Development of TMP fibers in LC- and HC- refining

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KEYWORDS: LC-refining, HC-refining, Mechanical pulp, TMP, Disintegration, Fiber dimensions, Fiber curl, Fiber wall thickness, Fiber width, Fibrillation, BIN, Sheet properties

SUMMARY: Low consistency (LC) refining and high consistency refining (HC) has been studied in a TMP mill. When strength properties were increased, the development of fiber properties was different in LC- and HC-refining. Fiber curl decreased in LC-refining but increased in HC-refining. LC-refining decreased fiber curl and increased tensile index simultaneously in this study. It is therefore likely that the decreased fiber curl contributes to the increase of tensile index in LC-refining. Furthermore, fiber wall thickness decreased and external fibrillation increased in HC-refining, while these properties were only slightly influenced in the LC-refining. Fibrillation was found to decrease in most cases for LC-refining while fiber wall thickness index increased slightly but consistently, which might indicate a less dense structure of the fiber wall or its surface layers.

Double-disc HC-refining with the same energy input as in a conical single-disc refiner resulted in fibers of higher external fibrillation, lower fiber wall thickness and higher fiber curl at a given fiber length.

The results indicate that analyzing individual fiber dimensions could be a better tool for understanding how fibers develop in different kinds of refining than analyzing conventional handsheet properties.

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There is a strong need to increase energy efficiency in mechanical pulping at maintained pulp quality. A common way to estimate energy efficiency is to evaluate the specific energy required to reach a given increase in tensile index. Tensile index of handsheets shows the development of the whole pulp as an average value of the weakest zones in the hand sheets, but lacks a more detailed description of the development of individual particles. Such a description is probably useful in order to achieve the pulp quality required to fulfill the demands placed by the end product (Reme et al. 1999).

LC-refining of mechanical pulps has been introduced in many mills and has been reported to increase tensile index in an energy-efficient way (Engstrand et al. 1988, Hammar et al. 1997, Musselman et al. 1966, Andersson et al. 2011, Hammar et al. 2010, Andersson 2011b, Lundin 2008). Mill data, for the LC-refining in Stora Enso Kvarnsveden, have shown that there is a considerable variation in the increase in tensile index of handsheets at approximately the same specific energy input. The influence of the sheetmaking procedure, including sample pre-treatment, on this variation, is not well established for LC-refining.

Differences in mechanical pulp properties when refining in different types of HC-refiners such as single disc (SD)- and double disc (DD)-refiners have been shown mainly using traditional testing methods (Falk et al. 1987, Ferritsius et al. 1989, Wedin et al. 1992, Kure et al. 1999). Furthermore Kure et al. showed that wall thickness was lower for pulp from DD-refiners than from SD-refiners, by using high-resolution SEM microscopes (Kure et al. 1999).

As a complement to standard testing methods, data from optical fiber analyzers have been analysed using a newly developed fiber characterizing method, BIN (Bonding ability INfluence). BIN correlates to the tensile index and density of handsheets of long fiber pulp fractions (Reyier 2008, Ferritsius et al. 2009, Reyier et al. 2012) and was developed to describe the bonding ability of HC-refined fibers.

The two main purposes of this study were to

i) investigate the possible errors introduced by variations in the sample preparation, handsheet making and tensile testing, when interpreted as effects of the LC-refining.

ii) investigate how fiber properties develop when tensile index increases in both LC- and HC-refining in mill scale, including comparisons of SD and DD HC-refining.

Materials and Methods

Materials

TMP samples evaluated in this study were all full-scale pulps manufactured from *Picea Abies*.

In the comparison between HC- and LC-refining all samples were taken in a mainline consisting of an HC-refiner of CD82 type from Metso running at 1800 rpm followed by a conical LC-refiner of CF82 type from Metso. The energy used in the HC-stage was 1500-2180 kWh/ADMT and in the LC-stage approximately 100 kWh/ADMT. The HC-refiner was running at 1700 kWh/ADMT when sampling the pulp before and after the LC-refiner.

Pulp samples representing different types of HC-refining were collected in the Kvarnsveden mill. One TMP plant consists of SD (single disc) refiners as seen in *Fig 1*. The other TMP plant consists of DD (double disc) refiners as seen in *Fig 2*.

The refining in the mainline is made in one HC stage in both TMP plants. Pulp samples were taken in two positions in the mainline as primary pulp, one from a DD68 refiner and one from a SD-refiner of conical type (CD82). The specific energy was around 1500 kWh/ADMT for both these pulp samples. The third pulp in this study was a DD-refined pulp produced with 3000 kWh/ADMT. This pulp was produced with DD-refiners in all stages and is shown in *Fig* 2 as the pulp before bleaching.

Methods

The standard procedure for the pulp sample preparation was to dewater the pulps to a pulp consistency above 30% directly after sampling. This was done in a centrifuge with recirculation of filtrate to ensure no loss of fines. The samples were then frozen in plastic bags (-18˚C) until further use. This procedure was used for all samples with the exception of samples collected before and after the LC-refiner used to make handsheets without disintegration. These handsheets were made from the pulp without a dewatering procedure and in close conjunction with the sampling occasion.

Standard procedure for handsheets in the research laboratory is to first prepare the pulp using hot disintegration (ISO 5263-3) and make the handsheets with whitewater recirculation based on the SCAN C26:76 standard. Long fiber handsheets of Bauer McNett fractions P16/R30 were produced in a 177cm^2 sheet former following the ISO 5269-1 standard after Bauer McNett fractionation (SCAN-CM6:05). Tensile index was evaluated in an Alwetron TH-1 according to SCAN-P 67 standard, STFI density according to SCAN-P 88:01 standard, light scattering coefficient according to ISO 9416 and Z-strength according to ISO 15754.

The standard testing procedure for handsheets described above was used for all pulps in this study. Handsheets for pulps taken before and after the LC-refiner were also made from the pulps after no, cold (ISO 5263-2) and hot disintegration (ISO 5263-3). These extra handsheets were prepared following the SCAN C26:76 standard without white water recirculation. The testing scheme of the pulps in the comparison of HC- and LC-refining is shown in *Fig 3*.

Pulp samples, which were refined at different levels of specific energy in the HC-refiner (CD82), were analysed according to standard procedure (c.f. *Fig 1*). These samples were also analyzed in a FiberLab™ using default settings (see below).

To evaluate the repeatability of tensile index increase in LC-refining, handsheets were produced on three different occasions for the disintegrated samples shown for LC-refining in *Fig 1*. For the first two occasions handsheets made, all the above mentioned physical properties were evaluated. On the third occasion only tensile index was measured. On the first two occasions, more handsheets than needed for physical testing were produced and tensile index testing was repeated on these residual sheets.

Optical fiber analyses were done in both Kajaani FS-200 (ISO16065-1) (fiber length) and FiberLab (Kauppinen 1998) (fiber length, projected fiber length, fiber wall thickness index, fiber width index and fibrillation index). The fiber measurements were performed on samples taken before and after the LC-refiner without disintegration or using either cold or hot disintegration. The reported values from FiberLab were based on arithmetic averages of the measurements of each fiber property mentioned above except for fiber length, which was length weighted. All fiber properties were not measured on all particles. The default setting in FiberLab is to report averages of such measurements. In this paper these values are referred to as "default values" using "default settings", all data based on at least triple samples in FiberLab.

