DEVELOPMENT OF WOOD GRINDING. 6. SIGNIFICANCE OF THE FRICTIONAL COEFFICIENT IN GRINDING OF SPRUCE WOOD

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The purpose of this study was to clarify whether the wood grinding model – based on an energy balance for the grinding zone – would improve understanding of wood grinding for pulp. This study relied on previously obtained data by the Finnish Pulp and Paper Research Institute. The frictional coefficient (P_c/P_t) computed and the power-specific groundwood production ($\dot{G}_w/P_t$) were important *x*- and *y*- variables, respectively. Fresh spruce wood samples were ground by application of a laboratory grinder, where the stone surface speeds were 30, 15 and 7 m/s, respectively.

The power-specific productivities of high- and medium-speed grindings followed one and the same mechanism, since both speeds led to a productivity of 0.99 [(kg/h)/kW]; the low-speed grinding, however, led to a level of 0.66 [(kg/h)/kW] at frictional coefficients closest to 100 mW/kW. The rate of formation of coarse rejects was – at the same frictional coefficient as before – 15.0, 4.3 and 2.3 mg/s for high-, medium- and low-speed grindings, respectively. However, the rate of fines formation determined by McNett apparatus was about ten times higher than that of formation of coarse rejects: 123.0, 42.2 and 23.7 mg/s, respectively. The fines-to-shives ratio (determined by a Somerville shive analyser) was assumed to indicate fiberisation for high-, medium- and low-speed grindings, and the true data, most close to 100 mW/kW, were 56.0, 55.9 and 36.1 units of fines-to-shives, respectively. The curves followed the same trend, but on slightly different levels.

As for the important sheet properties, the tensile strengths of high-, medium- and low-speed grindings were low, medium and high, respectively: 37.1, 46.9 and 56.2 Nm/g. The light scattering coefficients of high-, medium- and low-speed grindings were low, medium and high, respectively, or as data being most close to 100 mW/kW: 59.2, 66.0 and 67.5 m^2/kg, respectively.

Some general conclusions may be drawn from these results. To achieve the best groundwood productivity, the frictional coefficient should be kept on a level close to 100 mW/kW. Generally speaking, it seems that high- and medium-speed grindings appeared to act as following the same mechanism as far as the productivity was concerned, but the rates of shives and fines formation did not follow such a pattern. The groundwood sheets showed lower tensile strength in high-speed grinding than in medium-speed grinding, while the light scattering coefficient was much lower for the high-speed grinding than for the medium-speed grinding. Because of its low productivity, the low-speed grinding does not seem to be useful, although high tensile strength and high light scattering of the sheets would plead for it.

Keywords: coarse shives, compression power in grinding (P_c), fines-to-shives ratio, light scattering coefficient, frictional coefficient (P_c/P_t), power-specific pulp production ($\dot{G}_w/P_t$), productivity, pulp production ($\dot{G}_w$), rate of fines formation, rate of shives formation, Somerville shives, spruce wood, stone surface speed (w), tensile strength, tension power in grinding (P_t)

INTRODUCTION

Since the introduction of wood grinding as an industrial process, around the middle of the 19th century, the mechanism of grinding has been studied to comprehend and improve the wood grinding process and its pulp properties. For the present study, the groundwood process was investigated by application of an energy balance comprising the hot stone surface and the hot wood surface, including the hot pulp slurry in between.[1] The still unaffected wood was supposed to act as initial wood. The tangential tension force (F_t) was required to maintain a constant speed of the grindstone surface. Simultaneously, a perpendicular compression force (F_c) was required to control the groundwood production. The mathematical product of the compression force and its feed rate represents the theoretical power required for feeding the wood (P_c), and that of the tension force and the surface speed of stone represents again the grinding power (P_t). The stone and wood surfaces have their own specific structures and heat conductivities *etc.*, and accordingly, grinding was supposed to remain constant during such a period of continuation. However, the fibrous structure of the wood surface is continuously alternating from low-density spring wood to high-density summer wood in annual rings. The spring wood fibres are typically thin-walled and have wide *lumina*, as the summer wood fibres are compact, thick-walled and have narrow *lumina*. Accordingly, it is evident that the speeds and forces selected would never simultaneously fit the extreme types of fibres. One reason is also the different structure of the fibres, and accordingly the different amounts of water occluded by the fibres of spring and summer wood. After all, balancing the energy input with the energy output through the contact area between the running stone surface and the wood surface compressed against the stone, resulted in a general model supplying diagrams for the power-specific groundwood production, *i.e.* productivity $\dot{G}_w/P_t$, [(kg/h)/kW], *versus* the power-based frictional coefficient P_c/P_t, mW/kW, *i.e.* 10^{-6}.

