

Adjusting refining intensity by changing refiner plate design and rotational speed - effects on structural fibre properties

K.-A. KURE ¹, M.J. SABOURIN ², G. DAHLQVIST ³, T. HELLE ⁴

PFI - Norwegian Pulp and Paper
Research Institute,
Høgskoleringen 6B,
N-7034 Trondheim, Norway ¹

Norske Skog Research,
P.O. Box 53,
N-1756 Halden, Norway ³

Andritz Inc,
3200 Upper Valley Pike,
Springfield, Ohio,
OH 45504, USA ²

Department of Chemical Engineering,
Norwegian University of Science and
Technology,
N-7034 Trondheim, Norway ⁴

Abstract

The effects on fibre properties, like fibre wall thickness, fraction of fibres with longitudinal cell wall splits and fibre length by using different refining segment designs in the primary stage, was studied. Two principally different refining processes were compared. One process had low residence time, high steam pressure and high rotational speed. The other process had longer retention time, lower system pressure and lower rotational speed. By changing refiner plate pattern it was possible to control pulp residence time and number of bar crossings and thus even structural fibre properties. Higher refining intensity by raised speed or more aggressive plate pattern gives more collapsible fibres with longitudinal splits in the fibre wall but even shorter fibres. The results also indicate that by increased thermal softening it is possible to preserve fibre length and at the same time obtain a lot of thin-walled fibres with split fibre walls. There is thus no rigid link between fibre length and cross-sectional fibre characteristics. For a given level of longitudinal splits, the high speed/high pressure configuration generated pulp with higher strength properties and fibre length. Significant energy savings are achievable using high intensity refiner plates.

Introduction

The refining process has two steps. In the first, chips are reduced to individual fibres and smaller wood particles (1). In the second, the fibre development step, the papermaking fibres are developed. The energy required to separate fibres is quite low (2), but the defibration process determines pulp quality and specific energy consumption (3, 4, 5). Using one specific, fine bidirectional pattern, Kure and Dahlqvist (6) identified process conditions combining low residence time, high steam pressure and high

rotational speed in the first refining stage. The conditions were beneficial for both specific energy consumption and fibre properties. Reduced energy consumption by high speed is frequently reported for both single and double disc refining (4, 7, 8, 9, 10, 11, 12, 13, 14). Very little is reported on fibre properties, especially cross-sectional characteristics like fibre wall thickness. The process conditions of Kure and Dahlqvist (6) gave more thin-walled fibres. A raised fraction of fibres with longitudinal splits was found, compared to a baseline process having longer preheating, standard system pressure and speed. Fibres produced at high speed collapse easily and contribute to a denser, smoother sheet (15, 16), thus an improved printing surface. Thin-walled fibres with high specific surface area also give higher light scattering (17).

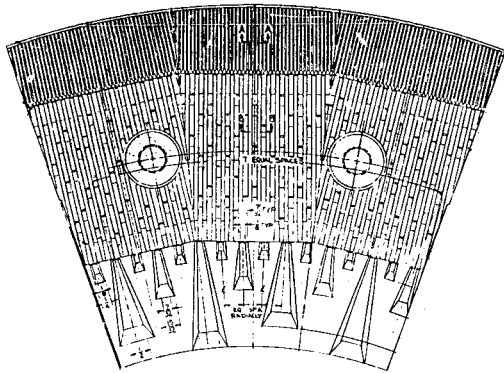
Refining intensity may be defined as specific energy per bar impact (18, 19). It is affected by changing number of bar impacts using different refining segments and pulp residence time. Changing speed and plate design affect both number of impacts and residence time. The difference in fibre properties between the high intensity process by Kure and Dahlqvist (6) and the baseline process is also affected by refining segments. The present study investigated the effects of primary stage segment designs and rotational speed on fibre properties, like wall thickness, fibre fraction with fibre wall splits and fibre length. Relating the changes in fibre characteristics to refining intensity was a key point.