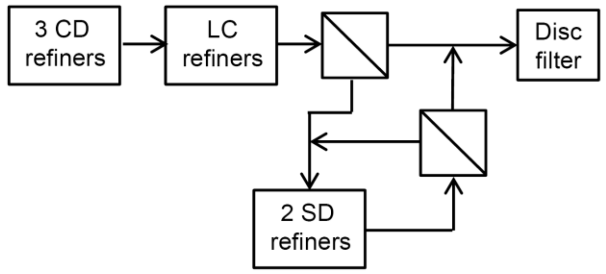

Fig 1. TMP plant with SD-refiners.

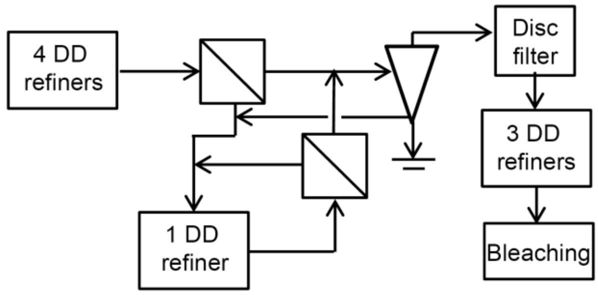

Fig 2. TMP plant with DD-refiners.

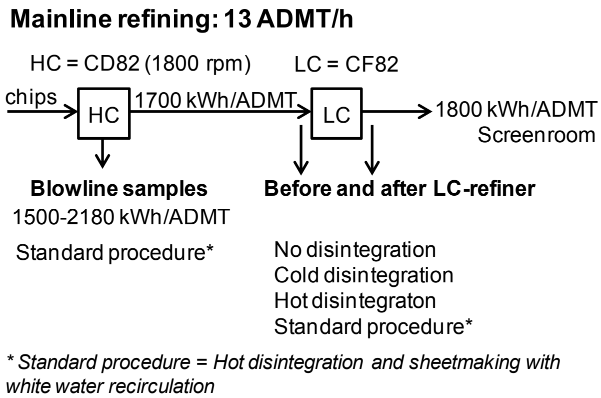

Fig 3. Samples taken for comparison of HC and LC refining.

Samples collected before and after LC-refining were also analyzed in FiberLab using the new procedures described below. In this case the pulps were only hot disintegrated before the measurements.

Samples collected on several occasions over two years before and after LC-refining were also analyzed in FiberLab using the new procedure described below. Samples representing SD- and DD-refining were analyzed in FiberLab using the new procedure below.

The FiberLab optical fiber analyzer has two perpendicular cameras to enable the measurement of fiber length, fiber width, fiber wall thickness and degree of external fibrillation (fibrillation index), which is evaluated as the ratio of the fibril area to the sum of fibril and fiber area (Kauppinen 1998). Fiber curl is defined as $(Lc\text{-}Lp)/Lp$ where Lc is the fiber length measured along the fiber centreline and Lp is the projected fiber length.

The fiber dimensions evaluated in the FiberLab device are not absolute but relative and have been shown to rank pulp samples in the same way as absolute values (Reyier 2008, Ferritsius et al. 2009, Reyier et al. 2011, Kauppinen 1998). Resolutions in the FiberLab measurements is 50 µm for the fiber length, 1 µm for the cross-sectional dimensions and <0.1µm for fibrillation index using grey scale sub-pixel calculation. Fibrillation index was found to have high repeatability with 95% confidence interval for triple samples of 0.16 units.

Fiber wall thickness, fiber width and fibrillation indexes were combined by multivariate analysis to the BIN-value, *Eq 1* (Ferritsius et al. 2009). The constant B is positive while C and D are negative.

$$BIN = A + B^{*}\ fibrill + C^{*}\ wall\,thick. + D^{*}\ width \qquad (1)$$

BIN, Bonding ability Influence, correlates to tensile index and density of handsheets made of long fiber fractions of HC-refined pulps, which was shown for the Bauer McNett fractions P16/R30 and P30/R50 of TMP and CTMP (Reyier 2008, Reyier et al. 2011).

To describe the properties observed for a long fiber fraction, which is roughly corresponding to the Bauer McNett fractions P16/R30 and P30/R50, a "digital fractionation" was performed on the data from the whole pulps. The fiber length interval 0.7-2.3 mm was chosen to represent the long fiber fraction of the pulp. This interval had about the same fiber length distribution as the major part of the fibers in Bauer McNett fractions P16/R30 and P30/R50, *Fig 4*.

By applying *Eq 1* on each fiber in the length interval 0.7-2.3 mm where fiber width index, fiber wall thickness index and fibrillation index have been measured, values of BIN were calculated. The corresponding procedure was also applied for other length interval of the fibers.

Results

Fiber development in LC-refining

The LC-refiners in this investigation were of conical type (CF82) and were running as second stage in the mainline refining. When mill data at the same energy input was evaluated as the differences in tensile index after and before LC-refining, the difference could vary between minus 1 to plus 12 Nm/g. A study was therefore performed to find out how much of the variations in the increase of tensile index in LC-refining that could be

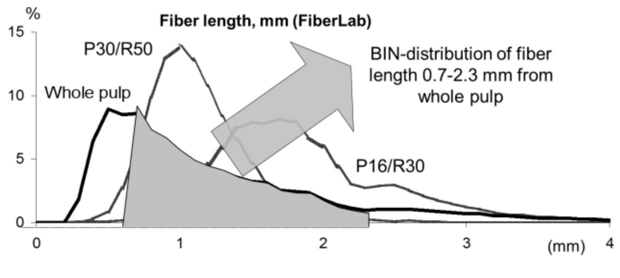

Fig 4. The fiber length interval 0.7-2.3 mm evaluated in FiberLab had about the same fiber length as the main part of the fibers in Bauer McNett fractions P16/R30 and P30/R50.

related to testing error or to sample preparation before sheet making. The pulps were prepared with no, cold or hot disintegration and handsheets were made without whitewater recirculation to resemble mill testing. The handsheets after hot disintegration were also made using whitewater recirculation, which is the standard procedure in the research laboratory. The pulp samples used in the study were collected before and after the LC-refiner running with an energy input of 100 kWh/ADMT.

Pulp properties before and after the LC-refiner including the first tested sheet properties using standard procedure are shown in Appendix 1. The decrease of freeness in the LC-refining was quite similar using cold or hot disintegration before the measurements; 30 and 29 ml CSF. The measured decrease in freeness was higher, 68 ml CSF, if the samples were not disintegrated before the measurements. This indicates that some of the effect of the LC-refining may be related to latency of the pulp.

Latency in the current study is defined alternatively as the difference in pulp property between cold and hot disintegration or as the difference between no and cold disintegration. It is clear that the LC-refining removed latency from the pulp using the latter definition, *Table 1*.

Average values of fiber dimensions before and after the LC-refiner are shown in *Table 2*. These were measured for no, cold and hot disintegrated pulp in Kajaani FS-200 and in FiberLab with default settings.