The present data were obtained by the Finnish Pulp and Paper Research Institute (FPPRI); FPPRI applied both its own unique laboratory grinder and unique wood samples.[2] The stone diameter and width were 300 mm and 50 mm, respectively, and the grinder opening was 35 mm × 35 mm. The grinding conditions existing between the original wood and the stone surface may be described by simple and measurable quantities. Such quantities given by the model are the compression or feeding force (Fc, N) and the rate of feeding (v, mm/s) and their product (Fc × v, mW), as well as by the tension or grinding force (Ft, kN) and the stone surface speed (w, m/s) and their product (Ft × w, kW). The structure of the stone surface (*e.g.* grits, land area, *etc.*) and the wood quality (*e.g.* moisture content, wood density, *etc.*) are also important quantities that affect grinding, but being impossible to measure or control during grinding, they are initially kept constant. Plotting various grinding quantities and pulp properties as a function of the frictional coefficient may help understand the groundwood pulping process in general, and perhaps its mechanisms.

RESULTS AND DISCUSSION

Grinding mechanism

In wood grinding, the stone surface and particularly, its grits load the fibres, when moving tangently across the fibres at high speed, and under vertical compression. Accordingly, fibres get removed from the wood surface dependent on the conditions in and around the grinding zone, *e.g.* moisture content of wood, stone grits and composites, as well as the stone surface speed, the shower water temperature *etc.* Fibres unfortunately get cut to finally provide an average length of about 1 mm, about half of the average length of the initial wood fibres. The power compressing the wood, P_c, vertically against the running stone surface is extremely small, compared to the tangential tension power, P_t, required to keep the stone running at a constant speed. These powers heat the grinding zone and release fibres as soon as their secondary walls have received a temperature specific for fibre softness, or more exactly the softening temperature of the lignin-rich middle lamella. The fibres should also attain a fibrillation level suitable for papermaking, and therefore, they also should be as long as possible. Fiberisation was, in this context, expressed by the amount of fines particles (<200 mesh McNett) relative the amount of shives and fibre bundles determined by a Somerville screen.

Figure 1 shows the power-specific groundwood production, $\dot{G}_w/P_t$, as a function of the frictional coefficient, P_c/P_t. $\dot{G}_w/P_t$ indicates the groundwood production (in kg/h) achieved by application of a power of 1 kW. The results were obtained when grinding at stone surface speeds of 30, 15 and 7 m/s, also named high-, medium- and low-speed grinding, respectively. The pulp productivities of high- and medium-speed grindings seemed to obey identical mechanisms, but the low-speed grinding showed a much lower productivity.

Figures 2 and 3 provide the rates of coarse rejects and fines formation as a function of the frictional coefficient, P_c/P_t, at high-, medium- and low-speed grinding, respectively. They probably indicate how fiberising and fibrillation develop, since the rates of formation might describe grinding mechanisms rather than the final groundwood proportions of coarse rejects and fines, respectively. Figure 2 shows the rate of coarse rejects formation, and it seemed to follow significantly different mechanisms at high-, medium- and low-speed grindings. Figure 3 indicates that the rate of fines formation (<200 mesh) was about ten times higher than those of coarse rejects, and high-, medium- and low-speed grindings appeared in a similar way as for the rejects formation.

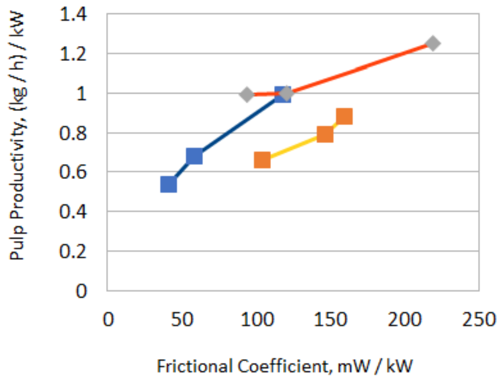

Figure 1: Power-specific groundwood production, $\dot{G}_w/P_t$, in grinding of spruce wood as a function of frictional coefficient, P_c/P_t, and as a function of stone surface speeds of 30, 15 and 7 m/s, respectively

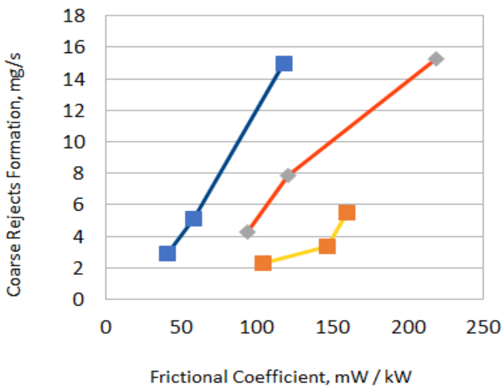

Figure 2: Rate of coarse rejects (>0.16 mm slots) formation as a function of P_c/P_t in grinding of spruce wood, and as a function of stone surface speed of 30, 15 and 7 m/s, respectively

