

Perspectives on High and Low Consistency Refining in Mechanical Pulping

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Recent developments in low consistency refining in mechanical pulping have raised questions about the differences between low and high consistency refining. This paper, originally presented to the UBC Energy Reduction in Mechanical Pulping Committee on 10 June 2015 at the PACWEST Conference in Whistler, BC, Canada, discusses the author's perspectives on these issues as well as on mechanical pulping in general.

Keywords: Mechanical pulping; Refining; Stone groundwood; Energy

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BACKGROUND

The discovery of mechanical pulping was a landmark event in the history of paper, indeed in the history of the world. The development of stone ground wood (SGW) pulping in Germany in the 1850's, followed by sulphite pulping about 10 years later, paved the way for the widespread use of wood fibre in paper. This in turn enabled mass print media such as the penny press to displace what was formerly a 'rich man's product,' paper made from various non-wood fibres.

An SGW grinder is shown in Fig 1. In essence, logs are pressed against a grindstone. Grits on the grindstone surface pass over the surface of the wood as shown to scale in Fig 2.

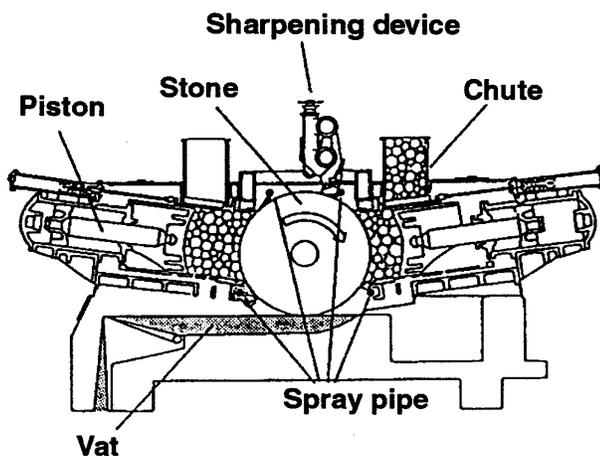


Fig. 1. Grinder to produce stone groundwood pulp. See Acknowledgements for figure credits and source information.

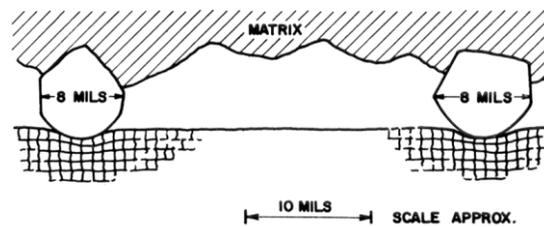


Fig. 2. Grinder grits sliding over wood surface (Atack and May 1958)

The grits of a grindstone accomplish two actions: removal of fibres from the wood (comminution) and development of the fibres into a paper-grade pulp. Comminution is accomplished by a rubbing and sliding action, as opposed to grinding, where the main action is due to cutting by the sharp edges of the grits (Atack and May 1958).

Grits in SGW create rolling friction and consequent heat from hysteresis, to the extent that the wood may char just under the surface. Consequently water is added. Once fibre ends are loosened, they turn in the direction of grinder rotation, as shown in Fig 3, and are eventually released very much as intact fibres (Atack 1977). The free pulp is further “developed” in what is called re-grinding, a heterogeneous process that causes fibre length loss.

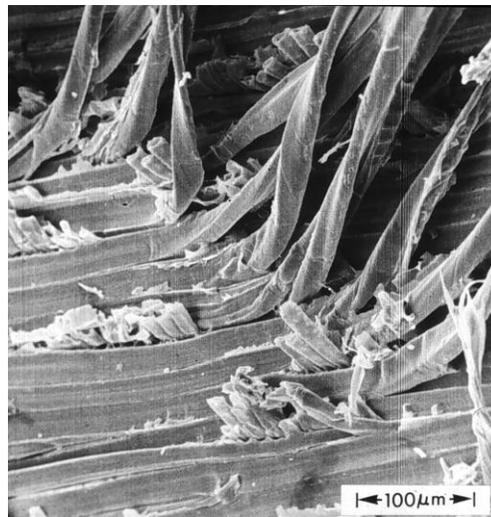


Fig. 3. Fibres being peeled from wood surface during grinding (Atack 1977)

Mechanical pulp thus produced is shown in Fig 4a, where it is compared to chemical pulp. A key feature of mechanical pulp is clearly evident: about one third to one half of the fibre mass is in the form of short fibres and fines. In contrast, chemical pulping produces long fibres with relatively few fines. Given this nature of mechanical pulp, Forgacs (1963) defined its two key properties as fibre length, L , and external specific surface, S , with the latter commonly measured by the freeness test.

