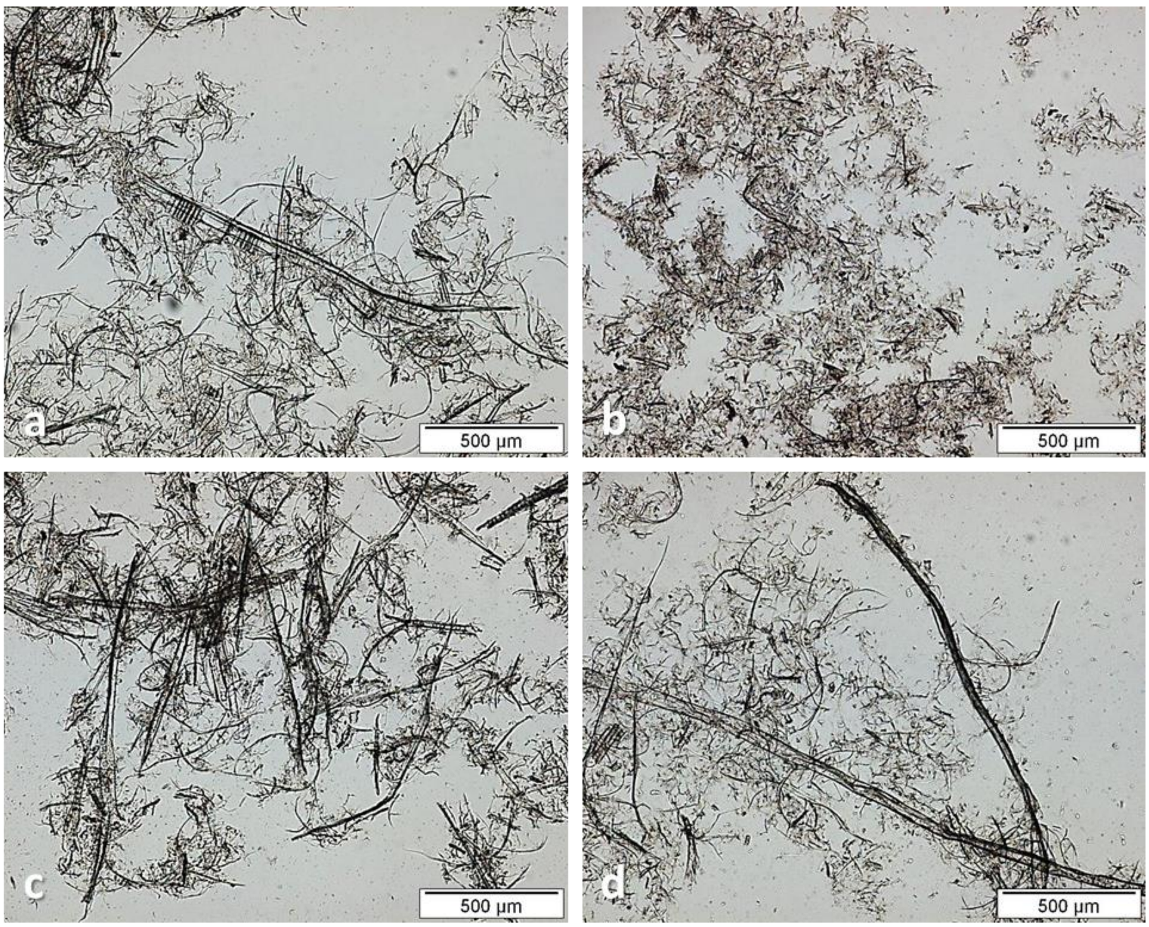

Fig. 5. Groundwood samples as observed by a transmitted light microscope. Above: Radial grinding (tangential grinding angle β = 0°) - image a: radial grinding angle α = 15°, image b: radial grinding angle α = 45°). Below: Tangential grinding (radial grinding angle α = 0°) – image c: tangential grinding angle β = 15°, image d: tangential grinding angle β = 90°.