Experimental

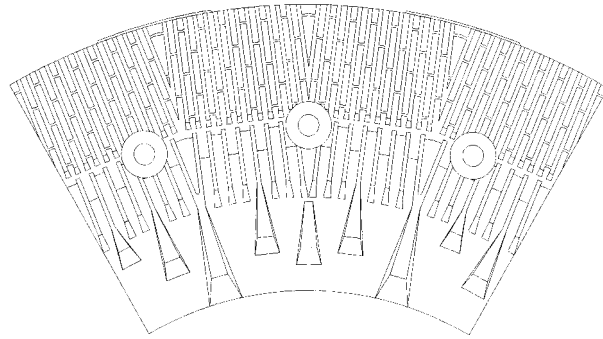
Refiner set-up

Pilot scale refining trials were made. TMP was produced from chips of Norway Spruce (*Picea abies* (L.) Karst) using a pressurized 91 cm diameter, variable speed single disc refiner. Refining was

a) ICPM = $4.3 \cdot 10^9$



b) ICPM = $0.643 \cdot 10^9$



c) ICPM = $2.2 \cdot 10^9$

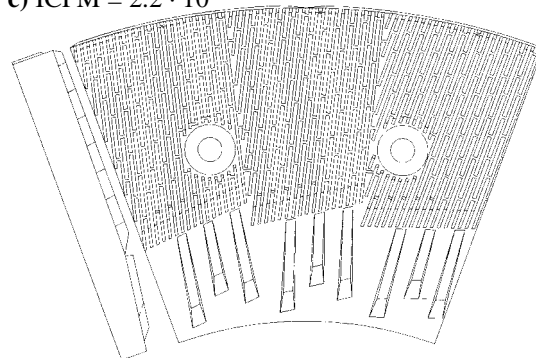


Figure 1. Illustrations of the three different plate patterns compared in the primary refining stage: **a)** a fine bidirectional pattern (Durametal D14-002), **b)** a coarse bidirectional pattern (Durametal 36602) and **c)** a directional pattern (Durametal 36604). The directional pattern was used both in a feeding mode (expel) and in a hold back mode by running the rotor in reverse. The formula most commonly defining plate pattern intensity, inch crossing per minute (ICPM), is given for each plate pattern at a rotational speed of 1800 rpm.

carried out in two stages, where the refining parameters were varied only in the first one. In the second stage only energy input was varied. Each trial started by feeding chips through a plug screw feeder, into a pressurized vertical steaming tube for retention at system pressure. The steaming tube discharge screw delivered the chips to the refiner feed screw into primary refiner. The screw's speed were synchronized to obtain the desired retention time.

Two basically different refining processes, I and II, were used in the first stage:

I) Process I were used for *Baseline TMP*, applying 150 seconds retention time, pressure of 2.8 bar and a rotational speed of 1800 rpm. A rotational speed of 1800 rpm is an offset of 300 rpm compared to most European mills running at 1500 rpm.

II) Process II were used for *RTS pulp*, applying 16-17 seconds retention time, 5.9 bar and 2600 rpm. 2600 rpm is 300 rpm higher than what is used in industrial installations of this process (22). The 300 rpm offset with the 91 cm diameter will better simulate larger diameter refiners operating at mill scale. Retention times for this process is 10-20 seconds (12, 13).

Three different **plate designs** were used in the first stage (Figure 1):

- (a) a fine bidirectional pattern,
- (b) a coarse bidirectional pattern and
- (c) a directional pattern.

The *directional* pattern was used both in

(c1) feeding (expel) and in (c2) hold back by reversing the rotor thus giving four *different plate modes*.

A *secondary refining stage* was conducted using a 91 cm double disc atmospheric refiner. Each primary pulp was followed by secondary refining using *four different specific energy levels*.

Fibre analysis

Cross-sectional fibre dimensions were measured on SEM micrographs by methods described by Fjerdingen et al. (20) using the Bauer McNett +50 mesh fibre fraction. After digitizing and binarizing the SEM images, cross-sectional fibre characteristics were assessed using Zeiss KS300 image analysis system and the MATLAB image processing toolbox. In SEM images the fibre wall pores may in somecases be judged as broken circumference, causing a small systematic error. All fibre cross-sections were thinned, leaving only a skeleton with a width of 1 pixel. For intact fibres this gave the mean fibre wall perimeter, P , for broken fibres the length of the thinned image, L . Fibre wall thickness, WT , was assessed using the cross-sectional fibre wall area, A_w , the thinned perimeter, P , and length, L , respectively. Fibre wall thickness is calculated as A_w/P . Wall thickness of broken fibres is calculated by replacing P with L . Fibre length was measured using PQM1000.

Other pulp testing

When standardized methods were available, testing followed SCAN-standards. Handsheets were made with recycled white water.