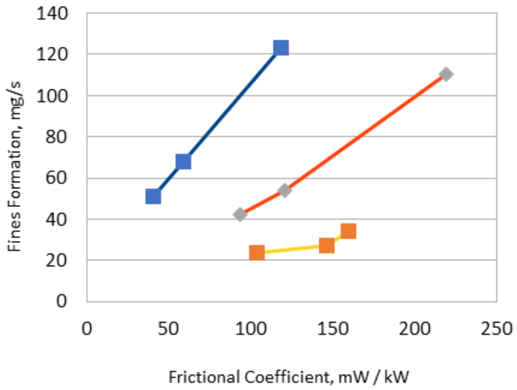

Figure 3: Rate of fines (<200 mesh McNett) formation as a function of P_c/P_t in grinding of spruce wood, and as a function of stone surface speed of 30, 15 and 7 m/s, respectively

Groundwood properties

The groundwood pulp and sheet properties are presented in Figures 4-6. Figure 4 presents the fines-to-Somerville shives ratio as a function of the frictional coefficient, P_c/P_t, in grinding of spruce wood. It may describe fiberisation and perhaps fibrillation; it indicates that the stone surface speeds studied followed each other closely at high values for high-speed grinding towards decreasing values for decreased grinding speeds. High-speed grinding provided, perhaps surprisingly, higher fines-to-Somerville shives, since high-speed grinding probably does not provide enough time for smooth heating, which would result in acceptable fiberisation and fibrillation rather than cut and crushed fibres that would produce minor particles rather than fibrillation.

The sheet properties are determined by the fines of the final pulp, their size and their chemical properties, as well as by the length distribution and fibrillation of the fibres. Figure 5 presents the tensile strength, and Figure 6 – the light scattering coefficient of laboratory groundwood sheets as functions of P_c/P_t and the stone surface speeds. The tensile strength obtained was highest for the low-speed and lowest for the high-speed grindings, as the medium-speed grinding produced tensile strengths in between.

Figure 6 provides the light scattering coefficient (LSC) in grinding of spruce wood, and it resulted in approximately similar trends as those for the tensile strength in Figure 5. However, the light scattering of high-speed grinding pulp was clearly lower than those of the medium- and low-speed grindings, which again were quite similar. The intersection between the LSC axis and the high-speed groundwood data was about 68 m^2/kg, as it was about 70 m^2/kg for the medium-speed groundwood.

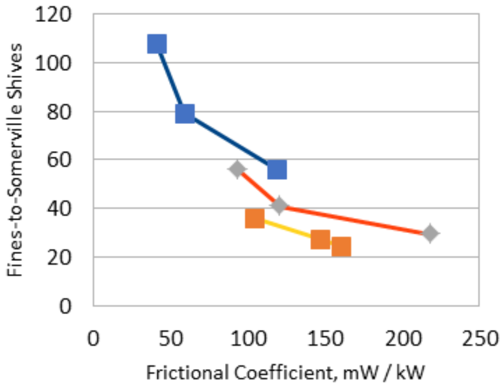

Figure 4: Fines-to-Somerville shives as a function of frictional coefficient P_c/P_t in grinding of spruce wood, and as a function of stone surface speeds of 30, 15 and 7 m/s, respectively

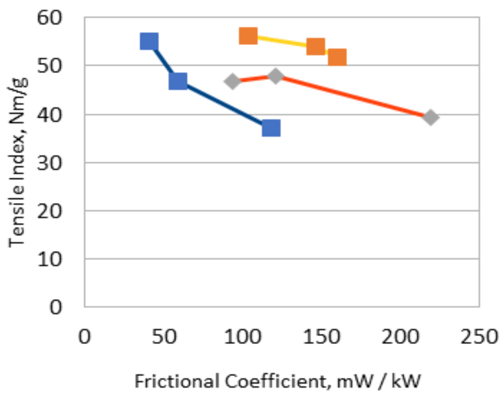

Figure 5: Tensile index of spruce groundwood sheets (100 g/m²) as a function of frictional coefficient P_c/P_t, in grinding of spruce wood, and as a function of stone surface speeds of 30, 15 and 7 m/s, respectively

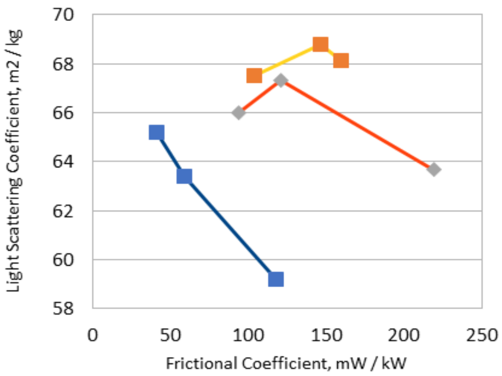

Figure 6: Light scattering coefficient (LSC) of spruce groundwood sheets (52 g/m²) as a function of frictional coefficient, P_c/P_t, in grinding of spruce wood, and as a function of stone surface speeds of 30, 15 and 7 m/s, respectively

