Ground Wood Fiber Length Distributions

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This study considers ground wood fiber length distributions arising from pilot grindings. The empirical fiber length distributions appear to be independent of wood fiber length as well as feeding velocity. In terms of mathematics the fiber fragment distributions of ground wood pulp combine an exponential distribution for high-length fragments and a power-law distribution for smaller lengths. This implies that the fiber length distribution is influenced by the stone surface. A fragmentation-based model is presented that allows reproduction of the empirical results.

Keywords: Grinding; Ground wood; Fiber length; Model; Theory; Mechanical pulp

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INTRODUCTION

Fiber length is a key attribute that determines fiber furnish quality for packaging and printing products utilizing mechanical pulps. Fiber length correlates strongly with paper tear strength, which is one measure of the web runnability (Mannström 1971). The portion of reinforcement chemical pulp often depends on mechanical pulp fiber length, yet the relation is not linear (Lehto *et al.* 2010). To describe the main tendency in simple terms, the longer the fibers in high yield pulp, the better will be the performance of the pulp. The rule applies for both highly specified attrition processes, namely ground wood (GW) and thermomechanical (TMP) pulps. In the case of ground wood pulp, which has a typically shorter fiber length than TMP, the need for high average fiber length is pronounced. Despite some disagreement, ground wood pulping still can be considered as a viable process (Alfthan 1974).

Mechanical pulping produces fibers and fines with high yield and low cost when compared with chemical pulps. Energy is a large cost factor in mechanical pulping, and its importance is now increasing (He *et al.* 2013). To manage the balance between pulp price and quality, it is beneficial to understand the factors governing fiber length in ground wood pulping. In addition, the pulp fines interlink with fiber length, as they are small parts of the fibers. Wood grinding cannot be tuned solely for high fiber length because papermaking sets discordant requirements on pulp quality—in terms of light scattering, fibrillation, strength, and flexibility (Alava and Niskanen 2006, Rusu *et al.* 2011). Mechanical defibration is designed to produce high amounts of fines—to scatter light and bond particles—and yet maintain high average length and fibrillation in long fiber fractions—to reinforce and resist tear rupture (Reyier-Österling *et al.* 2012). According to Atack (1981), the objective of grinding wood and refining wood chips is "to produce 'debris' with certain physical characteristics". Hence, the actions in mechanical pulping should not be regarded as plain fragmentation. For harsh and intensive defibration of low energy pulps, maintaining the fiber length represents a challenge. The concept of an energy efficient grinding surface (EES) (Björkqvist 1995a,b) has recently changed the trade-off between cost and quality by introducing a fatigue treatment (Salmi *et al.* 2011; Salmén 1987) followed by harsh defibration.

As the name TMP states, thermal pretreatment has a significant role in refining. The pretreatment methods are numerous. Thermal and chemical pretreatment in grinding cannot be considered as viable approaches, since fluid impregnation of wood and thermal conduction into wood are too low for practical applications. Therefore, electron-beam (Granfeldt *et al.* 1992) and mechanical pretreatment leading to fatigue are the feasible methods to soften wood and thus improve energy efficiency in grinding. Energy may apparently be wasted when electricity is used to produce mechanical work that eventually turns to heat in mechanical pulping. The balance between tear strength and specific energy consumption can also be advanced by elevating the shower water temperature if pulp brightness can be compromised (Sundholm 1999; Lind *et al.* 2004). Nonetheless, wood friction and viscous losses provide a unique method to heat the solid wood on demand, *i.e.*, only in the vicinity of the surface of the grinding stone. This is because water cannot flow and therefore convect heat well in intact wood. Other, more cost-effective forms of energy that heat the wood cannot be as instantaneous and localized, therefore leading to extended thermal exposure and disadvantageous pulp brightness. The degeneration of pulp brightness is difficult to compensate for, and for any graphical paper pulp, brightness is a welcome quality; hence, the alternative methods used to heat wood are not favored.