The fiber length measured in FS-200 showed no decrease in this LC-refining irrespective of the preparation of the pulp. The default FiberLab results, which include fines and larger fragments of fibers, showed very small differences before and after LC-refining with the exception of fiber curl, which decreased (bold numbers in *Table 2*). This decrease was most pronounced when the measurement was performed without disintegration, cf. *Table 1*. Default values from FiberLab might include higher measurement errors than the corresponding values generated using the procedures for BIN. For the calculation of BIN, all fibers are individually characterized for fiber wall thickness index,

Table 1. Latency defined as difference in freeness between either no and cold disintegration or between cold and hot disintegration.

	ΔCSF (no-cold) ml	**ΔCSF (cold-hot) ml**
Before LC	60	11
After LC	22	10

Table 2. Results from FiberLab (default) and Kajaani FS-200 for pulp after no, cold and hot disintegration.

Disintegration	**no**		**cold**		**hot**	
LC refining	**Before**	**After**	**Before**	**After**	**Before**	**After**
Kajaani FS-200						
Fiber length l/l (mm)	1.68	1.67	1.66	1.65	1.72	1.73
FiberLab						
Fiber length C(l) (mm)	1.70	1.66	1.70	1.66	1.66	1.63
Fiber width index	30.7	30.0	30.2	29.9	30.1	29.7
F. wall thickness index	10.3	10.3	10.4	10.4	10.4	10.4
Fiber curl index	**16.5**	**14.1**	**14.1**	**13.2**	**14.0**	**12.8**
Fibrillation index	6.10	5.67	5.65	5.66	5.58	5.66

fiber width index and fibrillation index. The fiber data for BIN could both be used with all measured fibers or using only the fibers in the length interval 0.7-2.3 mm (Reyier 2008). The same samples were run again in the FiberLab using this procedure developed for BIN. These values are compared to the values based on the default settings, *Table 3*.

Fibrillation index showed a small increase and the fiber wall thickness increased slightly in this LC-refining, as evaluated with the BIN procedure, which was not seen using standard settings. As a result of the increase in fiber wall thickness, BIN decreased in the LC-refining. This might indicate some structural changes of the fiber wall or the outer fiber layer, which makes the structure less dense and therefore increases the thickness of the fiber (sometimes referred to as "internal fibrillation"). Naturally, this will also increase the amount of water inside the fiber wall, which may be described as "swelling".

Bauer McNett fractions and Somerville shives for the pulp before and after the LC-refining, are shown in *Table 4*. These analyses were made after hot disintegration.

The Somerville shives (large shives) were reduced in the LC-refining. There are vague indications that the amount of the longest fibers, the R12 Bauer McNett fraction, was slightly reduced. It is probable that this fraction consists of small shives and untreated fibers. Except for this, the size of Bauer McNett fractions was very similar before and after LC-refining. The fines content in the pulp was almost the same before as after this LC-refining, based on Bauer McNett measurements.

Since former mill experience has shown considerable variations in the increase of tensile index at LC-refining,

Table 3. Results from FiberLab with default settings and with new settings and data selection.

FiberLab method	Default (incl. fines and fibrous material without intact walls)		All fibers* (no fines or fibers without intact walls)		Fibers cut 0.7-2.3 mm* (no fines or fibers without intact walls)	
LC refining	Before	After	Before	After	Before	After
BIN			24.0	23.8	19.3	19.1
Fiber width index	30.1	29.7	29.8	29.6	31.0	31.0
F.wall thickness index	10.4	10.4	8.3	8.4	9.1	9.3
Fiber curl index	14.0	12.8	13.0	11.9	13.1	12.1
Fibrillation index	5.6	5.7	6.5	6.6	5.6	5.8

*In the BIN method are only included fibers where the fiber wall area, fibrillation index and fiber curl are not zero (Reyier et al. 2012)

Table 4. Somerville shives and Bauer McNett fractions of the pulp before and after LC-refining

LC refining	Before	After	Δ (After – Before)
Somerville shives (%)	0.45	0.25	-0.20
Bauer McNett >12 SCAN (%)	11.8	10.7	-1.1
Bauer McNett 12-16 SCAN (%)	13.1	13.9	0.8
Bauer McNett 16-30 SCAN (%)	26.5	26.8	0.3
Bauer McNett 30-50 SCAN (%)	11.7	11.9	0.2
Bauer McNett 50-100 SCAN (%)	6.9	7.2	0.3
Bauer McNett 100-200 SCAN (%)	5.9	5.9	0.0
Bauer McNett <200 SCAN (%)	24.1	23.7	-0.4

handsheets were produced at three different occasions from disintegrated samples to evaluate the variation due to sheetmaking and testing. On the first two occasions, handsheets were produced to make repeated testing of tensile index possible. Tensile index before LC-refining is shown below, *Fig 5*. Both cold and hot disintegration increased the tensile index compared to testing without disintegration. Whitewater recirculation increased tensile index slightly, probably as a result of higher fines retention. It is also seen that tensile index could vary with three units in repeated tests although the same testing procedure for the samples was used. The variation could also be of the same magnitude in repeated tensile testing of sheets from the same batch. The various preparations methods for the handsheets seemed to result in approximately the same variation in tensile index on the different testing occasions. Standard deviations for the tensile index measurements are also shown in Appendix 2 and 3.

The variations in tensile index were very similar both before and after LC-refining i.e. compare *Fig 6* with *Fig 5*.

The increase in tensile index in LC-refining was shown to vary from 2 to 7 Nm/g based on results from different testing occasions, as seen in *Fig 7*. One explanation of the large variations in tensile index increase could be that the increase was calculated as the differences between two

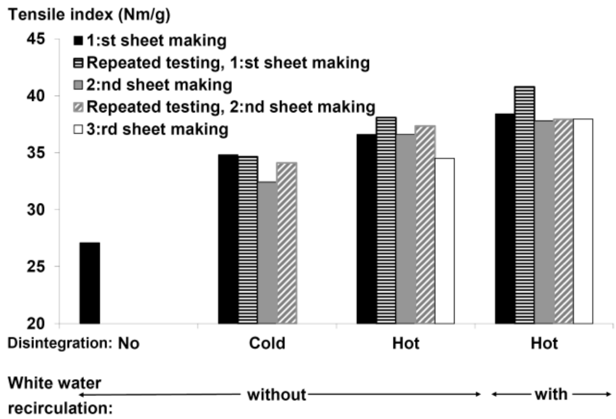

Fig 5. Tensile index before LC-refining using no, cold and hot disintegration on different testing occasions.

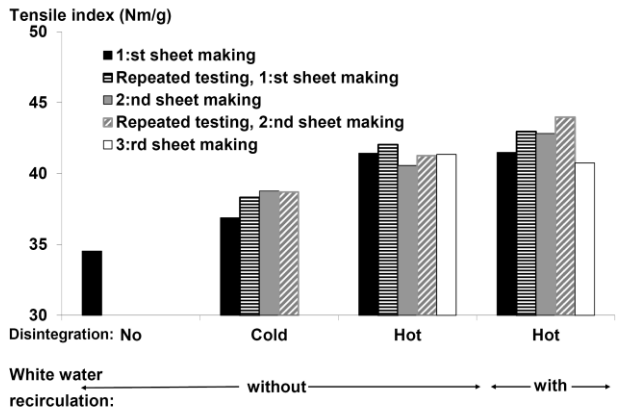

Fig 6. Tensile index after LC-refining using no, cold and hot disintegration on different testing occasions.

values which both exhibited measurement errors. This indicates that the large variations in tensile index increase, which were reported from mill evaluations, could be a result of testing errors. Further, to enhance repeatability this testing was performed by the same technician at a research center with SCAN standardized methods. It is probable that mill testing where different technicians make the handsheets and perform the testing, with slightly simplified methods, may result in higher testing errors.