Results and discussion

Effects on structural fibre properties

Figure 2a depicts mean fibre wall thickness and 2b the fraction of fibres with broken circumference vs total energy consumption after refining stage 2. Plate pattern *a*, the fine bidirectional plate, was used in the first stage. Process II, low residence time, high steaming temperature and high rotational speed, yields low fibre wall thickness at low energy levels. At high energy levels the two processes are equal. Process II yields more fibres with longitudinal splits in the fibre wall. This difference remains at higher energy levels. The first refining stage thus set a finger print on the fibre cross-sections. This support findings by Kure and Dahlqvist (6).

Figure 3 illustrates a typical fibre with broken circumference. There is a long fibre wall split.

Figure 4a and 4b depict the effects of different plate patterns on fibre wall thickness and the fraction of fibres with broken circumference for process I. The fine bidirectional plate pattern, (*a*), gave slightly higher fibre wall thickness than the other patterns. The coarse bidirectional plate pattern, (*b*), and the directional plate pattern used in expel mode, (*c1*), gives much more fibres with broken circumference compared to the fine bidirectional plate pattern, (*a*), and the directional pattern used in hold back mode, (*c2*).

Figure 5 depicts fibre wall thickness the fine bidirectional pattern (*a*) and the directional pattern in expel mode (*c1*), compared for similar energy consumptions. Combining the distributions for intact and split fibres yields the total fibre wall thickness distribution. The distributions for the two plate patterns differ significantly. Pattern (*a*) yields larger split fraction. Figure 6 shows the plate pattern effect

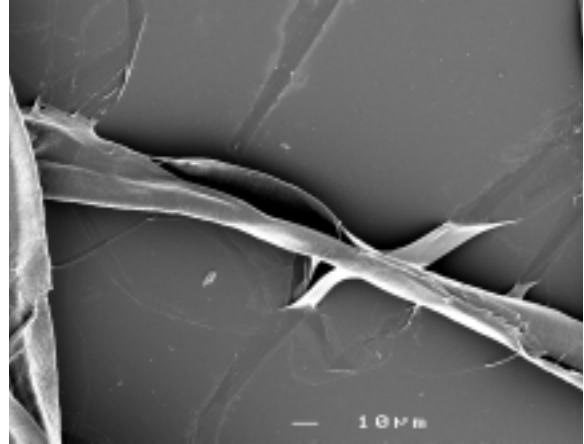


Figure 3. SEM image of a TMP fibre with a typical longitudinal split in the fibre wall.

on fibre wall thickness and the split fibre fraction, for process II, using high speed. As for process I, the differences in mean fibre wall thickness after the second refining stage are minor compared to the effect on the split fibre fraction. Pattern (*b*) and (*c1*) gave more split fibres. Compared to process I, process II gives larger fraction of split fibres. This is true especially for pattern (*a*) and (*c2*). The difference between the patterns is lower for process II than I. The plate patterns also cause different fibre lengths, cf. Figure 7a and 7b for process I and II respectively. Plate pattern (*b*) and (*c1*) gave significantly shorter fibres for both processes. Even if process II increased the fraction of split fibres, process II gave longer fibres compared to process I. Interpolated values for wall thickness, split fibre fraction and fibre length at a given specific energy level (1800 kWh/t) is given in Table 1.

Differences in structural fibre characteristics explained in terms of refining intensity

How can the observed differences in the development of fibre properties be explained in terms of refining intensity? Here, refining intensity is defined as

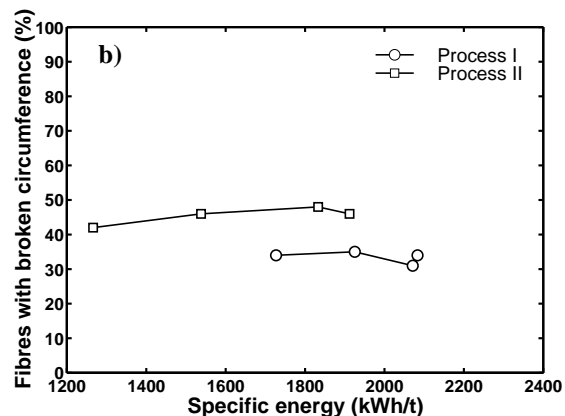
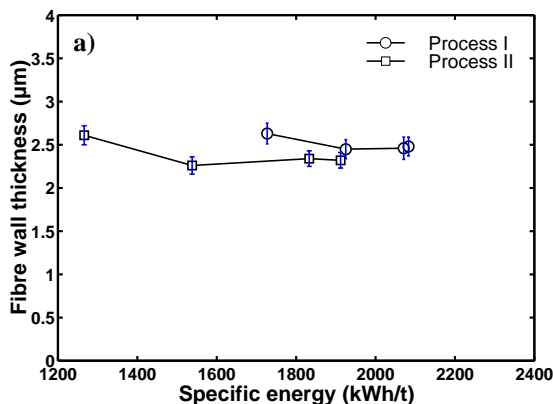