In mechanical pulping, specific energy consumption, average fiber length, and drainage are common product attributes. Energy consumption relates to work that is needed to create the new surfaces (Campbell 1934) and heat (Sundholm 1999), but it does not pertain in a straightforward way to fiber length. To save energy, grinding targets the largest intensity that still maintains sufficient fiber length (Björkqvist *et al.* 2012). This is the most crucial relationship between energy consumption and fiber length. Average fiber length characterizes the large particles, whereas drainage described by the Canadian standard of freeness quantifies the surface area. Wood has a natural fiber length distribution; for Norway spruce, the typical mean length is 3 mm (Stamm 1964). The fiber length distribution in the wood is a major determinant of the resulting pulp fiber length after mechanical pulping. The optimal mechanical distribution of pulp fiber length is not known (Campbell 1934), and maybe it cannot ever be determined. This is because untouched, defect-free, or natural mechanical pulp does not exist. Any mechanical defibration method cuts some fibers and thereby modifies the fiber length distribution. To maintain the value of pulp well, the defibration process should not cut fibers excessively and yet fibrillate all surfaces thoroughly. Due to the stochastic features of the grinding processes, the fibers of the pulp have a wide length distribution. This is in one way evidenced by the similarity of microscopic images of paper structure at different magnifications. Paper structure is somewhat scale-free, *i.e.*, fractal. A quantitative description of stone surface grits is challenging, as is the grit penetration depth of wood. It has been proposed that grinding surface grits do not really cut the fibers, but instead dislodge the fibers by friction (Campbell 1934). This assumption relies on the very slight depth of cuts that occur during the grinding. In addition to the grinding stone, *i.e.*, geometry and grit dimensions, surface and feed velocities also have significance for fiber length. Surface velocities—typically 28-30 m/s—are much higher than feed velocities of about 1.5 mm/s.

Relatively few theoretical studies of grinding phenomena have been carried out. Eighty years ago, Campbell made the first computations on the energy efficiency of grinding. If grinding is pure surface creation, then according to his computation, the ratio of useful to supplied work ratio ought to be negligible, *i.e.* 0.012% (Campbell 1934). Among the defibration pioneers, Atack (1955) analyzed the deformations incurred in grinding. He concluded that plucking and grabbing are the most plausible of the mechanisms of fiber liberation. One peculiarity of grinding is that pulp properties vary within a relatively small window. This implies that in the process of grinding, wood is turned into fibers, regardless of the control (Alfthan 1974). To understand the elementary action, Steenberg *et al.* (1957) set up a superb in-situ pressure measurement system and summarized the findings. They observed that, “Only the protruding parts of the stone and the log touch each other” (Steenberg *et al.* 1957). Each fiber is impacted by the abrasive pulpstone grits some 3000 times before it comes away from the parent wood (Campbell 1934). The multitude of grit actions is not useless. Since the early 1980s, grit actions and refiner bar passings have been assumed to produce fatigue in the wood material (Atack 1981). First, wood exhibits viscoelasticity and thermal conduction; second, grinding introduces stress alternation with thermal convection; together, these were modeled by Björkqvist to quantify temperatures and stresses (Björkqvist 2001a). In comparison to experimental temperature profile (Atack and Pye 1964; Sundholm 1999) the model overstates the penetration of stress and heat, but it has significance for the physics of grinding, as the work led promptly to EES grinding. Assuming that the grits in the stone are ploughing like slats, perpendicular with the wood longitudinal axis, Havimo *et al.* (2010) were able to reproduce the empirical temperature profile inside the ground wood by calculation. An earlier study on Hertzian contact revealed tensile stress near the edge of the grit (Hamilton and Goodman 1966). To conclude, the origin of the ground wood fiber length is beyond de facto understanding.

There are two possible modes for fiber cutting. The first alternative assumes that fiber cutting after fiber segment liberation—so-called regrinding—has a significant role in the emergence of fiber length distribution (Atack 1977). The second option is to assume that during grinding, the situation between grindstone and wood is such that regrinding is unsubstantial.