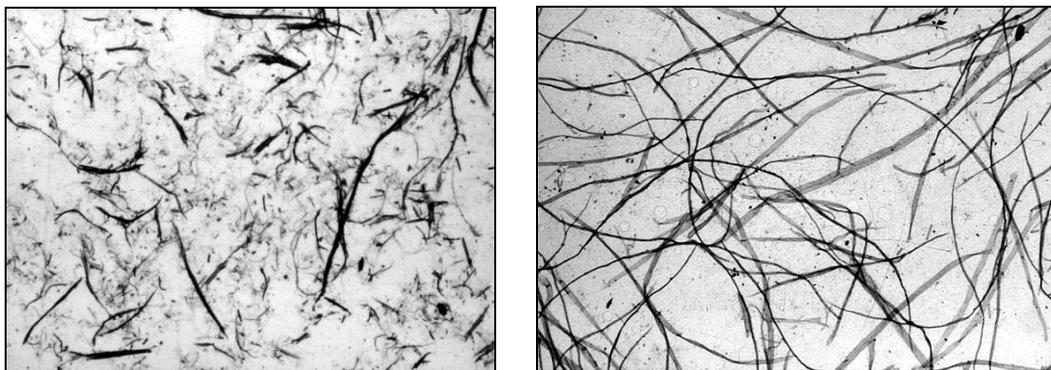


Fig. 4. Mechanical pulp (left), chemical pulp (right)

The 1950's saw the introduction of refiner mechanical pulping (RMP). This came after the development of well-engineered disc refiners for chemical pulps in the 1930's. The three main drivers for RMP were: availability of wood as chips rather than whole logs needed for SGW; less intensive labour; and a continuous process as opposed to the batch SGW process. An RMP refiner is shown in Fig 5.

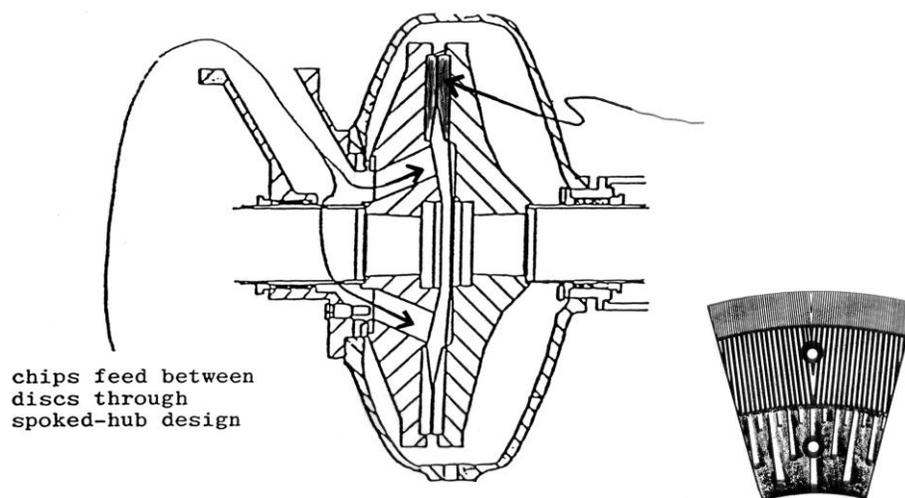


Fig. 5. Disc refiner and typical plate

In operation, wood chips enter the eye of the refiner where the star-bolt and breaker bars impart a rotational motion to them, giving the centrifugal acceleration that drives the pulp radially through the refiner. At the same time, these bars comminute the wood, to an extent that the fibrous material entering the remaining bar section is a coarse pulp. This was demonstrated by Neill and Beath (1963) using specially-made plates having only the star bolt and breaker bar section. From this they concluded that the wood comminution step required no more than about 400 kWh/t of the typical total 1500 kWh/t, in short about 25% of the energy of mechanical pulping. The rest is for fibre development.

Fibre development in RMP occurs by a mechanism similar to that in SGW, but with bar edges rather than grits sliding over fibres, as shown in Fig. 6. Another difference is that fibres are held in place by bar edges and frictional forces in RMP rather than by the wood matrix as in SGW. Restraint of some form is required for fibres to strain rather than accelerate when force is applied upon them.

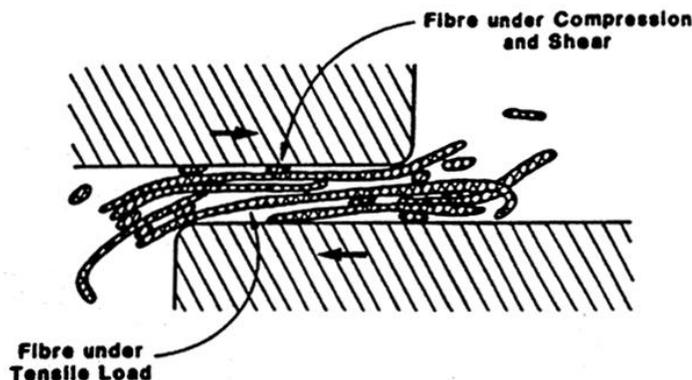


Fig. 6. Illustration of fibres in gap between crossing bars (Page 1989)

The next major advance in mechanical pulping was the introduction of Thermo-Mechanical Pulping (TMP) in the early 1970's. A major driver here was reduction of refining energy. It was known that lignin softens at high temperature, and therefore it is reasonable to expect that the middle lamella binding fibres together would rupture more easily. This would reduce the energy required to comminute the wood into fibres and at the same time inflict less damage on fibres. However, to some surprise, TMP consumed more, not less, energy than RMP or SGW, as shown in Table 1. At the same time TMP also produced longer fibres, fewer shives, and fewer fines.