Figure 2. a) Mean fibre wall thickness of both intact fibres and fibres with broken circumference and b) fraction of fibres with broken circumference versus total specific energy consumption applied after the second refining stage using the fine bidirectional plate pattern (*c1*) or both refining processes in the first refining stage. The error bars show 95% confidence interval for the mean.

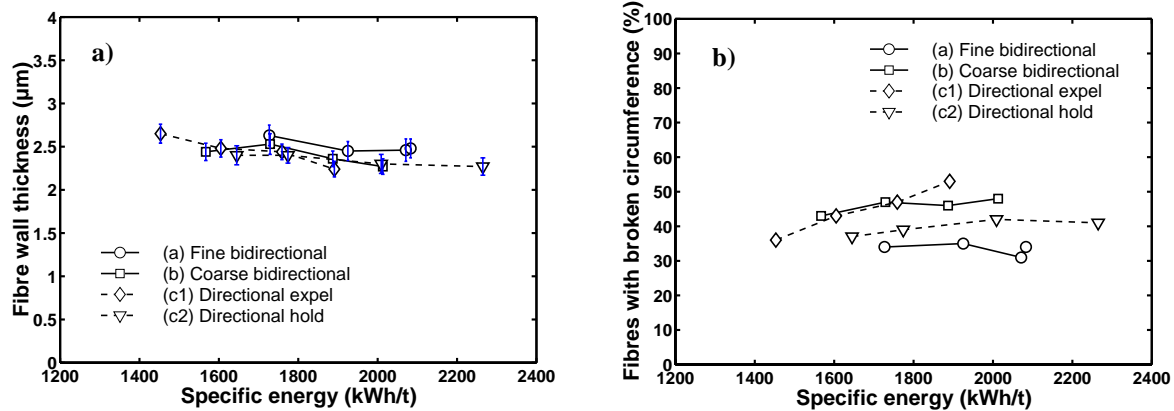


Figure 4. a) Mean fibre wall thickness including both intact fibres and fibres with broken circumference and b) fraction of fibres with broken circumference for process I versus total specific energy consumption applied after the second refining stage using different plate designs in the primary stage. The error bars show 95% confidence interval for the mean.

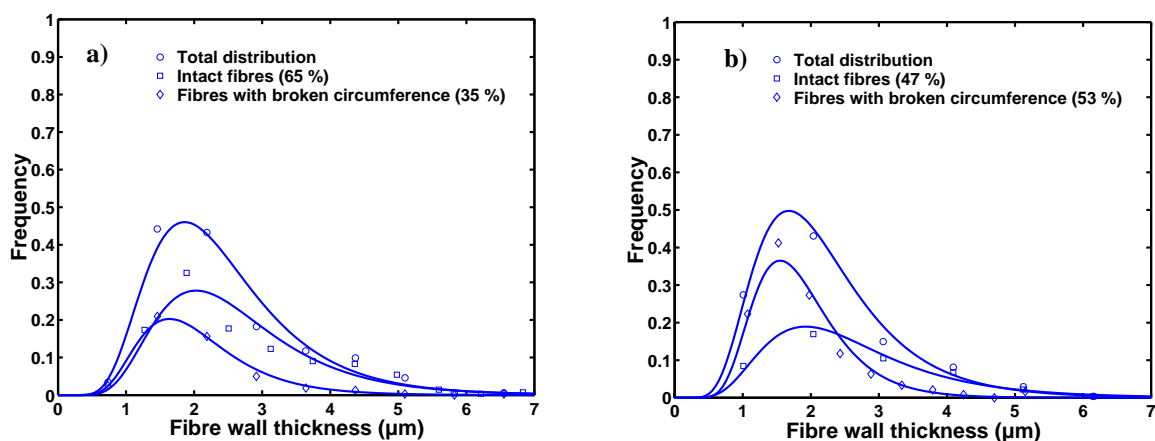


Figure 5. Distribution of fibre wall thickness after the second refining stage for process I using a) the fine bidirectional (Total SEC 1925 kWh/t) and b) the directional plate pattern in feeding mode, (c1), (Total SEC 1891 kWh/t) in the primary refining stage.