Disunion of a wood fiber can be performed one or several times. The number of pieces created characterizes the defibration process in a statistical sense. The two grinding processes of ground wood and pressure ground wood (PGW) seem similar with respect to fiber dissection principles. In the manufacture of pressurized ground wood and in the thermomechanical pulp, the casing pressure is increased to increase the temperature at the fiber liberation. In TMP pulping, the temperature distribution in the refiner plate gap describes in part the refining process. In most cases the temperatures reach temporal equilibrium, but possess spatial variations. The temperature difference between the lowest and the largest temperature in a large refiner can be even 40 degrees centigrade (Härkönen *et al.* 1997). Excessive fiber cutting is evidenced by the plate gap temperatures (Härkönen *et al.* 1997; Fredrikson *et al.* 2009) in the case of high consistency. Fiber length reduction is shown first in larger temporal variations in plate gap temperatures, whereas more severe cutting generates a spatial temperature peak, which can be 10 degrees centigrade high and 50 mm wide in a small refiner (Fredrikson *et al.* 2009). First, the consistency occasionally becomes too high, and the frictionally created thermal energy cannot be assigned to water evaporation. This results in temperature variation, which is the initial evidence of fiber cutting in refining. If the lack of liquid water is lasting, the temperature in the plate gap will obviously persist over time. In grinding, the steam volume inside the defibration zone is small; therefore, the temperature distribution shows different features (Sundholm 1999). Moreover, excess shower water is applied to limit the temperature at the boundary between stone and wood. In a way, PGW and TMP pulp consistencies reflect this difference.

Persuaded by the paradigm of mechanical pulping that states that the product of quantity and quality remains constant (Brecht 1979), this study looked at the mechanisms in grinding. The ground wood process was investigated via empirical and computed fiber length distributions. First, wood was ground to pulp and the fiber length distributions were measured. A simple fragmentation model was constructed to resemble the fiber dissection due to grit-to-wood events. Experimental and computationally simulated fiber length distributions were then compared, and their statistical features were quantified.

EXPERIMENTAL

Pulp Characterization

Semi-pilot PGW pulps were produced from fresh Norway spruce trees in southern Finland of 20 to 30 cm diameter at breast height. Two kinds of trees were used: fast-grown annual ring width 3 mm, and slow-grown below 2 mm. Slow-grown wood was roughly twice as old as the fast-grown. Sapwood and heartwood logs from the tree butt were compared with top logs, and the diameter was about 8 cm. Original wood fiber widths were measured by SilviScan using image analysis and X-ray spectroscopy. Macerated original wood and ground pulp fiber lengths were quantified by automated image analysis using Metso FS200 and FS300 devices. This study focused only on fiber length and not on width, curl, or coarseness. The excluded quantities were indeed affected by the defibration process. The grindings were run with stone 38A601 at fairly sharp state, stone surface velocity 20 m/s, casing pressure 450 kPa, and shower water temperature 135 °C to a consistency of 1.5%. Two wood feed velocities, 0.5 and 0.75 mm/s, were used, except in one trial, where the feed velocity was 0.25 mm/s. The grinding sample size was 5 kg, and the dry solids content was between 38% and 73%. Sapwood samples were the moistest at 38% to 44%, and the heartwood sample was the driest at 63% to 73%. The top log dry solids content was 42%. The grinding process was kept practically constant to underline differences in the wood. Moreover, other pulp properties than the fiber length as well as the handsheet properties also were affected by the spectrum from fast-grown heartwood to slow-grown sapwood.

Simulated Length Distributions and a Fragmentation Model

The fiber length shortening can be studied by removing segments according to the pulp length distribution of fibers from the wood fiber length distribution. This was simulated by the naïve Monte Carlo method to calculate artificial pulp length distributions. The distributions thus generated were close to the experimental distributions, but not exactly equal. Examination suggested that, on average, an initial wood fiber is divided into 2.5 to 3.2 pulp fibers. Due to the mentioned inexactness, this method is not presented further in this paper.

The original fibers can be broken down into shorter fiber material along different principled paths. The prevailing view of fundamental mechanisms of grinding is based on the work of Atack and May (1962a). They proposed three distinct stages that rule the defibration. The stages are: preliminary treatment, fiber removal, and finally regrinding. The initial stage of pre-treatment is assumed to cause fatigue the fibers in the wood matrix by shear and compression forces. The cyclic loading could induce viscous heating that plasticizes the thermo-softening lignin and hemicellulose (Sundholm 1999). The details of fiber removal are challenging to observe; however the combing hypothesis is widely accepted. This second stage, *i.e.* organized and gradual fiber liberation, is probably controlled by the height of the grits in the pulp stone and it probably consumes relatively little energy. There is a consensus on the features of the first two stages (Stationwala *et al.* 1995, Björkqvist *et al.* 1995b). The third stage is re-grinding or post-grinding of fibers, and this happens between the stone and the wood. It includes further breakdown sequences during passage through the grinding zone. The last stage has never been observed directly or indirectly. It is likely that all three stages of fragmentation are present simultaneously. Depending on their relative significance, different fiber length distributions are produced. In this work, the hypotheses are that Atack's suggestion of post grinding is correct and that a fragmentation model describing this type of regrinding produces theoretical fiber length distributions that can be compared with the empirical distributions.