The tensile index increase was around 4 Nm/g, except for the case with no disintegration. The making of handsheets with no disintegration was only performed once, but it may still be possible that the increase in tensile index could be higher when no disintegration was used. This was in agreement with the higher latency (defined as the difference in freeness for no and cold disintegration) in the pulp before as compared to after LC-refining.

One observation from this study was that tensile index after LC-refining, evaluated from handsheets made without disintegration, was very similar to tensile index before LC-refining if cold or hot disintegration was used, as seen in *Fig 8*. Tensile index increased with decreasing fiber curl for this LC-refining, and this effect was quite similar to disintegration.

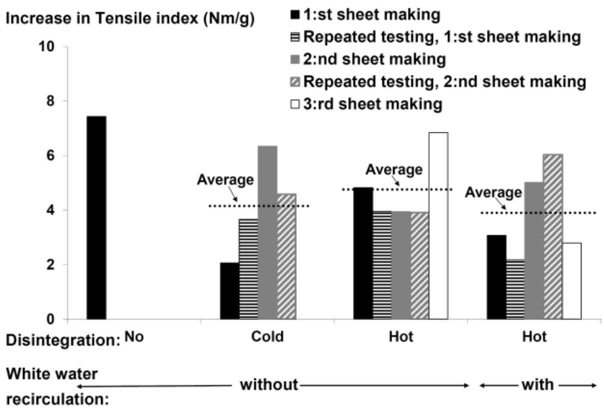

Fig 7. Increase in tensile index in the LC-refining for no, cold and hot disintegration at different testing occasions.

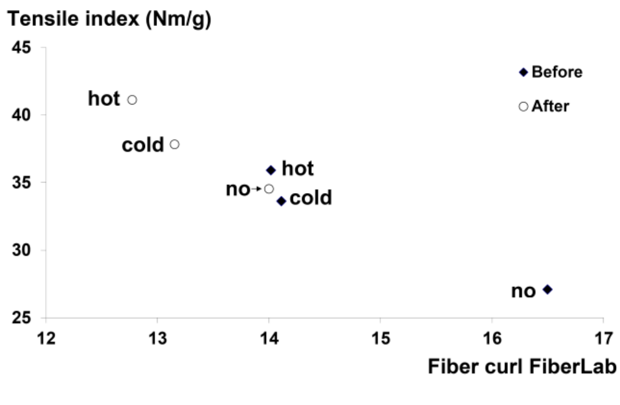

Fig 8. Tensile index versus fiber curl (default values) for pulps before and after LC-refining and tested after no, cold and hot disintegration. The handsheets were made without whitewater recirulation.

Table 5. Tensile index of the P16/R30 fraction produced from samples before and after LC- refining.

LC-refining	Before	After
16-30 Density STFI (kg/m^3)	285	302
16-30 Tensile index (Nm/g)	12.1	14.5

The combination of LC-refining and cold or hot disintegration resulted in higher tensile index and lower fiber curl index compared to only one of these treatments. Hot disintegration increased the tensile index and reduced the fiber curl only slightly more, compared to cold disintegration. It is also known from literature that fibers are straightened as a result of latency removal and strength properties are increased (Beath et al. 1966). Since both cold disintegration and LC-refining of the pulp resulted in a similar decrease in fiber curl and an increase in tensile index, the reduction in fiber curl might be an important reason for the increase in tensile index in LC-refining.

Long fiber sheets of the P16/R30 fraction were also made with hot disintegrated pulp. Both density and tensile index for the long fiber fraction were increased as a result of the LC-refining, *Table 5*.

The increased tensile index of the long fiber in the pulp could also be a result of straighter fibers although no measurement in FiberLab of the separate long fiber fractions was carried out in the current study.

The handsheets shown in *Figs 5-7* were also tested for tensile stretch at break, Z-strength and light scattering coefficient. This LC-refining influenced stretch only to a very slight extent and not consistently in the same direction for the different pre-treatments before sheetmaking, *Fig 9*. Using standard procedure for sheetmaking, the tensile stretch at break was slightly decreased in this LC-refining.

Fig 10 shows the increase in Z-strength in LC-refining, which showed similar results as the increase in tensile index, c.f. *Fig 7*.

Using whitewater recirculation in the sheetmaking gave a higher light scattering coefficient, most probably due to higher fines retention. This increase was about 2-3 m^2/kg before LC-refining and about 5 m^2/kg after LC-refining, resulting in an increase in light scattering for this LC-refining as shown in *Fig 11*.

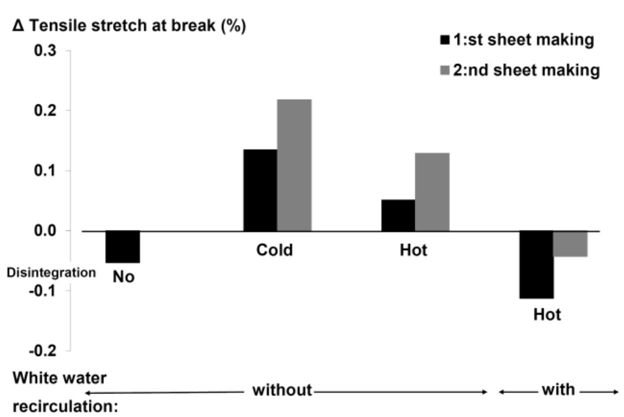

Fig 9. Delta tensile stretch at break in the LC-refining for no, cold and hot disintegration on different testing occasions.

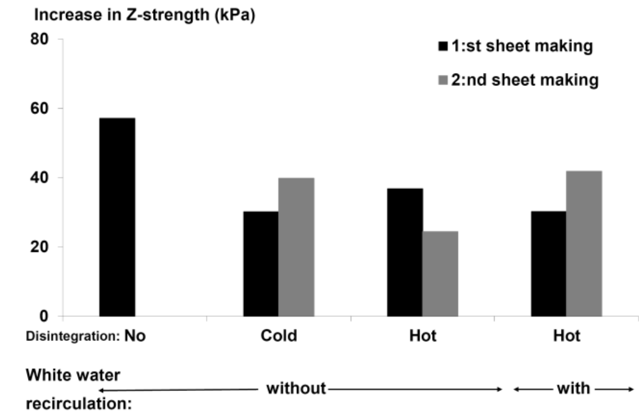

Fig 10. Increase in Z-strength in the LC-refining for no, cold and hot disintegration on different testing occasions.

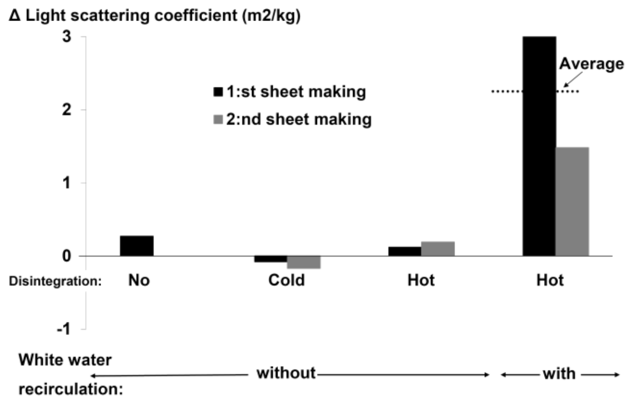

Fig 11. Differences in light scattering coefficient in the LC-refining for no, cold and hot disintegration on different testing occasions.