specific energy per bar impact or specific refining power (18, 19). Changing speed or plate pattern affect the number of impacts and the pulp residence time in the refiner. Residence time then determines specific energy per bar impact and the energy application rate on the passing fibres during the refining. Estimated specific energy consumption value per impact and specific refining power, using the approach of Miles (19) and Senger et al. (23), are listed in Table 1. According to Miles, refining intensity is proportional to the square of the speed of the disc. Bar crossings per unit time are proportional to the speed, whereas residence time is inversely proportional to the cube of the speed. The number of bar impacts on the fibres thus drop when increasing the speed causing higher refining intensity. As seen from Table 1, for all plate patterns, process II yields higher specific energy per bar impact and higher specific refining power. This may explain why process II having high speed, causes stronger material peeling from the fibre surface, leading to thin-walled fibres. Process II will also generate more split fibres, Figure 2. The energy transfer rate (specific refining power) during high

speed refining will be much higher than at lower speeds. Sabourin et al. (13) demonstrated that for equal refining intensity, the energy transfer rate was than three times higher. Based on literature (e.g. 7), one might also expect shorter fibres from a high speed process. This was not found. Process II actually yielded somewhat longer fibres than process I, for all refiner plates (Figure 7, Table 1). The two processes also have significantly different residence times and temperatures in preheating of the chips before the refining zone. Process I has a residence time of 150 seconds at a system pressure of 2.8 bar compared to 12-20 seconds and 6 bar for II. A reasonable explanation for the longer fibres for process II is that the high temperature makes the fibres less prone to fibre shortening. Figure 4 illustrates the effect of different plate patterns on fibre wall thickness and the fraction of fibres with broken circumference. The coarse bidirectional pattern, (b), and the directional pattern used in expel mode, (c2), developed significantly more split fibres. Design (b) gives a lower number of impacts compared to (a), causing higher refining intensity. This is evident from the

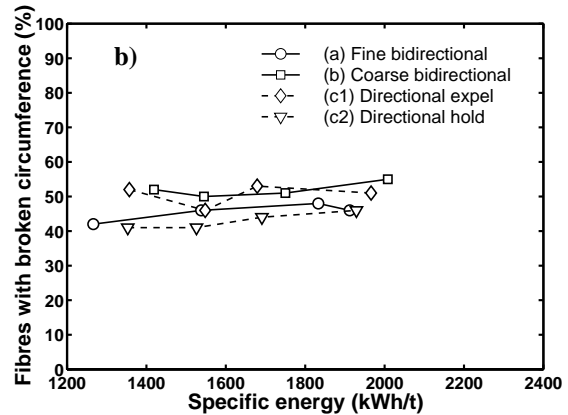
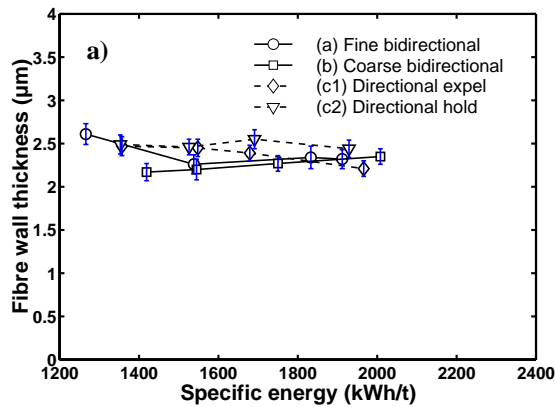


Figure 6. **a)** Mean fibre wall thickness including both intact fibres and fibres with broken circumference and **b)** fraction of fibres with broken circumference for process II versus total specific energy consumption applied after the second refining stage using different plate designs in the primary stage. The error bars show 95% confidence interval for the mean.