The fragmentation model follows from the one presented by Krapivsky *et al.* (2000). The main idea is that each fiber fragment may either produce daughter fragments or exit from the grinding process. This can be described by a probability p of further fragmentation. This probability is taken to be independent of the "depth" of fragmentation or the length of the fragment l. The daughter fragments are created so that the "break" takes place uniformly over the parent fragment. The result of the model is such—as can be shown mathematically—that the fragment length distribution $P(l)$ will be of a power-law type, l^{-2p}. Thus, the shape of the distribution is controlled only by the fragmentation probability p. The model is further defined by the minimum fragment size allowed and the initial fiber length distribution. Close to the initial length, the probability distribution will assume an exponential tail. The model includes the idea of regrinding and is open in the sense that it mimics the situation with a steady input of new non-fragmented material.

RESULTS AND DISCUSSION

In sap wood logs, the length-weighted average of fiber length was 3.2 to 3.3 mm; in heartwood logs, it was 2.1 to 2.4 mm; and in the top log, it was 2.1 to 2.7 mm. The slow-growth wood had higher average lengths than the fast-growth. The drainages of pit pulps were between 30 and 140 mL, and the length weighted fiber length averaged between 0.9 and 1.1 mm (Table 1). In light of the large variation in drainage and original fiber length, the average fiber length of pulps varied little. The sapwood pulps had the highest average fiber length, which was also the case with the wood samples (Liukkonen *et al.* 2005). The average fiber length of the top log pulp was slightly lower than that of the slow-grown heartwood pulp, although it was somewhat higher in the wood (Table 1 and Figs. 1 and 2).

Figure 3 shows the results of fitting the model to the empirical ground wood fiber length distributions. Above 0.5 mm, the curves had an exponential shape (decay), with an exponential distribution parameter of about 0.75 mm. For shorter lengths, the distributions followed a power-law with exponents close to −1.2 (Krapivsky and Ben-Naim 2003), down to very small fragments of 20 µm and below, thus of the fiber diameter scale. This exponent of –1.2 corresponds to the value 0.6 for the fragmentation parameter p. To get an idea of the significance of p, if one assumes that each fiber meets 3000 grits before fiber liberation, and this means that each single contact between a pulpstone grit and spruce wood cuts fiber in two parts with a probability of 2×10^{-4}.

Table 1. Trial Grinding Conditions and Pulp Properties

	SEC MWh/t	Drainage CSF mL	Mean Fiber Length mm	Wood Feed mm/s
Fast sap	1.54	36	1.12	0.50
Fast sap	1.23	51	0.92	0.75
Slow heart	1.07	71	1.10	0.25
Slow heart	0.89	138	1.04	0.75
Fast heart	1.19	112	1.09	0.50
Fast heart	1.03	128	1.07	0.75
Slow top	1.66	36	1.02	0.50
Slow top	1.21	65	1.03	0.75
Fast top	1.31	79	1.07	0.50
Fast top	1.11	104	1.07	0.75

This study's result with an exponent of –1.2 for the small fragments differed from the expected exponent –3, which would be characteristic for steady source processes (Ben-Naim and Krapivsky 2000). The exponent –1.2 is peculiar to shattering fragmentation when the smaller of two colliding particles splits (Krapivsky and Ben-Naim 2003). According to the theoretical computations, the only asymptotically relevant parameter would be the feed rate (Ben-Naim and Krapivsky 2000), and these grinding trials revealed a faint correlation of feed rate with fiber length distribution.