The average increase was 2 m^2/kg for this LC-refining if whitewater recirculation was used. The ability of the fibers to retain fines might have increased as an effect of LC-refining, since the amount of fines was not increased in the LC-refining. However, no increase in light scattering coefficient was found in this LC-refining, when the handsheets were produced without whitewater recirculation.

Samples taken before and after the LC-refiner on different occasions in the same position as in the study described above, were analyzed in the FiberLab device using the procedure for BIN calculations, where fiber length was between 0.7 and 2.3 mm. The samples were collected on six different occasions during a period of two years. In *Table 6* below, average values are shown of the changes in fiber curl index, fibrillation index, fiber wall thickness index and fiber width index.

The fiber curl was considerably decreased in LC-refining for all samples. All fiber dimensions were only slightly influenced, and for fibrillation index and width index not consistently in the same direction. Fibrillation was found to decrease in most cases and the fiber wall thickness index increased slightly but consistently, which might indicate fiber swelling.

For all these occasions, BIN was decreased in the LC-refining. This was expected, since calculation of BIN is based on fibrillation index, fiber wall thickness index and fiber width index.

Table 6. Differences (after-before LC-refining) in fiber dimensions on different occasions for LC-refining.

	Δ (Difference after – before LC refining)			
Sample occasion	Δ Fiber curl index	Δ Fibrillation index	Δ Fiber wall thickness index	Δ Fiber width index
1	-1.46	-0.24	0.08	-0.21
2	-0.95	-0.09	0.01	0.04
3	-1.44	-0.08	0.03	-0.16
4	-1.85	0.02	0.09	0.10
5	-1.30	-0.10	0.07	-0.12
6	-1.09	0.11	0.05	0.04

Comparison of fiber development in HC-refining using CD- or DD-refiners

The fiber measurements in FiberLab using the procedure for BIN have been made for the comparison of SD-(single disc) and DD-(double disc) refining at approximately the same specific energy input. Both these pulps were taken after one stage refining in mainline. The SD-refiner in this study is of conical type (CD). In this study a DD-refined pulp with higher specific energy was also included (DD+DD).

The data on fiber properties for the three pulps were divided into eight fiber length intervals, within the range of 0.7-2.3 mm. The arithmetic average of fibrillation index, fiber wall thickness index, fiber width index and fiber curl index were plotted against the average fiber length of these specific length intervals, *Fig 12a-e*.

The DD-refined pulp showed a higher degree of fiber wall treatment at a given fiber length over the whole investigated length intervals than the CD-refined pulp. The fibrillation index was higher and both fiber wall thickness index and fiber width index were lower and consequently also BIN was higher for the DD-refined pulp. Fibre curl was also higher for the DD-pulp than for the CD-pulp. Fiber curl at given fiber length was further increased with additional refining of the DD-pulp (DD+DD). Further refining of the DD-pulp also increased fibrillation index and decreased fiber wall thickness.

The level of fiber curl index was highest for the pulp with the highest specific energy input (DD+DD) over the whole length interval, *Fig12d*. Further, both fiber curl index and fibrillation index were increased and fiber thickness index was decreased with decreasing fiber length for all pulps. This indicates that both a higher energy input in HC-refining and a more developed fiber (i.e. higher fibrillation index and lower fiber wall index) gives a higher level of fiber curl for HC-refined fibers.

Fiber development and sheet properties after a CD82 refiner

Mill experience with the HC-refiner (CD82) placed before the LC-refiner, c.f. *Fig 1*, has shown that tensile index increases around 2 Nm/g at an energy input of 100 kWh/ADMT. Tensile index at varying specific energy for samples collected at one occasion after the HC-refiner is shown in *Fig 13*.

The pulp properties of these HC refined pulps are also shown in Appendix 1. These pulps were also measured in FiberLab using the default settings.

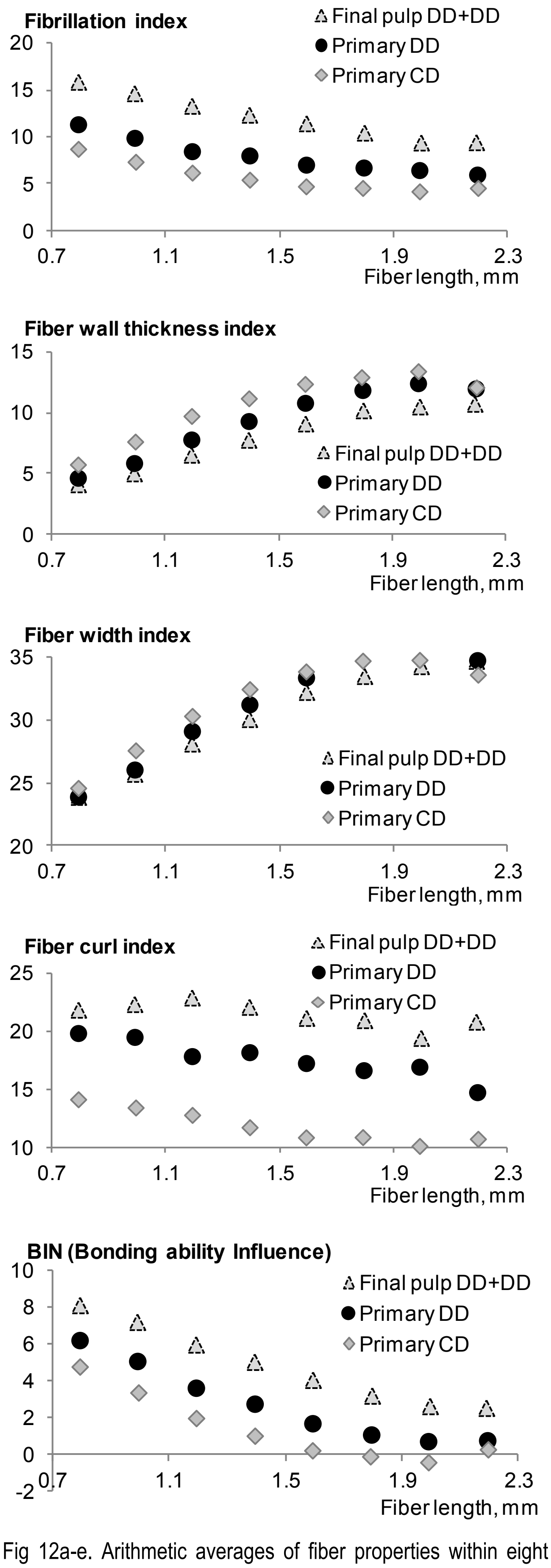

Fig 12a-e. Arithmetic averages of fiber properties within eight fiber length intervals plotted against the arithmetic average fiber length of each interval for primary refined CD- and DD-pulps, and a final DD-pulp.