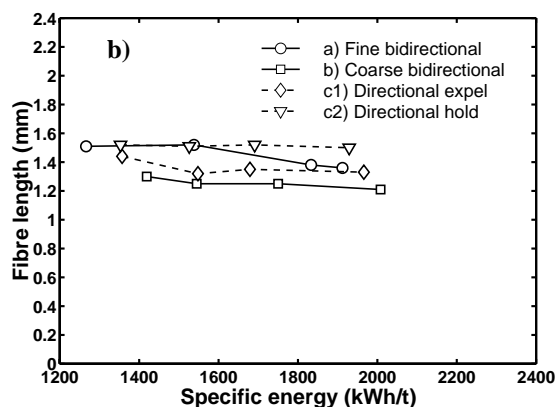
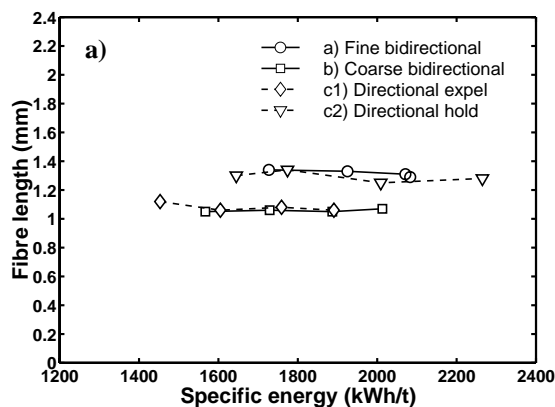


Figure 7. Mean fibre length after the second refining stage for **a)** process I and **b)** process II versus total specific energy consumption applied after the second refining stage using different plate designs in the primary stage.

calculated specific energy per bar impact and specific refining power, Table 1. With respect to intensity, it is reasonable that design (b) give shorter fibres and more split fibres compared to design (a). The directional pattern used in expel mode (c1) also gave shorter fibres and more split fibres, similar to design (b), although the pattern is very fine, causing a large number of bar crossings. Increased number of bar crossings alone should lead to lower refining intensity according to calculated intensity values, Table 1. The effect on fibre structure indicate high refining intensity. Changing plate design and thus the feeding ability of the refiner segments, allows variation of pulp residence time in the refining zone as described by Høydahl and Dahlqvist et al. (5). The directional pattern in expel mode (c1) has strong feeding capacity causing short residence time and high refining intensity. These results point to a limitation in the theory of Miles and May (18, 19). Their theory does recognize the number of bars, however, does not incorporate bar angles and the direction of rotation. Using a full-sized machine Høydahl and Dahlqvist et al. (5) showed how fibre length distribution is changed, going from a symmetrical, straight design to a directional pattern. Using the directional pattern in

hold back mode, (c2), the plate gap becomes much larger. The residence time in hold back mode, (c2), is higher than in expel, (c1), leading to lower intensity. This may explain the longer fibres and less fibre splitting for the (c2) design. Comparing Figure 4b and 6b shows that the split fibre fraction may be raised by increasing refiner speed. This is especially true for (a) and (c2). The difference between process I and II is much less pronounced for (b) and (c1). Speed and plate design are thus not independent for production of split fibres. For all designs, process II with high speed caused larger fibre length compared to process I. This may be explained by better thermal softening of the fibres.

Effects on pulp properties

The effect of plate design and refining modes on specific energy consumption to reach a given freeness is illustrated in Figure 8 for process I. The coarse bidirectional pattern, (b), and the directional pattern used in expel mode, (c1), demonstrate significant energy savings compared to pattern (a) and (c2). Effects of plate design and refining mode on various pulp properties are shown in Table 1. The two plate designs demonstrating the largest refining intensity,

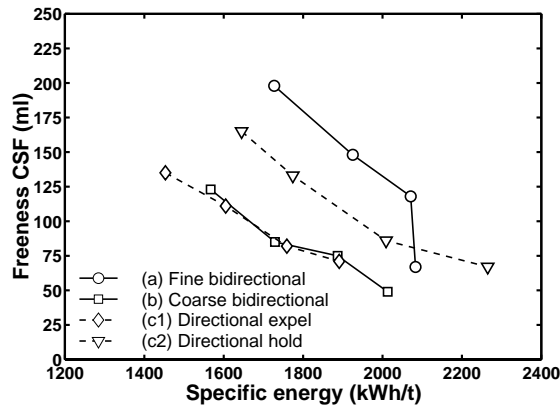


Figure 8. Freeness versus total specific energy consumption for process I after the second refining stage using different plate patterns in the primary stage.