The reason for the higher energy is evident in Fig. 7. Wood comminution takes place through the softened lignin of the middle lamella. This produces lignin-rich fibres and consequently more energy is required for the subsequent fibre development. Since most energy is consumed in this stage of the process, overall energy increases. In contrast, breakage through the P1 layer shown in Fig. 7 exposes cellulosic components of the fibre wall.

Table 1. Comparison of Pulp Properties

	SGW	RMP	TMP
Energy required (GJ/ton)	5.0	6.4	7.0
Freeness (mL)	100	130	100-150
Burst index	1.2	1.6	1.8-2.4
Tear index	3.5	6.8	7.5-9.0
Breaking length (km)	3.2	3.5	3.9-4.3
Shive content (%)	3	2	0.5
Long fibre content (R48)%	28	50	55
Fines content (P100)%	50	38	35
Brightness (unbleached)	61.5	59	58.5

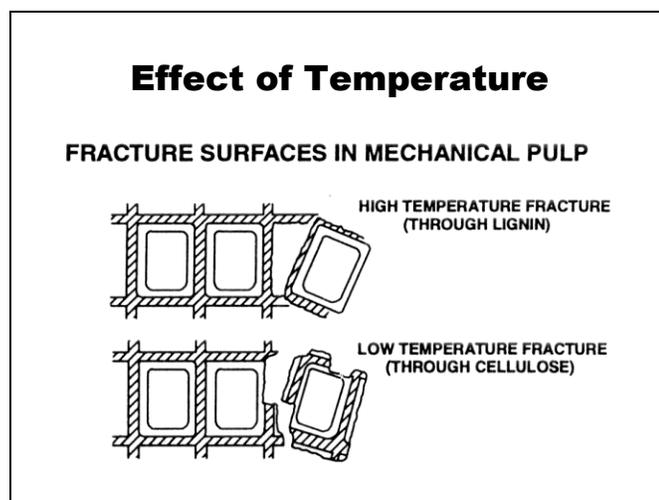


Fig. 7. Illustration of effect of temperature on fracture zones during comminution (FPInnovations)

ENERGY FOR MECHANICAL PULPING

The large electrical energy required for mechanical pulp production has long been a major issue. It raised an important question: how much energy is theoretically needed? The first estimate of this was by Campbell (1934). In essence, he multiplied the surface free energy of a crystalline solid, 650 ergs/cm^2 , by the amount of new surface created in SGW, which he measured to be $1.2 \text{ m}^2/\text{g}$. This gave an astonishing low efficiency of 0.012% for 1600 kWh/t SGW. Later, Atack (1981) estimated new surface to be around $7 \text{ m}^2/\text{g}$, which gave an efficiency of 0.07%, which is still very small.

Campbell noted that his estimate did not take into account the energy required to produce new surface. In mechanical pulping the new surface is created by straining wood to rupture, a problem in fracture mechanics. In the early 1960's, two separate groups conducted experiments on fracture mechanics of wood. Lamb (1960, 1962) employed wood peeling, and Atack *et al.* (1961) used wood cleavage. The latter group also related their findings to Griffiths crack propagation model, modified for ductile materials. In both studies, the energy of fracture was found to be about 10^5 ergs/cm^2 , giving an efficiency in the range of 10 to 15% for mechanical pulping. This value was verified later by studies of wood cleavage by Ottestam and Salmen (2001). In summary, the efficiency of mechanical pulping based in fracture mechanics to create new surface is about 13%.

Efforts to measure efficiency of mechanical pulping directly were conducted by determining the lowest limit of energy to produce SGW. Using a specially constructed grindstone at low rotational speed, Salmen *et al.* (1999) produced paper-grade pulp at 700 kWh/t, giving an efficiency of about 50% based on the conventional energy of 1500 kWh/t. Nevertheless, there remains a large gap between theoretical energy of 13% and the lowest practical efficiency of 50%. Why is this the case?

Fibre development consumes most of the energy in mechanical pulping. Some development may take place by chemical softening without new surface creation, and

some by internal cracking (Maloney and Paulapuro 1999). However, Karnis (1994) showed that most fibre development takes place by removal of surface layers of fibres, *i.e.*, by a “de-coarsening” effect, as shown in Fig. 8. He determined that about 50% of the fibre wall is peeled away, with about 28% becoming short fibres and about 27% becoming P200 fines. Fibre flexibility is increased due to its fourth power dependence on outer diameter.

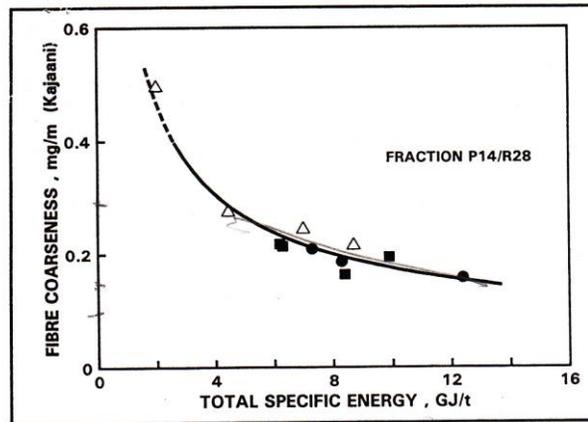


Fig. 8. Effect of energy on coarseness reduction of fibres (Karnis 1994)

Surface material removed by solid bodies sliding over one another is a form of wear. The amount of material removed is related to energy expended, as given by the Holm-Archard equation (Rabinowicz 1995):

$$V = k.F_N.s = \frac{k}{\mu} F_S s = k^* E \quad (1)$$

Here V is the volume of material abraded, and k is a constant reflecting material properties of the abraded material and surface geometry of the abrading solid. F_N and F_S are normal and shear forces, μ is the coefficient of friction, s is sliding distance, and E is the energy expended by the moving hard solid.