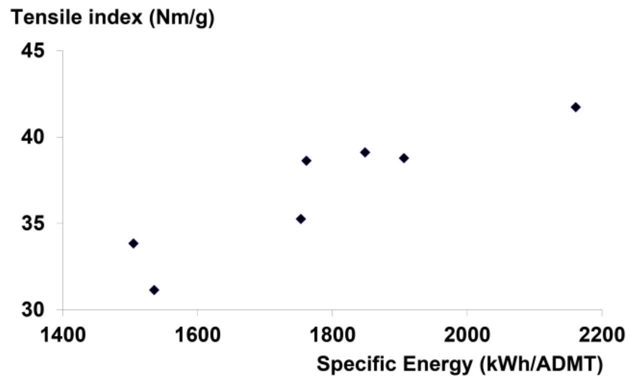

Fig 13. Tensile index versus specific energy for pulp samples from a CD-refiner.

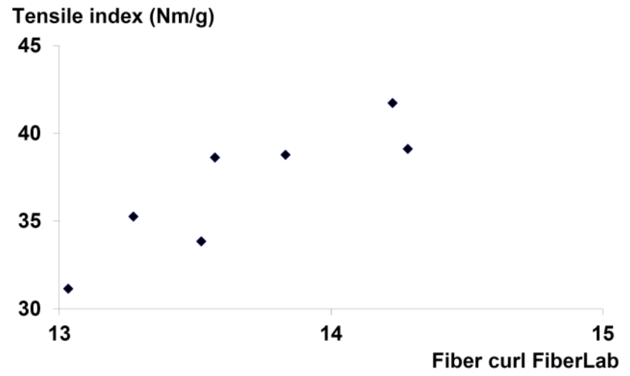

Fig 14. Tensile index versus fiber curl (from default report values in FiberLab) for pulp samples from a CD-refiner running with different specific energy.

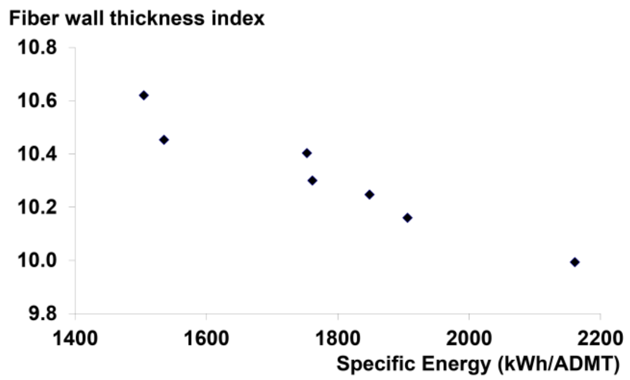

Fig 15. Fiber wall thickness index (from FiberLab default report) versus specific energy for pulp samples from a CD-refiner running with different specific energies.

The default values from the FiberLab show increasing fiber curl index with increasing tensile index, *Fig 14*. This means that the fiber curl index increased with increasing energy input, c.f. *Fig 12d*.

Fibrillation index evaluated from default FiberLab values showed no clear trend versus specific energy. Arithmetic average of fibrillation index as calculated with default settings in FiberLab might include more measurement error than the evaluations using the BIN method. Data from FiberLab using the procedure for BIN was not available for these samples.

The fiber wall thickness (default values) was reduced with increasing specific energy, *Fig 15*.

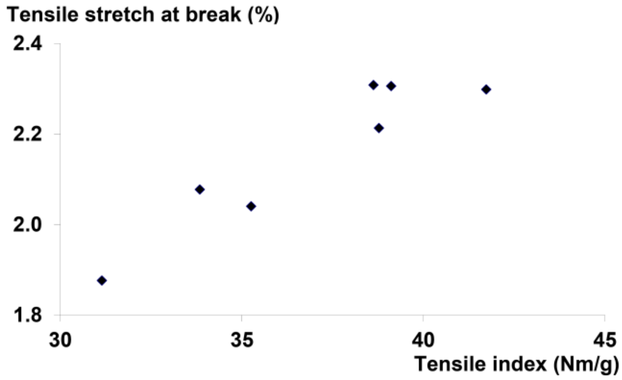

Fig. 16. Tensile stretch at break versus tensile index for pulp samples from a CD-refiner.

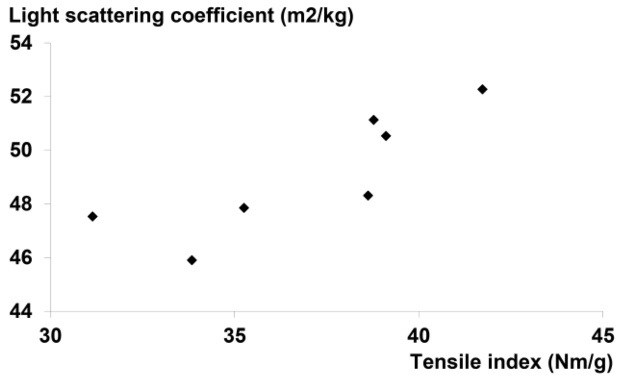

Fig 17. Light scattering versus tensile index for pulp samples with different specific energy taken at one occasion from a CD82-refiner

At an tensile index increase of 4 Nm/g using this HC-refiner, the tensile stretch at break was increased around 0.2 % and the light scattering coefficient was increased by 2 m^2/kg, as seen in *Fig 16* and *Fig 17*.

Development of fiber and handsheet properties as a result of LC- and HC-refining.

The tensile index measured on handsheets was found to increase both in HC- and LC-refining in these studies, as expected. The data used for the comparison of HC- and LC-refining are based on samples taken from the same pulp line but at different occasions for the two refiners. The data are also shown in Appendix 1. Although the sampling was made at different occasions, the pulp quality at certain specific energy was very similar. The evaluation of the samples before and after LC-refining showed an average tensile index increase of about 4 Nm/g for this LC-refiner (CF82 from Metso) running at an energy input of about 100 kWh/ADMT. The energy input in the HC-refiner (CD82 from Metso) before this LC-refiner is higher for the same increase in tensile index, which is in agreement with investigations made by others (Reme et al. 1999, Engstrand et al. 1988, Hammar et al. 1997).

The increase in light scattering coefficient was similar at a tensile index increase of 4 Nm/g for this LC-refining and this HC-refining, using the standard testing procedure in the laboratory. Tensile stretch at break decreased slightly with increasing tensile index in this LC-refining, but increased slightly with increasing tensile index in this HC-refining.

Table 7. Development of sheet properties in HC- and LC-refining at an energy input of ~100kWh/ADMT.

	Tensile index	Stretch	Density	Z-strength	16-30 Tensile index	Light scattering
HC	↗	↗	↗	↗	↗	↗
LC	↗	↗ →	↗	↗	↗	↗

Table 8. Development of fiber properties in HC- and LC-refining at an energy input of ~100kWh/ADMT, fibers 0.7-2.3mm.

	BIN	Fibrillation index	Fiber wall thickness index	Fiber width	Fiber curl
HC	↗	↗	↘	↘	↗
LC	↘ →	→	↗ →	↗ →	↘

The fiber wall thickness index and sometimes also the fiber width index were slightly increased in the investigated LC-refining, while HC-refining resulted in a decrease of the same properties. A number of investigations have shown that fibrillation index increases with increasing specific energy in HC-refining, c.f. for example *Fig 12a*. The DD-pulp with higher specific energy (marked DD+DD in the figure) had higher fibrillation index in the whole fiber length interval than the DD-pulp with lower specific energy (marked DD in the figure). The fibrillation index was in most cases not increased in the LC-refining.