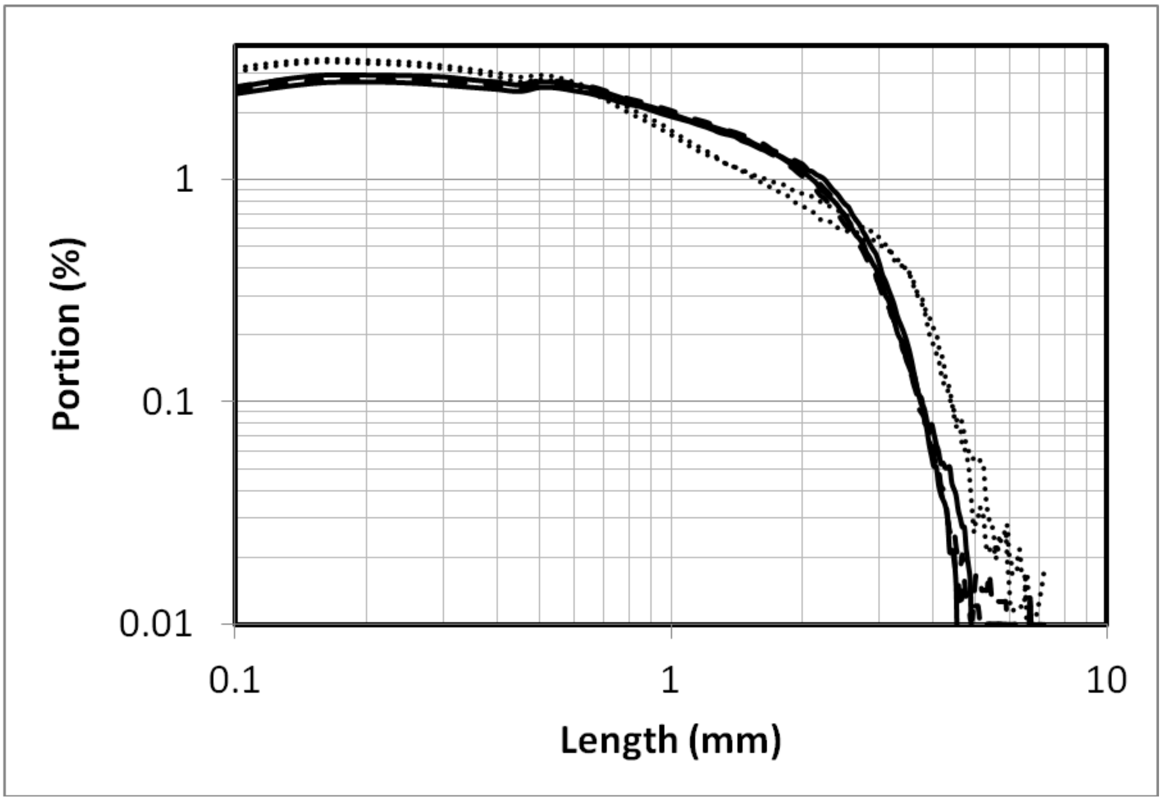

Fig. 1. Ground wood pulp fiber length distribution for fast-grown wood on logarithmic scales. The dotted line is for sap wood, the dashed line is for heart wood, and the solid line is for top log. There were two different feed velocities, 0.5 and 0.75 mm/s, for each raw material. The histogram category width is 0.05 mm.

According to the experimental evidence, the distributions of pulp fiber length were all similar to each other. Thus, the fiber length of ground wood pulp does not associate much with wood or feed velocity, *i.e.*, specific energy consumption. The only remaining alternative is that fiber length is dictated by the grinding stone surface. That is not to say that changes in fiber length are insignificant, but to propose that wood and feed have a smaller effect on the fiber length than on other ground wood pulp properties. As in other studies (Heikkurinen *et al.* 1999; Mörseburg 1999), these trial results can be summed up with a statement that the shorter and thinner-walled fast-grown wood retained its original fiber length better than the longer and thicker-walled or slow-grown wood (Liukkonen *et al.* 2005).