From the pulp images in Fig. 5, the different fines' character in radial grinding, with the tangential angle β = 0° between the pulps ground with low radial angle α = 15° (image a) and high radial angle α = 45° (image b), becomes obvious. Not only does the amount of fines differ (Bauer-McNett fraction $F_{<200}$: 51.7% and 88.6%, respectively), but also the fines shape described by sedimentation behavior was changed as well (specific sedimentation volume at 1.5 g/L consistency: 470 cm^3/g and 130 cm^3/g, respectively). Images c and d in Fig. 5 show tangentially ground samples with the radial angle α=0°. It can be concluded that a small tangential angle β = 15° (image c) results in shorter fibres, compared to the larger tangential angle β = 90° (image d), but the mean length-weighted fibre length of both samples does not differ significantly. The fines proportions are similar too, but the pulp ground with the larger tangential angle β of 90° has more fibril-like material. In the pulp ground with the smaller tangential angle β of 15°, (image c), short fibrils tend to cluster in strong, non-destructible "clouds" around longer fibres.

Figure 6 shows the effect of grinding direction on wood blocks with a high tangential grinding angle β of 90° and a radial grinding angle α of 15°. For the reference sample, the radial angle α was 0°.

Grinding along the fibre direction (β = 90°) created well-preserved long fibres, which often appear twisted. Large flakes of peeled-off outer fibre wall also contained pit areas, and many coarse fibrils or thicker macrofibrils with a wider length distribution were produced as well.

As can be seen from the wood surfaces in confocal microscopy (Fig. 3), grinding against the fibre direction (β = -90°) is a rather destructive process in regards to the fibre dimensions and shape. The resulting fibres and the broken pieces of mainly thick-walled latewood fibres are rather straight. Fibrillar fines have low weight and can be seen in transmitted light because their high numbers and strong clustering to larger entities provide suitable optical contrast. Many small and slender particles are the reason that both with grinding along and against the fibre direction, a similar proportion of small middle fraction $F_{100\text{-}200}$ was measured in the Bauer-McNett apparatus. Clustering of the lightweight fines to heavier particles is also affecting the sedimentation ability of the material, thus resulting in small numbers for the specific sedimentation value (see right chart in Fig. 1).

Compared with the samples ground along and against the fibre direction, the reference groundwood pulp contained more and longer fibrils, as well as well-preserved fibres from latewood. Brush-like shives, often seen in the grinding against fibre direction (image b in Fig. 6) occurred only occasionally.

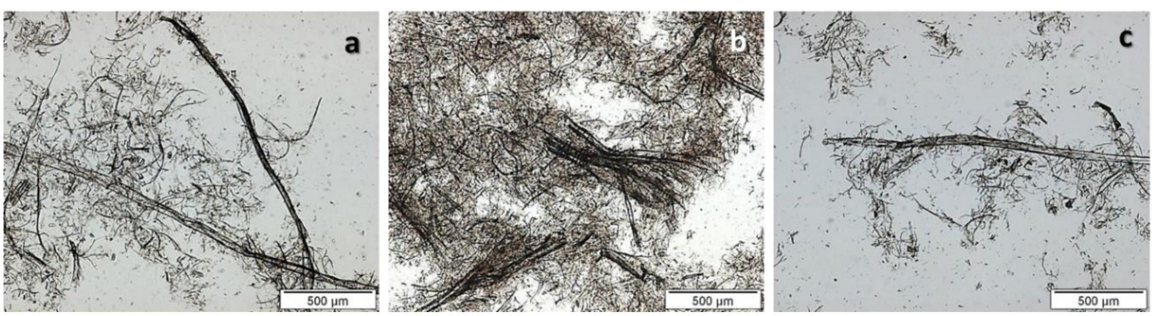

Fig. 6. Ground samples as seen through a transmitted light microscope. Image a: Reference (radial grinding angle α = 0°, tangential grinding angle β = 90°), image b: grinding direction against the fibre direction (radial grinding angle α = 15°, tangential grinding angle β = -90°), image c: grinding direction along the fibre direction (radial grinding angle α = 15°, tangential grinding angle β = 90°).

CONCLUSIONS

1. 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, and produces shorter fibres and more fines. When using a radial angle higher than 30°, almost pure fines are produced.

2. The radial angle largely determines the quality of fines. Radial refining with small angles (5 to 15°) leads to fatigue-based refining, in which the fibre structure is loosened by fatigue before the fibres are bent onto the surface. Pressure pulses produce fibrillar fines. When the angle becomes bigger, the fibres are worn and crushed immediately on the surface into small particles with low bonding ability.
3. The change in the tangential grinding angle does not have an effect as drastic as the change in the radial angle. An angle of 90° in the tangential direction produces higher amounts of fines compared to transversal grinding.
4. The results indicate that grinding occurs simultaneously for both force-based and fatigue-based conditions. The quality of the produced groundwood pulp is determined by its dominating feature.

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