In LC-refining, fiber curl was decreased, while it was increased in HC-refining. In HC-refining, the fibers are treated at a pulp consistency above 30 % in temperatures around 160˚C. The treatment at high temperature and high pulp consistency might introduce fiber curl in the fibers. In LC-refining the fibers are treated at 4% pulp consistency and at around 70˚C. It might be both the lower temperature and lower pulp consistency than in HC-refining that results in a decrease of fiber curl in LC-refining. It is possible by both cold (20˚C) and hot disintegration (85˚C) to reduce the fiber curl in the HC-refined pulp to approximately the same extent. The reduction of fiber curl in the disintegration seems then only to be slightly dependent on temperature. This indicates that low pulp consistency is most important for the reduction of fiber curl. The disintegration is done at 2.2% pulp consistency, i.e. lower than in LC-refining.

BIN was observed to decrease slightly or not be influenced at all in LC-refining. That is the opposite development to HC-refining. Since BIN is a combination of fiber wall thickness index, fiber width index and fibrillation index, fiber dimensions which were almost not changed in the LC-refining, this explains the small effect on BIN.

Table 7 and *Table 8* summarize how the sheet and fiber properties were developed in HC- and LC-refining in the studies reported above. In these tables, tensile index, tensile stretch at break, density, light scattering coefficient and Z-strength obtained from handsheets made using the standard procedure. An upwards pointing arrow indicates an increase; a downwards pointing arrow indicates a decrease, and a horizontal arrow indicates no significant difference.

Discussion

Large variations of tensile index have been observed in LC-refining based on mill testing. In this paper, it is shown that a large part of the variations may be the result of testing errors, as the tensile index increase in LC-refining could vary between 2-7 Nm/g for repeated testing of the same pulps. These results and previous experience seem to indicate that it is more the measurement of tensile index than the sheetmaking procedure that results in high variations in tensile index. The SCAN standard method for tensile index is measurements of 10 stripes. Probably at least the double amount of stripes should be measured to obtain more accurate values of tensile index. Using single measurement with the standard method (with 10 stripes) for process evaluations could therefore result in incorrect conclusions.

Most probably some of the measured variation in tensile index increase for the LC-refining in the mill is due to actual changes in the process, but the extent of these may be obscured by experimental variations. It has been shown in pilot scale that there is an optimum plate gap in LC-refining for highest increase of tensile index (Luukkonen 2011). It might be possible that LC-refiners in mills are running at the optimal plate gap only part of the time, thus contributing to variation in tensile index increase.

Fiber curl measured in FiberLab showed that the fibers were straighter after than before LC-refining of an HC-refined pulp. This is also seen in Lundin's study (Lundin 2008). Fiber curl in the present study was also decreased and tensile index increased in a quite similar way as LC-refining when the HC-refined pulp (taken after latency removal in the mill) was either cold or hot disintegrated. The comparatively mild fiber treatment in disintegration is evidently sufficient to achieve the same development of fiber curl and tensile index as LC-refining. Hot disintegration decreased fiber curl and increased tensile index only slightly more than cold disintegration, especially for the pulp before LC-refining. Further, the effects of combination of LC-refining and disintegration on tensile index and fiber curl were additive. The disintegration is done at even lower pulp consistencies compared to LC-refining. Hot disintegration is done at slightly higher temperatures, but cold disintegration is done at considerably lower temperatures compared to the LC-refining in this study. This indicates that it may be the treatment in low consistency itself that is important for decreasing fiber curl and increasing tensile index in this study.

Increased specific energy in HC-refining increases tensile index as expected, but fiber curl was also increased despite using hot disintegration before the sheetmaking. The different changes in fiber curl with increasing tensile index indicate different fiber developments in LC- and HC-refining.

It is difficult to know how much of the increase in density and tensile index depends on the decrease of fiber curl in LC-refining. It is probable that straighter fibers could form a denser sheet, resulting in higher tensile index, as is well known in latency removal (Beath et al. 1966). Lower fiber curl indicates straighter fibers, but the underlying reasons for this are unknown. A very small but consistent increase of fiber wall thickness was seen as a result of the LC-refining. This might indicate some structural changes of the fiber wall or the outer fiber layer, which makes the structure less dense and therefore increases the thickness of the fiber wall (sometimes referred to as "internal fibrillation"). Naturally, this will also increase the amount of water inside the fiber wall, which may be described as "swelling". If the fibers are more swollen this might partly be a reason for the straightening of the fibers in LC-refining. Lundin (2008) showed that increasing intensity in LC-refining of TMP increased water retention value WRV, which may be interpreted as increased swelling. However, this was measured on the whole pulp, not solely the fibers, and the fines might have influenced the WRV-measurement.

Unlike LC-refining, the fiber wall thickness was decreased and fibrillation was increased with increasing tensile index in HC-refining, as expected. This further supports that different fiber developments are behind the increase of tensile index in LC- and HC-refining. It might be possible that a similar increase of fiber wall thickness as in LC occurs also as an effect of HC-refining, but this cannot be measured as an increase in fiber wall thickness because of the more extensive peeling of the fiber wall.

Since tensile index increases with increasing fiber curl in HC-refining, it might be the reduction of the fiber wall thickness and the increase in fibrillation that increases the tensile index and this might counteract the negative effect of increased fiber curl. The different development of fiber curl with increasing tensile index might be a partial explanation of the higher increase of tensile index in LC-refining than in HC-refining at a certain energy input.

The measured fiber curl in FiberLab might also partly be caused by more flexible fibers, which could be bent in different directions during measurement. It should be investigated how much of the fiber curl is of a permanent nature. Fiber length might also influence the measured fiber curl, but the effect of that should be small in the present investigation, since the fiber length was similar in the comparisons of the pulps.

It is possible that both LC- and HC-refining increases the "internal fibrillation" and thereby the fiber wall flexibility, fiber characteristics which were not evaluated in this study. It is recommended in future work to evaluate which changes in the fiber wall occur during the two different process types at the same increase in tensile index.

The HC-refined pulp discussed here, taken before the LC-refiner, was from a first stage refiner, i.e. refining of chips. The same effects on fiber curl and tensile index could be seen for refining of fibers, as in the example of a DD-refined pulp with additional energy input in a second stage compared to the corresponding first stage DD-refined pulp.

If the increase in tensile index in LC-refining is at least partly due to a reduction in fiber curl, the whole process from the refining to the paper machine must be considered. If LC-refining increases the tensile index in the mainline, as in the present investigation, the pulp might be subjected to some treatment later in the process line, which again increases fiber curl, for example reject refining. If the pulp is subjected to treatment reducing fiber curl in the process line, for example MC-pumps, this effect of LC-refining might then decrease in the paper machine, compared to the earlier evaluation of the LC-stage, since the fiber curl would be reduced anyway. It is probably beneficial to have a lower fiber curl in the pulp before screening. The potential to decrease fiber curl may be higher if fiber curl is high before the LC-refiner. It might therefore be possible that the fiber curl in the pulp before LC-refining influences the increase of tensile index in the LC-stage.

It is probably important to know which developments on fiber level cause the increase in tensile index, when developing new energy-efficient process concepts. The effect on paper machine runnability and paper quality may well be different, depending on how the tensile index was increased. To optimize refining based on final product requirements, it would probably be more useful to correlate performance on the paper machine and paper quality to distributions of fiber properties rather than to tensile index and other laboratory sheet properties, which necessarily represent average values.