The fiber length distribution, *i.e.*, the number of pieces originating from one fiber, depends on the 1) original wood fiber length, 2) grinding conditions, and 3) grinding surface. However, the current results point to the possibility of the "typical" distribution being due only to the stone surface. The effect of shower water temperature was not examined here, although it is an important element of grinding conditions. The presented model fits the available data fairly well. It specifically predicts a universal distribution that is only weakly dependent on the original pulp (average length, length distribution). It also contains some specific assumptions about how the fragmentation proceeds in grinding. Krapivsky's model, which reproduces the experimental results reasonably well, includes regrinding inherently. Therefore, it is plausible that significant fiber regrinding happens in real ground wood pulping. Therefore, ground wood pulp fiber length is largely an inherent feature of the process.

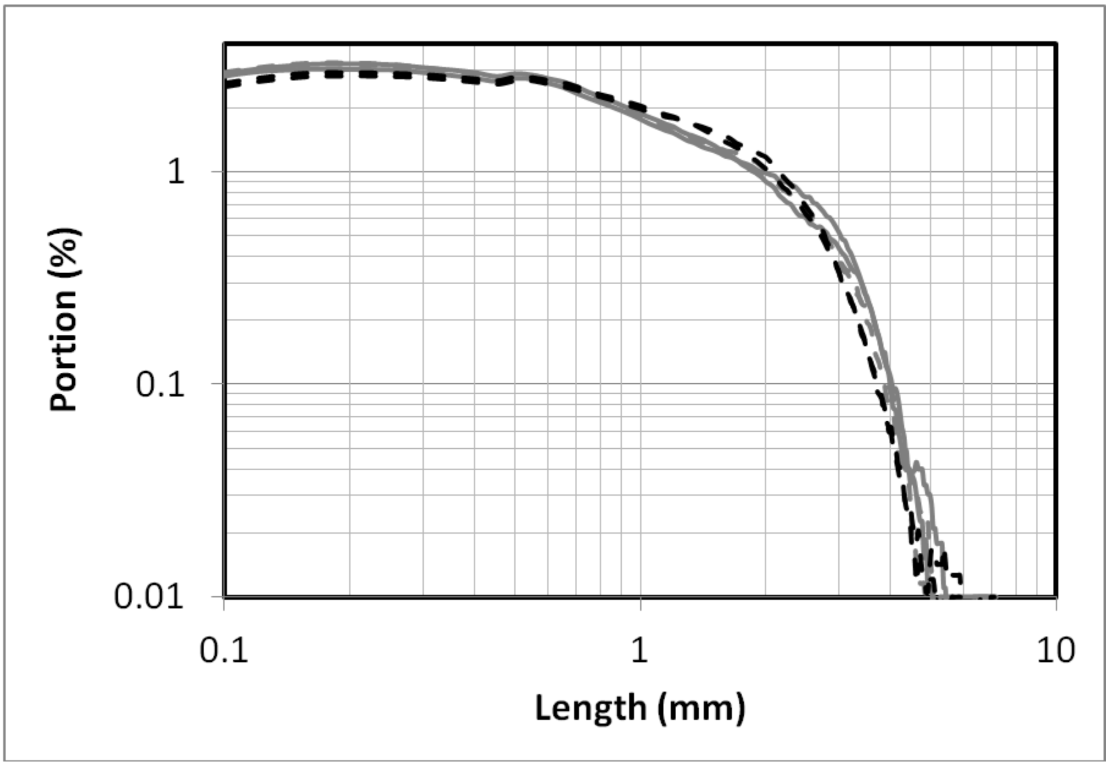

Fig. 2. Ground wood pulp fiber length distribution for slow-grown wood on logarithmic scales. The gray dashed line is for heart wood, the gray solid line is for top log, and for reference, fast-grown top log is represented with a dashed black line. There were two different feed velocities, 0.5 and 0.75 mm/s, for each raw material, except for slow-grown heart wood, where the feed velocity was 0.25 mm/s. The histogram category width is 0.05 mm.

A similar approach is difficult to apply in the case of TMP refining because of the differences in the setup. In grinding, the parent wood is stationary in a well-defined orientation, and fibers and fines are carried away eventually, whereas in a refiner the chips, fiber bundles, fibers, and fines have no preferential orientation. In refining, some fibers are treated in a longitudinal direction. Such treatment in grinding is known (Alfthan 1974) to yield high fiber length and energy consumption, and that is precisely what is found in refining.