The energy E to produce volume V is dictated to a considerable extent by constraints on the desired quality of V . Just as energy for wood comminution is constrained by preservation of fibre length, new surface V is constrained by the desire for either “fibrillar” material to enhance bonding or “chunky” material to enhance opacity. The mechanisms to produce these qualities differ and may be described colloquially as “ripping out chunks” or “jiggling loose fibrils”. Both mechanisms are linked to energy in the form of Eq. 1. However, a second parameter is needed to account for the quality constraint. This parameter is called refining intensity.

REFINING INTENSITY

Energy in mechanical pulping is applied in a cyclic manner and thus may be described as the product of the number of loading cycles (impacts), N , and the intensity of each Impact, I , *i.e.*

$$E = N \cdot I \quad (2)$$

This concept is illustrated in Fig. 9.

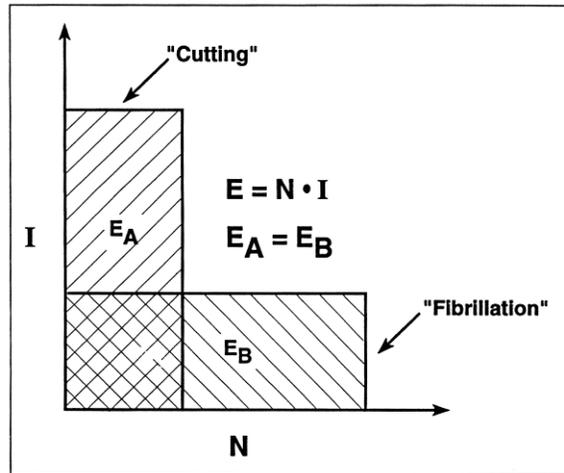


Fig. 9. Refining impacts and intensity at a common energy (Kerekes 1990)

Only two of the variables in Eq. 2 are independent. It is common to use only energy E and intensity, I . There are two approaches to quantifying intensity. One is by a “machine intensity” which describes how the energy is distributed among the bar crossings. The other is by a “fibre intensity” which describes the energy imparted to fibres during each bar crossing. These two intensities differ because not all fibres are impacted at each bar crossing.

REFINING INTENSITY FOR LC CHEMICAL PULPS

Chemical pulps have historically been refined at low consistency (3 to 5%). The earliest work on refining intensity took place for chemical pulp refining, and therefore it is useful to discuss it first. Brecht and Siewert (1966) developed an intensity called the Specific Edge Load (*SEL*), a machine intensity that remains in widespread use to this day. It is a measure of the energy distribution among bar crossings and is calculated by dividing the net power to the refiner by the number of bars on rotor X number of bars on stator X bar length X rotational speed. Although developed empirically, the *SEL* has been shown to represent the energy expended per bar crossing per bar length (Kerekes and Senger 2006). Typical recommended values for chemical pulps are *SEL* = 2 J/m for softwood and 0.2 J/m for hardwood (Baker 1995). Several variants of *SEL* were developed in later years.

Fibre intensities were developed by Danforth (1969), Leider and Nissan (1977), and through a C-factor by Kerekes (1990). A key need for fibre intensities is to account for the probability of fibre impact at a bar crossing, and thereby the amount of fibre in a gap captured from the adjacent groove. This fraction captured may range from 5 to 20% (Heymer 2009). A significant merit of fibre-based intensity is that it provides a common scientific basis for comparison. For example, although *SEL* values for chemical pulp hardwood and softwood differ by an order of magnitude, these both represent the same

level of fibre intensity (Kerekes 2010). This is understandable, as the composition of hardwoods and softwoods are rather similar. The level is about 10 kJ/kg/impact.

REFINING INTENSITY FOR HC MECHANICAL PULPING

Both RMP and TMP are produced at a high consistency (HC) of about 30%. Refining intensity for this consistency is a difficult matter owing to the complex rheology of HC suspensions. These are heterogeneous three-phase mixtures of wet fibres in steam or air. As shown in Figs. 10 a,b they are discontinuous, compressible mixtures. They have an aerodynamic specific surface of about 50 m²/kg, whereas the hydrodynamic specific surface of a pulp fibre is about 1000 m²/kg (Garner and Kerekes 1978).