The LC-refining in this study resulted in a light scattering coefficient increase of 2 m^2/kg and a tensile index of around 4 Nm/g, if the handsheets were produced using recirculation of whitewater, which was the standard procedure in the laboratory. Evaluation of light scattering coefficient for handsheets made without whitewater recirculation showed no increase in light scattering coefficient for this LC-refining. Analyzing the pulps with less fines retention could therefore result in incorrect evaluation of the refining. The increase in light scattering at an increase in tensile index by 4 Nm/g was similar for LC- and HC-refining in this comparison. A lower increase in light scattering at a certain increase in tensile index for LC-refining than for HC-refining has been reported (Andersson 2011b). The different results could depend on either testing procedure, fiber quality before refining or refiner type or a combination of these.

The investigated LC-refiner was found to increase the tensile index both for handsheets from whole pulps and from the fiber fraction P16/R30, but BIN decreased, which was due to the different development of fiber properties as compared to HC-refining. All fiber characterizations for evaluation of BIN have earlier been done for different HC-processes, where BIN has shown good correlations to tensile index and density of handsheets of fiber fractions (Reyier 2008, Ferritsius et al. 2009, Reyier et al. 2012). BIN increases with increasing fibrillation index, decreasing fiber wall thickness index and decreasing fiber width index. This was not observed in LC-refining, where a slight increase in fiber wall thickness instead was seen, which explains that a large number of evaluations showed a slight decrease of BIN.

Conclusions

A study of LC-refining of HC-refined TMP in a CF82-refiner running at an energy input of 100 kWh/ADMT in mill scale has shown the following:

- Both disintegration in laboratory and LC-refining decreased fiber curl and increased tensile index in a similar way. The effects were additive, e.g. disintegration after LC-refining increased tensile index and reduced fiber curl further, compared with only one of the treatments.
- Latency, defined as the difference in freeness between no and cold disintegration, is reduced in LC-refining.
- Averages of five evaluations of tensile index showed the same increase in tensile index (4 Nm/g) in the LC-refining for handsheets prepared using a number of different procedures. Results from standard measurements performed once varied between 2-7 Nm/g depending on the testing error. At least double testing of tensile index, corresponding to twenty test stripes, is recommended for process evaluations.
- The light scattering coefficient increases in the investigated LC-refining if the handsheets are made with whitewater recirculation but not if they are made without. To evaluate light scattering coefficient correctly it is important to maintain efficient fines retention in the handsheets by using whitewater recirculation.
- Evaluations of fiber dimensions showed small differences before and after LC-refining with the exception of fiber curl. Fiber wall thickness index, fibrillation index and fiber width index were only slightly influenced in the LC-refining.

A study of HC-refining of TMP in CD- and DD- refiners in mill scale has shown:

- Fibrillation index and fiber curl index were higher and fiber wall thickness index was lower for the DD-refined pulps than for the CD-refined pulp. This was also valid when compared at the same fiber length and at approximately the same level of specific energy.
- Increased specific energy in DD-refining (two stage refining) increased fibrillation index, decreased fiber wall thickness index and increased fiber curl index compared at given fiber length intervals.

A comparison of LC- and HC-refining has shown the following:

- Different fiber development seems to be behind the increase in tensile index for HC- and LC- refining. One observation was that fiber curl decreased in LC-refining, but increased in HC-refining.
- BIN did not increase in LC-refining as it does in HC-refining. However, BIN is based on fibrillation index, fiber wall thickness index and fiber width index, fiber dimensions which were marginally influenced in LC-refining compared to HC-refining.
- Light scattering coefficient increases with tensile index in a similar way for LC-refining and HC-refining in this study (provided that handsheets are made with whitewater recirculation).
- Analyzing individual fiber dimensions could be a contribution to understanding the fiber development in

different refiners to a greater extent than analyzing average values of conventional handsheet properties.

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Appendix 1

	Before LC-refiner	After LC-refiner	HC-refining in CD82 with different specific energy, samples are taken in blow line						
Specific energy	*1700*	*1800*	*1505*	*1535*	*1753*	*1761*	*1848*	*1906*	*2161*
CSF (ml)	173	144	223	241	196	170	168	184	150
Fiberlength Kajaani FS-200 l/l (mm)	1,7	1,7	1,8	1,8	1,8	1,8	1,8	1,8	1,6
Fiber length FiberLab C(l) (mm)	1,7	1,6	1,8	1,8	1,8	1,7	1,7	1,7	1,6
Fiber curl FiberLab (l) (%)	14,0	12,8	13,5	13,0	13,3	13,6	14,3	13,8	14,2
Fiber width FiberLab (l) (µm)	30,1	29,7	30,7	31,1	30,7	30,1	30,1	30,0	29,8
CWT FiberLab (l) (µm)	10,4	10,4	10,6	10,5	10,4	10,3	10,2	10,2	10,0
Somerville (%)	0,45	0,25	0,90	0,97	0,63	0,39	0,36	0,28	0,20
Bauer McNett >30 SCAN (%)	51,4	51,4	57,2	58,4	56,1	53,9	53,7	52,7	51,0
Bauer McNett 30-200 SCAN (%)	24,5	24,9	21,1	21,6	21,8	22,2	22,4	23,7	25,0
Bauer McNett <200 SCAN (%)	24,1	23,7	21,8	20,0	22,1	23,9	24,0	23,6	24,0
Tensile index (Nm/g)	38,4	41,5	33,8	31,1	35,3	38,6	39,1	38,8	41,7
Stretch (%)	2,2	2,1	2,1	1,9	2,0	2,3	2,3	2,2	2,3
Tear index (mNm2/g)	8,6	8,0	8,8	8,6	8,7	9,2	8,9	8,7	8,4
Z-strength (kPa)	375	406	275	248	314	326	328	367	405
Density STFI (kg/m3)	446	463	380	367	406	409	414	457	467
Lightscatt. coeff. (m2/kg)	46,8	49,8	45,9	47,5	47,9	48,3	50,5	51,1	52,3
16-30 tensile	12,1	14,5	12,3	10,7	13,9	12,1	12,2	11,2	18,6

Appendix 2

Tensile Index before LC-refining

Disintegration:	no		cold		hot		hot	
WhiteWater recirculation:	no		no		no		yes	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1:st sheetmaking	27.09	0.96	34.82	1.18	36.61	1.66	38.41	1.51
1:st recidual			34.65	2.13	38.09	2.28	40.78	1.58
2:nd sheetmaking			32.43	1.28	36.61	2.18	37.80	2.40
2:nd recidual			34.11	2.44	37.35	1.56	37.94	1.80
3:d sheetmaking					34.51	2.94	37.95	2.05

Appendix 3

Tensile Index after LC-refining

Disintegration:	no		cold		hot		hot	
WhiteWater recirculation:	no		no		no		yes	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
1:st sheetmaking	34.53	1.90	36.88	1.54	41.43	2.62	41.49	2.46
1:st recidual			38.31	1.70	42.04	1.86	42.95	1.65
2:nd sheetmaking			38.77	2.27	40.56	1.99	42.82	1.68
2:nd recidual			38.69	2.56	41.26	2.93	43.97	3.07
3:d sheetmaking					41.35	2.15	40.75	2.13