If surface friction also plays a role at high deformation rates (Atack and May 1962b), then tensile stress on the leading edge of the grit (Hamilton and Goodman 1966) probably causes fiber detachment. The matter of optimal fiber length distribution was not addressed here. However, pulps containing only long fibers can have good strength properties. Of course, many eventual pulp end-use properties are dependent on, for example, fiber wall properties, which are not revealed by the length distribution alone.

The model combines two physical ideas. One is the original removal of the fiber after it is detached at one "site." The second consists of the subsequent breaks that follow a stochastic fragmentation process (Krapivsky *et al.* 2000). This two-step model includes the empirical features seen in the data. The models and simulations focus on fiber liberation by plucking and thereby contribute to Atack's concept (Atack 1955). It is also suggested that ground wood fiber length is independent of all parameters expect grinding surface sharpness. This statement corroborates one figure in Paulapuro's revolutionary work (Paulapuro 1976).

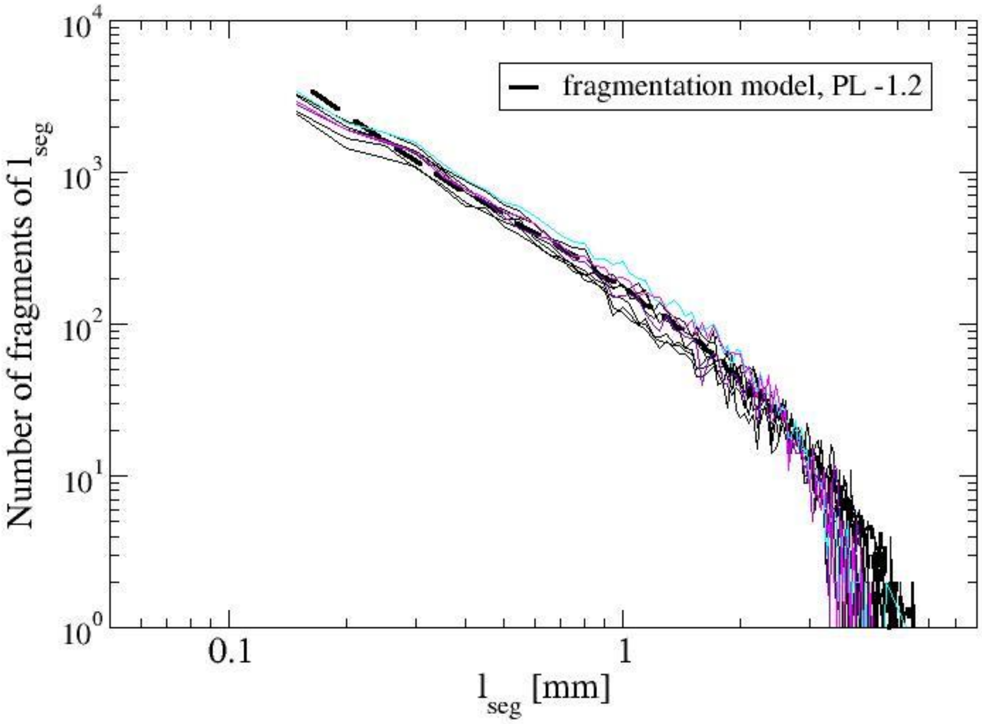

Fig. 3. Ground wood pulp fiber length distribution on logarithmic scales. The thin colorful lines show measured distributions, and the thick black line is result of model computations. The histogram category width is 0.05 mm.

CONCLUSIONS

1. The presented fragmentation model fits the available data fairly well and predicts a universal distribution that is only weakly dependent on the original pulp. It also contains an assumption of regrinding. The model considers only the evolution of the length distribution. Further information on the fragment properties (width) could be used to refine the model.
2. The distributions of pulp fiber length were all similar to each other. Thus, the fiber length of ground wood pulp does not correlate in the cases studied with wood or feed velocity, *i.e.*, specific energy consumption. The sole contributor to fiber length is the grinding stone surface. The validity of this observation should be tested for varying grinding surfaces, process temperatures, larger variation of feed rates and the role of the stone velocity.
3. The shorter and thinner-walled fast-grown wood retained its original fiber length better than the longer and thicker walled or slow-grown wood.

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