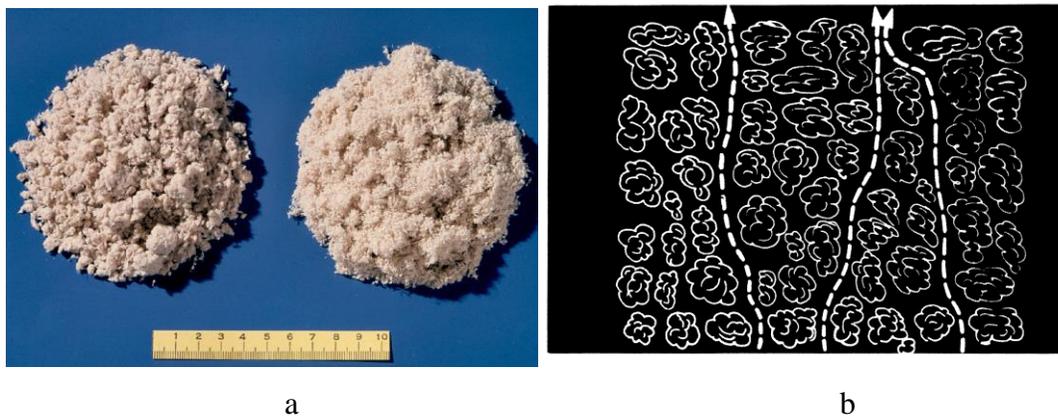


Fig. 10. HC Pulp in bulk form (a), showing aerodynamic specific surface (b) (Kerekes *et al.* 1985)

Given the discontinuous nature of HC pulp, the motive power to force HC pulp to flow through a refiner must come from the refiner itself, specifically from the centrifugal forces imposed by the rotor. In contrast, LC pulp can be pumped through a refiner by an upstream pump. Once in flow, HC pulp tends to be quite heterogeneous, as shown in the discharge flow of a TMP refiner in Fig. 11.



Fig. 11. HC pulp (36% consistency) discharging from a TMP refiner (Kerekes *et al.* 1985)

The compressibility of HC suspensions means that the amount of pulp in a refiner is unknown. Accordingly, although machine intensity (*SEL*) may be readily calculated, its meaning with respect to action on pulp is less certain than for LC refiners, which are entirely full of pulp.

The heterogeneity of HC suspensions produces heterogeneity of fibre distribution on bars. This is illustrated by measurements of forces at a point on a bar in HC and LC refiners shown in Fig 12. If one assumes that the temporal variability shown reflects the spatial variability along a bar, bar coverage of HC is much more heterogeneous than is the case for LC.

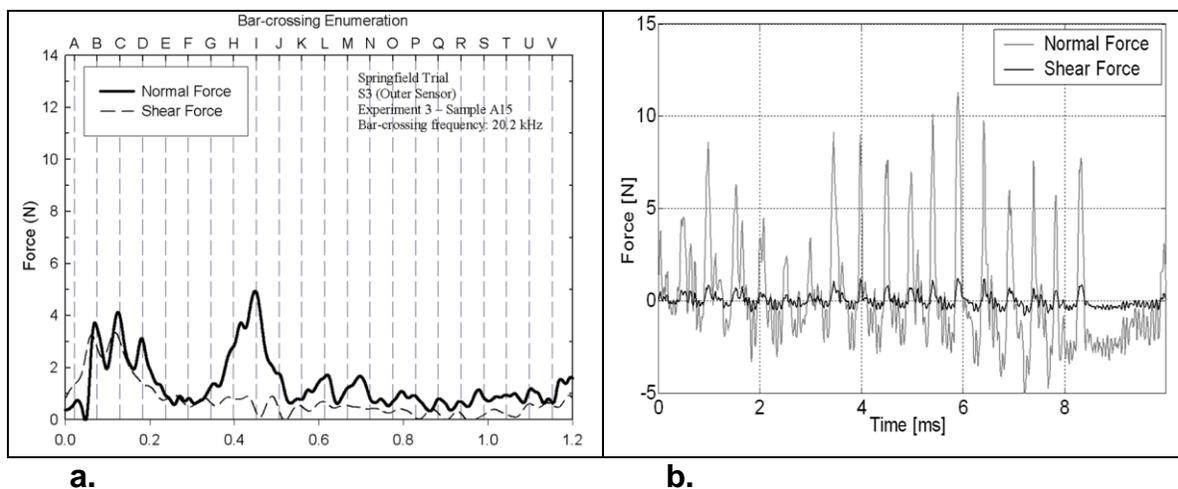


Fig. 12a. Force measurements on a bar in an HC chip refiner (vertical lines indicate bar crossings (Olender *et al.* 2007); **b:** Force measurements on a bar in an LC mechanical pulp refiner (Prairie *et al.* 2008)

FIBRE-BASED INTENSITY FOR HC MECHANICAL PULP REFINERS

Estimates of refining intensity in mechanical pulping have focused on fibre intensities. An early indirect measure of this in SGW was made by Campbell (Atack 1977). He noted that fibres experienced about 3000 grit impacts. For a specific energy of 1500 kWh/t, this would give an intensity of about 1.6 kJ/kg/impact.

Miles and May (1990) carried out the first rigorous analysis of fibre-based intensity in HC mechanical pulp refiners. They did so by a radial force balance on pulp consisting of an outward centrifugal force, inward frictional resistance, and positive or negative force from steam flow before and after the stagnation point. Doing so gave an average radial velocity of the pulp. From this and the length of the radius, they determined pulp residence time in the refiner. Assuming fibres in grooves were impacted at each crossing, from the number of bar crossings at a point in the refiner and the specific energy they obtained a specific energy per impact, I , to be in the range 0.3 to 0.9 kJ/kg/impact.