FINAL CONSIDERATIONS AND CONCLUSIONS

As shown in a number of previous studies,[1,3-6] mechanical wood grinding seems to act as a fast viscoelastic process, during which fibres or parts of them are wrenched off rather than ideally removed from the wood fibre matrix. By decreasing a normal stone surface speed to its half, some groundwood pulp properties may get improved. Moreover, by decreasing the half speed once more to its half, one may further improve some properties due to changing the fibre release to a further gentle removal. In this case, however, the significantly lower pulping productivity would rather diminish its economy. In normal wood grinding, the feeding rate is close to 1 mm/s, which suggests that 30-40 fibre layers would be pulled off in every second and that one single fibre layer accordingly would require only about 30 ms.

Mechanical pulping carried out on a laboratory scale makes it possible to apply comparable wood samples through one entire experimental series. The wood density is very important, as being low for spring wood and high for summer wood, it is accordingly dependent on the proportions of spring and summer wood. The moisture content of the wood affects its viscoelastic behaviour due to the fact that the varying heat transfer in grinding finally also affects the pulp properties. Moreover, the structure of the grinding stone surface, *e.g.* the grit number, size and sharpness, affect the respective contents of shives and fines of the final groundwood.

The data utilised in this context were initially reported by the Finnish Pulp and Paper Research Institute.[2] In the present evaluation of the data, the pulp productivity, $\dot{G}w/Pt$, and important pulp and paper properties were presented as functions of the power-based frictional coefficient, Pc/Pt. Wood grinding is technically uncomplicated, but the grinding zone procedures – heating the wood and releasing the fibres – do not yet seem to be fully understood. It is difficult to continuously measure important quantities of the grinding zone. Accordingly, the grinding procedure could perhaps be better understood and technically developed by creating a useful model[1,2] that would take into account both force and speed in both main directions of the grinding zone, *i.e.* the compression and tangent directions, respectively. Thus, the measurable grinding variables based on the energy balance resulted in useful variables, such as the power-specific groundwood production, briefly called productivity, and the frictional coefficient expressed as the ratio between the wood feeding or compressing power and the grinding power in tangential direction. If the grinding stone concerning its design in a broad sense would affect the grinding procedure identically from test to test, it is evident that the wood density and the wood moisture content would determine the heat conductivity of the wood sample. In this study, the surface speed of the grinding stone was changed from one test series to another as to simulate occurring changes in rupturing the wood fibres. In addition to one specific grinding stone, also the wood sample should be one specific sample from test to test, being wood of the same density and the same moisture content.

Concerning fiberising and fibrillation in wood grinding, one may realize how complicated the grinding zone procedures are. Fiberising of the heated wood probably appears in the lignin rich middle lamella, which softens at a lower temperature than the crystalline cellulose of the fibre wall. Dependent on the surface speed of the grinding stone and the middle lamella temperature, ruptures of the middle lamella may occur as in a brittle, *i.e.*, elastic body, at high speed, rather than as in a soft, *i.e.*, viscoelastic body, at low speed of the stone surface. The productivities of grinding at high and medium speed grindings occurred comparable as functions of the frictional coefficient, while the low speed grinding showed a significantly lower productivity.

The rate of formation of coarse rejects in grinding at a frictional coefficient of about 100 mW/kW provided levels of 15.0, 4.3 and 2.3 mg/s, respectively, for high-, medium- and low-speed grinding. The rate of formation of fines again showed corresponding levels of 123, 54 and 23 mg/s, respectively. Still, the ratio of fines (<200 mesh) to shives (>0.16 mm slit) may better describe the wood fiberisation. However, the slow-running tests with a stone surface speed at 7 m/s led to about 20% higher fines-to-shives in groundwood, which implies that a stone surface speed between 15 and 7 m/s, *e.g.* 10 m/s, would present some profits in productivity.

The tension-power specific production of the groundwood occurring at the power-based frictional coefficient $P_c/P_t \approx 100$ mW/kW was about 1 [(kg/h)/kW] for high- and medium-stone surface speeds of 30 and 15 m/s, respectively, while it was only about 0.7 [(kg/h)/kW] for a low speed of 7 m/s. Evaluating the production of fines and shives as such, it was evident that decreased stone surface speed also decreased both fines and shives production, respectively. However, the fines-to-shives ratio improved slightly for slow-speed grindings, but considerably regarding their tensile strength and light scattering coefficient measured on groundwood sheets.

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