(b1) and (c1), gave higher sheet density, lower tear index, higher tensile strength and light scattering and less shives for both process I and II. These plates also gave less long fibres (Bauer McNett +30 fraction) and more fines (Bauer McNett -200 fraction). Extensive energy savings along with better optical properties and similar strength have been reported for process II in the literature (11, 12, 13). Here, process II only gave lower energy consumption at a given freeness for plate design (a). For all plate designs, process II yielded higher tear strength and similar optical properties, and a somewhat higher tensile strength. Process II tends to produce less shives compared to I

as already described in the literature (11, 13, 22). In the present trials, retention time at system pressure was estimated to be 16-17 sec. This is somewhat higher than described in literature (12 sec.). This configuration typically produces pulps with similar brightness and higher strength than for conventional TMP pulping (12).

Conclusions

By controlling the pulp's residence time in the refiner, the number of bar crossings and degree of thermal softening of the fibres it is possible to manipulate important fibre properties. Higher refining intensity due to higher rotational speed or a more aggressive plate design resulted in much more collapsible fibres caused by longitudinal fibre wall splits. The results also indicate that increasing thermal softening allows a better preservation of fibre length and a large fraction of splitted thin-walled fibres; the latter being the effect of high rotational speed.

These findings may be utilised in order to raise the fraction of easily collapsible fibres in TMP production. Such fibres are beneficial to surface smoothness. The combination with the conservation of fibre length is beneficial for paper strength and runability on the paper machine. Finally, this study demonstrated that significant energy savings are achievable by application of high intensity refiner plates and high rotational speed.

Table 1. Pulp properties after the second refining stage compared at a specific energy consumption of 1800 kWh/t (interpolated values).

Process	I	II	I	II	I	II	I	II
	coarse bidir.	coarse bidir.	dir. expel	dir. expel	fine bidir.	fine bidir.	dir. hold back	dir. hold back
Plate pattern/refining mode	(b)	(b)	(c1)	(c1)	(a)	(a)	(c2)	(c2)
e (GJ/t per impact · 10 ⁴)	8.49	19.34	4.31	9.50	4.03	9.35	4.16	9.37
\hat{e} (GJ/t per sec.)	3.05	10.05	3.20	10.21	2.98	10.01	3.09	10.06
CSF (ml)	81	105	82	118	184	112	130	165
Apparent density (kg/m ³)	433	418	438	403	361	413	392	367
Tear index (mNm ² /g)	5.7	7.5	5.8	7.7	7.9	8.1	7.3	9.0
Tensile index (Nm/g)	35.3	37.5	33.7	36.2	28.8	39.1	34.2	34.1
Stretch (%)	1.9	2.3	2.0	2.3	1.8	2.2	2.0	2.1
Opacity (%)	96.4	96.1	96.3	95.8	94.7	96.0	95.1	94.4
ISO Brightness (%)	55.1	54.8	55.6	54.7	53.2	55.7	55.0	54.8
s (m ² /kg)	53.5	52.4	50.2	49.2	47.3	48.5	48.7	46.1
k (m ² /kg)	4.3	4.1	4.2	4.2	3.9	4.5	3.8	3.7
Pulmac shives < 0.10 mm (%)	0.53	0.34	0.24	0.20	0.82	0.46	0.70	0.74
Bauer McNett +30 (%)	25.0	43.9	26.5	38.7	43.5	47.8	40.6	52.8
30/50 (%)	22.3	17.6	19.4	15.6	16.9	14.1	16.8	12.7
50/100 (%)	16.6	11.8	15.8	10.7	11.4	9.5	12.0	7.8
100/200 (%)	8.0	5.9	8.6	5.1	5.4	4.7	5.6	3.8
-200 (%)	28.1	20.8	29.7	29.9	22.8	23.9	25.0	22.9
Fibre wall thickness (µm)	2.40	2.28	2.35	2.31	2.57	2.27	2.37	2.47
Fibres with broken circumference (%)	46	53	49	51	34	47	39	45
Fibre length (mm)	1.0	1.2	1.1	1.3	1.3	1.4	1.3	1.5