FIBRE-BASED INTENSITY FOR LC MECHANICAL PULP REFINERS

Historically, LC refiners for mechanical pulp were used only as post-refiners in paper mills. The principal aim was shive reduction and freeness control. These refiners were found to cut fibres and therefore were deemed unsuitable for fibre development. Although their intensities were not measured, they probably operated in the chemical pulp range, *i.e.* near to 10 kJ/kg/impact.

At some point it was found that significantly lower intensity could produce fibre development and minimize cutting. This was accomplished by spreading input power over more bar crossings. One way of achieving this was by a refiner called the Beloit Multi-Disc refiner, shown in Fig 13. In it the flow splits into 4 or more working zones, giving a machine intensity in the range of $SEL= 0.10$ to 0.34 J/m.

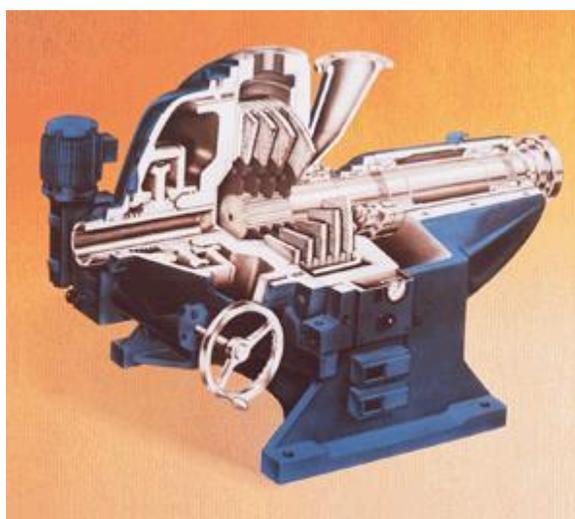
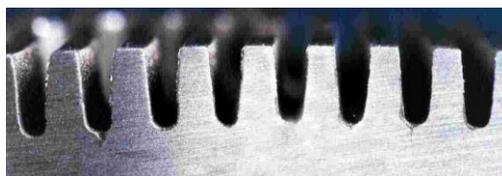
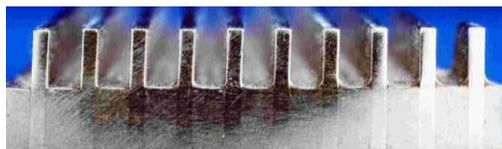


Fig. 13. A “Multi-Disc” LC refiner (courtesy GL&V)

An alternate approach to attaining low intensity in recent years has been by use of very narrow bars that permit more bars per plate. Such plates were developed for hardwood chemical pulps by the FINEBAR™ and are shown in Fig. 14 in comparison to a traditional cast plate.



Cast



FINEBAR™

Fig. 14. Comparison of bars on cast plate (above) and a fusion-bonded plate (below) (courtesy, FINEBAR)

COMPARISONS OF INTENSITIES

It is interesting at this stage to compare the various intensities for mechanical pulp discussed this far on the basis of fibre intensity. We do so by converting the Beloit Multi-Disc SEL to I using the C-factor and by adjusting the values obtained by Miles-May to have the same probability factor as the C-Factor. The resulting values and Campbell's estimate are shown in Table 2. They are all about the same value, with an average of 1.8 kJ/kg/impact.

It is interesting to note that this level of intensity is only about 20% of that of chemical pulps. We may speculate why this is the case. As stated earlier, the role of intensity is to account for quality of new surface. In chemical pulping, a main aim is internal fibrillation, which is imposed by internal strains, but not to the extent of rupturing the fibre. In contrast, in fibre development in mechanical pulping, the main aim is removal of surface material, preferably in fibrillar form. Here the constraint is avoidance of rupturing fibrils/fines, for example into a powdery form. Assuming that the coarseness of the fines/fibrils is about an order of magnitude smaller than that of the whole fibre, their strength is correspondingly smaller. Consequently, to avoid their rupture, the intensity of the force acting on them should also be correspondingly smaller. This explanation is plausible, but it should be noted that at this stage it is merely a hypothesis.

Table 2. Fibre Intensities of Three Mechanical Pulp Refiners

Refiner	I , kJ/kg/impact
SGW	1.6
HC Refiner	2.1*
LC Multi-Disc	1.8

* adjusted to have impact probability used in Multi-Disc estimate

FORCE-BASED INTENSITIES

Bar Forces

All intensities discussed thus far are energy-based. However, force not energy, ruptures fibres. Force on a bar in the direction of motion is a vector component of the energy expended per bar crossing. Consequently, we may obtain bar force by factoring bar energy, SEL , into its components, force per unit bar length in the direction of motion, F , and the sliding distance over which this force is exerted, s , analogous to how we factored energy into number and intensity of impacts. This is illustrated in Fig. 15.

Stress is more useful than force because it reflects the area over which force is exerted. To obtain shear stress in the direction of motion, we employ b , the size of the zone over which peak force is exerted and z , the fractional bar coverage along a bar length, (discussed later). This is converted to a normal stress, that is pressure on the bar surface using a coefficient of friction, μ . Thus one obtains an expression for pressure, P , as follows (Kerekes 2011),

$$P = \frac{SEL}{\mu \cdot b \cdot z \cdot s} \tag{3}$$

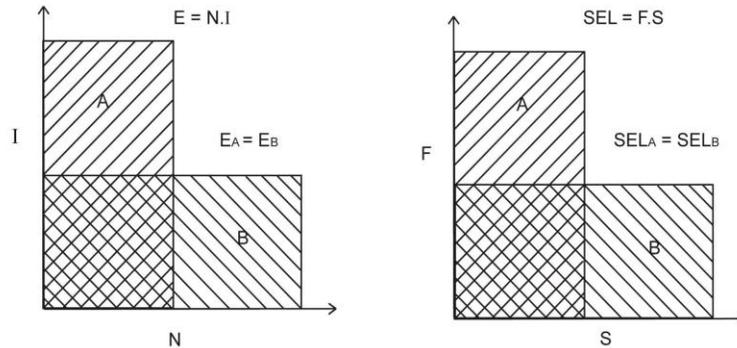


Fig. 15. Comparison of factoring energy and SEL into their component variables

WIDE BARS

When bar widths are larger than a fibre length, as has been typical for many years, Goncharov (1971) showed that the peak force on refiner bars occurs on the bar surface near the leading edge over a distance about a fibre length, as shown in Fig. 16. The likely reason is that fibres are captured as flocs, and the size of flocs is generally about 2X fibre length (Kerekes and Schell 1995). It is reasonable to estimate that the major load-bearing zone within flocs, where most fibres cross, is about one fibre length.

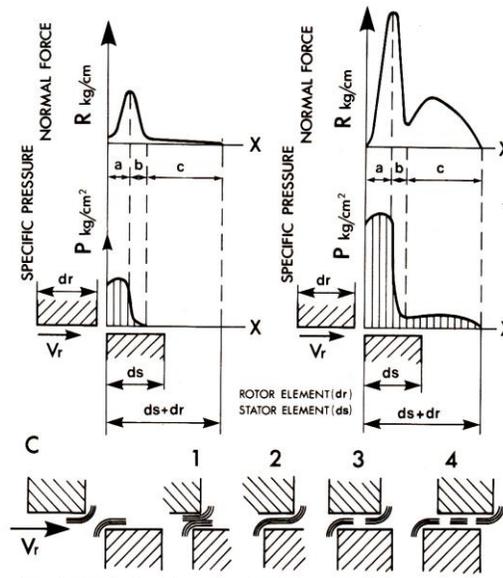


Fig. 16. Measurement of pressure on bar surface during a bar crossing (Goncharov 1971; reported in Atack 1977)

Taking fibre length as both the sliding distance and the zone over which peak pressure is exerted, *i.e.* $l=b=s$, one obtains

$$P = \frac{SEL}{\mu \cdot z \cdot l^2} \quad \text{when } l < W \quad (4)$$

The next issue to consider is a desirable target pressure. Dynamic compression tests by Amiri and Hoffmann (2003) have shown that compressive strain increases with pressure up to a plateau level and then flattens out with increasing pressure, as shown in Fig. 17. In the plateau region, additional pressure produces little additional internal strain in fibres and hence little additional internal rupture that causes internal fibrillation. However, increasing pressure also produces increased shear, though this increased external fibrillation by abrasion, along with some possible internal fibrillation. In the limit, however, these high stresses will cause fibre shortening. Assuming that these arguments are valid for mechanical pulp refining, a useful target pressure is the onset of the plateau, which is about $P=3$ MPa.

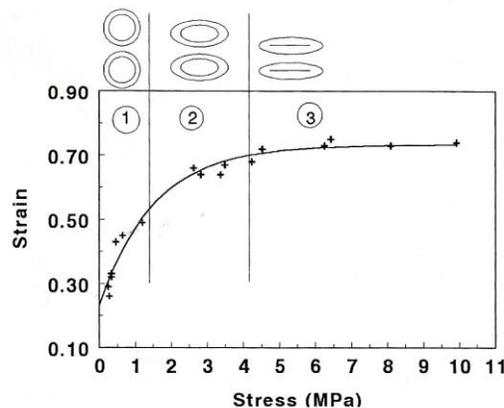


Fig. 17. Illustration of fibre compression with increasing pressure (Amiri and Hoffmann 2003)

For chemical softwood pulps, using $\mu = 0.11$ (Goncharov 1971), $z=1$, and fibre length $l=2.5$ mm, the recommended SEL for softwood (2 J/m) corresponds to a target pressure 2.9 MPa. For hardwood of length 0.8 mm, the recommended $SEL= 0.2$ J/m corresponds to a pressure of 2.8 MPa. Thus, both are close to the value of 3 MPa described above.

For mechanical pulps, assuming a desirable $SEL= 0.2$ J/m, and assuming fibre length is 1.6 mm, the target pressure would be 0.71 MPa, which is about 23% of the chem. pulp value. Measurements of force on bars by Prairie *et al.* (2008) gave a pressure in the range 0.16 to 0.78 MPa for mechanical pulp (Kerekes 2011).