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Literature cited

1. Karnis, A. The mechanism of fibre development in mechanical pulping. *Journal of Pulp and Paper Science* 20 (10) J280-J288, 1994.
2. May, W.D. A theory of chip refining - The origin of fibre length. *Pulp Paper Mag. Can.* 74 (1), 70-78 (1973).
3. Miles, K.B., May, W.D., Karnis, A. Refining intensity, energy consumption and pulp quality in two stage chip refining. *TAPPI* 74 (3), 221-230 (1991).
4. Stationwala, M.I., Miles, K.B., Karnis, A. Effect of feed rate on refining. *Journal of Pulp and Paper Science* 20 (8), J236-J240 (1994).
5. Høydahl, H.-E., Solbakken, M., Dahlqvist, G. TMP for SC-grades - a challenge in fiber modelling. *Proceedings 1995 International Mechanical Pulping Conference*, 233-237, Ottawa 1995.
6. Kure, K.-A., Dahlqvist, G. Development of structural fibre properties in high intensity refining. *Pulp & Paper Canada* 99 (7), T233-T237 (1998).
7. Sundholm, J., Heikkurinen, A., Mannström, B. The role of rate of rotation and impact frequency in refiner mechanical pulping. *Paper ja Puu* 70 (5), 446-451 (1988).
8. Falk, B., Jackson, M., Danielsson, O. The use of single and double disc refiner configurations for the production of TMP for filled super calendered and light weight coated grades. *Proceedings 1987 International Mechanical Pulping Conference*, 137-143, Vancouver 1987.
9. Stationwala, M.I., Miles, K.B., Karnis, A. The effect of first stage refining conditions on pulp properties and energy consumption. *Journal of Pulp and Paper Science* 19 (1), J12-J18 (1993).
10. Sabourin, M.J., Cort, J.B., Musselman, R. High speed double-disc TMP from northern and southern softwoods.... one or two refining stages? *Pulp & Paper Canada* 95 (10), T400-T406 (1994).
11. Sabourin, M.J., Cort, J.B., Musselman, R., Ryan, K. Effect of residence time, temperature and speed on TMP properties produced from radiata pine, black spruce/balsam fir wood furnishes. *Proceedings 50th Appita annual general conference Vol. 2*, 567-577, Auckland 1996.
12. Sabourin, M.J., Xu E, Cort, J.B., Boileau I., Waller, A. Optimizing residence time, temperature and speed to improve TMP pulp properties and reduce energy. *Pulp and Paper Canada* 98 (4) 38-45 (1997).
13. Sabourin, M., Xu, E., Musselman, R. Evaluation of refiner disc speed, plate design and consistency on high pressure/low residence (RTS) TMP pulps. *Proceedings 1997 International Mechanical Pulping Conference*, 241-249 Stockholm 1997.
14. Strand, B.C., Falk, B., Mokvist, A., Jackson, M. The effect of production rate on specific energy consumption in high consistency refining. *Proceedings 1993 International Mechanical Pulping Conference*, 143-151, Oslo 1993.
15. Reme, P.A., Helle, T., Johnsen, P.O. Fibre characteristics of various mechanical pulp grades. *Proceedings 1997 International Mechanical Pulping Conference*, 297-308, Stockholm, 1997.
16. Kure, K.-A., Helle, T., Omholt, I. Properties of mechanical printing paper as affected by cross-sectional characteristics of TMP fibres. *1998 Progress in Paper Physics: A Seminar*, Vancouver 1998.
17. Braaten, K.R. The impact of fibre geometry, fibre splitting and fibrillation on the light scattering. *Proceedings 1997 International Mechanical Pulping Conference*, 349-353, Stockholm 1997.
18. Miles, K.B., May, W.D. The flow of pulp in chip refiners. *Journal of Pulp and Paper Science* 23 (8), J63-J72 (1990).
19. Miles, K.B. A simplified method for calculating the residence time and refining intensity in a chip refiner. *Paperi ja Puu* 73 (9), 852-857 (1991).
20. Fjerdingen, H., Forseth, T., Gregersen, Ø., Helle, T., Johnsen, P.O., Kure, K.-A., Reme, P.A. Some mechanical pulp fibre characteristics their process relationships and papermaking significance. *Transaction of the 11th Fundamental Research Symposium*, 547-604, Cambridge 1997.
21. Münster, H., Dahlqvist, G. Operational experience with the first commercial high speed refiner at Perlen Papier AG, Switzerland. *Proceedings 1995 International Mechanical Pulping Conference*, 197-202, Ottawa 1995.
22. Sabourin, M., Mackenzie, S., Urquhart, N. Evaluation of two stage and three stage refining processes for production of TMP pulp for SCA+ paper. *Pulp & Paper Canada* 98 (12), T464-468, 1997.
23. Senger, J., Ouellet, D., Bennington, C.P. The effects of pulp furnish and refiner speed on residence time in a high consistency refiner. *Proceedings 1996 TAPPI Pulping Conference*, 279-284, Nashville 1996.