NARROW BARS

Pressure on narrow bars differs from that on wide bars. When bar width is less than a fibre length, bar width not fibre length, determines the size of the zone of pressure and sliding. This is so because parts of a fibre lie outside the gap. Thus, pressure is given by,

$$P = \frac{SEL}{\mu \cdot z \cdot W^2} \quad l > W \quad (5)$$

where W is the bar width.

It is apparent that to maintain a target pressure for small bar widths, *SEL* must be reduced. If this is not done, in the limit as $W \rightarrow 0$, then $P \rightarrow \infty$. In essence, the crossing bars act as a pair of scissors. Some typical examples for small bar widths are given below in Table 3.

Table 3. A Comparison of *SEL*'s to Attain 3 MPa Pressure for 1.5 mm Fibre

<i>W</i> (mm)	<i>SEL</i> (J/m)
1.0	0.3
0.5	0.075

FIBRE DISTRIBUTION ALONG BAR LENGTH

The z term in the above equations accounts for fibre distribution along a bar length. This is an important factor because bar force is transferred to load-bearing columns of fibre. If there are few of these, *i.e.* if z is small, then a given bar force will impose a large force on pulp.

On the other hand, if the fibres are well distributed along a bar length, for example $z \rightarrow 1$, then the same bar force will give a smaller force on fibres. Thus, one way to keep forces on fibres low is to ensure as uniform distribution of fibres as possible along bar lengths.

FORCES ON INDIVIDUAL FIBRES

Ultimately, fibres rupture because forces on them exceed fibre strength. Determining this force is a complex matter which requires numerous assumptions. An estimate has been made by Kerekes and Senger (2006) and is shown below,

$$f_n = \frac{\sqrt{\pi}}{4} \frac{d_o \ell^{\frac{3}{2}}}{a} \frac{C_s \sqrt{kG}}{T} \left(\frac{SEL}{\mu s b z} \right)^{0.7} \quad (6)$$

where C_s is the consistency, T is gap size, G is groove width, k is capture factor, a and b represent pulp compressibility, and z is the bar coverage.

A key observation in Eq. 6 is the independent effect of *SEL* and gap size, T . In practice, these are linked because during refiner operation power is changed by gap size. For example, power is increased by decreasing the gap size. This has a double effect on fibre force: increasing *SEL* and decreasing gap size both increase force on fibres.

Equation (6) has been tested in a recent study on TwinFlo72 LC mill refiner for mechanical pulp refiner (Berg *et al.* 2015). It predicted a force f equal to 0.06 N at the point where fibre length dramatically decreased. This is close to the rupture strength of softwood fibres.

RECIRCULATION

Recirculation is a key feature of LC refiners not found in HC refiners. Here part of the discharge from the refiner is circulated back to the entry of the refiner, as shown in Fig. 18.

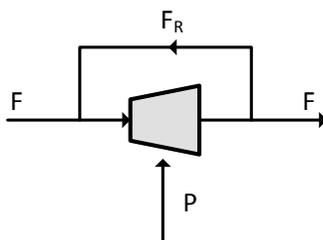


Fig. 18. Schematic of recirculation in an LC refiner

Recirculation is commonly employed to maintain the flow in the refiner within the design range when the flow to downstream is reduced or when the refiner has been over-designed, as is common. Recirculation does not increase the average specific energy imparted to pulp, which is solely determined by the power P divided by the mass throughput to downstream operations, F . However, recirculation changes the distribution of energy in flow F substantially (Kerekes 2014). Some part of the flow passes through the refiner only once, whereas other parts pass through many times. For example, at 43% recirculation rate, 57% of the flow passes through the refiner only once and experiences 57% of the average energy of the discharge. On the other hand, 12% of the flow experiences 2 X the average energy or more

If energy during recirculation were distributed on pulp in the proportion predicted by theory for distribution on flow, the pulp outflow would consist of a mixture of pulps refined to differing levels. However, there may be a smoothening effect due to a load shift from the pulp fraction that has experienced many passes to the fraction that has had few passes. This appears to be the case in recent findings by Sandberg and Berg (2015) for mechanical pulp with the 43% recirculation.

Recirculation provides LC refining of mechanical pulp with a significant advantage over HC refiners. There is a “double-decoupling” of throughput from refiner operation. First, flow within the refiner is decoupled from refiner rotational speed. Second, flow within the refiner is decoupled from flow to downstream operations as a result of recirculation. These extra degrees of freedom provide opportunities for optimization not possible in HC refiners.

SUMMARY AND CONCLUSIONS

There are numerous commonalities between LC and HC refining of mechanical pulp when considered from a basic scientific point of view, for example fibre intensity. However, there are also some key differences that may offer advantages to LC refining. In the opinion of this author, the key advantages of LC compared to HC are:

- easier pulp handling and pumping
- potentially lower forces on fibres for a given bar force and energy owing to more uniform distribution of fibres along bar length

-possibilities for independently optimizing rotational velocity and radial velocity of pulp owing to the decoupling of these from throughput

Whether these are advantages of significance remains to be determined in future work.

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