Fibre and fines quality development in pilot scale high and low consistency refining of ATMP

Dmitri Gorski, Kathrin Mörseburg, James Olson and Antti Luukkonen

KEYWORDS: Low-consistency refining, High-consistency refining, ATMP, Fibre characterization, Fibre development, Energy efficiency

SUMMARY: The objective of this study was to characterise and compare the development of fibre and fines properties in high consistency (HC) and low consistency (LC) refining of mechanical pulp. Primary refined pulp was produced using the Advanced Thermo-Mechanical Pulp (ATMP) refining process. Pulps were characterized to evaluate external and internal fibrillation, fibre shape and dimensions, surface area of fines and the proportion of split fibres.

Based on the results, a different mode of fibre development was proposed for LC and HC refining. The LC refining resulted in a greater reduction in the shives content and R30 Bauer-McNett fibre fraction. The reduced R30 fraction considerably increased the middle fibre fractions; however it showed no further development in terms of surface fibrillation. While HC refining resulted in a significant reduction in fibre wall thickness associated with fibre collapse and increase in external fibrillation, LC refining mainly generated structural changes, seen in fibre straightening and increased flexibility.

The HC and LC refined pulps had different property profiles compared at equal handsheet tensile index. The LC refined pulps contained less long fibres and fines but significantly more middle fraction particles. Extensive internal fibrillation of the straighter LC refined fibres appeared to have compensated for lower fines content and external fibrillation, producing well bonded sheets with good tensile strength.

ADDRESSES OF THE AUTHORS: Dmitri Gorski Norske Skog Saugbrugs, N-1756, Halden, Norway **Kathrin Mörseburg** (kathrin.morseburg@pfi.no), Paper and Fibre Research Institute (PFI), NO-7491, Trondheim, Norway, **James Olson** (james.olson@ubc.ca), University of British Columbia, Mechanical Engineering Dept., Pulp and Paper Centre, 2385 East Mall, Vancouver, British Columbia, V6T 1Z4, Canada, **Antti Luukkonen** (antti.luukkonen@andritz.com), Andritz Inc., 3200 Upper Valley Pike, Springfield, Ohio, 45504, USA.

Corresponding author: Dmitri Gorski Present address: (dmigor54@kth.se), REINERTSEN AS, Sandslimarka 35, 5254, Bergen, Norway

The Advanced Thermo-Mechanical Pulp (ATMP) refining process has been introduced as a means of reducing the refining energy demand while preserving and/or enhancing the quality of the final product (Sabourin et al., 2003; Hill et al., 2010; Johansson et al., 2011; Gorski et al., 2011a). The main innovation of the ATMP process is the separation of the defibration and fibre development phases into subsequent process stages with the addition of chemicals to the fibre development phase. A combination of aggressive primary ATMP refining with secondary low consistency stages was shown to lead to further energy reduction (Sabourin et al., 2011).

Low consistency refining of mechanical pulp has a long history where both reject and post refining have seen early commercial applications. Nowadays, LC refiners are installed in several mills to substitute a second or third mainline HC refining stage. Research into the mechanisms of LC refining has been intensified in recent years, often aiming at understanding the influence of the refining conditions such as intensity, refining consistency and other variables on energy efficiency and final product quality (Eriksen, Hammar, 2007; Hammar et al., 2009; Luukkonen et al. 2010; Sabourin et al., 2011; Andersson, 2011).

In terms of pulp quality in LC refining, the main focus has been on changes in pulp freeness, shive content, fibre length distribution and handsheet properties. Engstrand et al. (1988) demonstrated in a series of pilot scale trials that LC refining of HC defibrated mechanical pulp can be performed without excessive fibre shortening and potential of achieving target pulp quality with reduced specific energy. Several studies indicate that low refining intensity is a pre-condition for preserving fibre length and strength development in LC refining of mechanical pulps (Demler, 1996; Wild, 1998; Lundin et al., 2008; Hammar, et al. 2009); however high specific energy input even at low intensity can lead to severe loss of fibre length (Welch, 1999; Hammar et al., 2009). High pH and to some extent high temperature were reported to counteract fibre shortening, which was primarily attributed to thermal softening and ionization of acidic groups (Hammar et al., 2009).

Studies of fibre and fines quality development in LC refining are less common. It has been suggested that the development of fibre properties proceeds in a different manner in HC and LC refining even when compared at similar handsheet properties such as tensile index and light scattering (Reyier et al., 2011). It is well known that an improvement of fibre properties translates into improved paper properties. Mechanical pulp fibre characteristics such as degree of longitudinal splitting, fibre flexibility, fibre wall thickness, fibre bendability and collapsibility have been all shown to influence the quality of the final paper product (Skowronski, 1990; Corson, 1989; Forseth et al., 1997; Remé et al., 1998; Kure, 1999; Braaten, 2000; Corson et al., 2003; Ferluc et al., 2010).

Fibre straightening, external development, reduction of kinks and fibre flexibility were reported during LC refining, particularly with respect to the stiffer latewood fibres (Welch 1999). The author compared HC and LC refining of mechanical pulp on the pilot scale and concluded that the latter produces handsheets of a quality similar to that from HC refined mechanical pulp, at a reduced energy input. Welch also concluded that LC refining may have potential to replace part or all of the latency removal process. Reyier et al. (2011) reported that fibre cross-sectional dimensions remained constant or even increased for the investigated mill-scale LC refining conditions, suggesting absence of external fibre wall peeling. External fibrillation and fibre curl were either maintained or reduced. Increased tensile index was attributed to closer fibre contact due to removed external fibrils, higher amount of fibrillar fines and straighter and more swollen fibres. It was hypothized that LC refining loosened the internal fibre wall structure, enabling and enhancing fibre wall swelling (internal fibrillation). Andersson (2011) suggested from pilot- and mill-scale research that more bonding-active fines are possibly created upon LC refining of TMP and that removal of external fibrils from fibre surfaces and enhancement of internal fibrillation may take place in the LC refiner.

The objective of this pilot scale study was to characterise and compare the development of fibre and fines properties in second stage refining of primary refined Advanced Thermomechanical Pulp (ATMP), specifically between a two stage LC refining process and conventional high consistency (HC) refining stage. An improved understanding of fibre property development and the fundamental mechanisms governing this development upon LC refining may promote new opportunities for improvement and optimization of LC refining.

Materials and Methods

Pilot refining

Mixed softwood chips obtained from a Canadian TMP mill were used in this study. The raw material consisted of approximately 80% Lodgepole pine from interior British Columbia with the 20% balance consisting of Sitka spruce and Western Balsam fir, also from Interior B.C. The ATMP concept was utilized for primary refining. The concept is well described in the literature (Hill et al., 2010; Johansson et al., 2011; Gorski et al., 2011a; 2011b). High-consistency refining was conducted at the Andritz pilot plant in Springfield, OH, USA. Chips were pre-heated and defibrated using mechanical pre-treatment consisting of a MSD Impressafiner (40 kWh/odt energy input) and a Fiberizer (220 kWh/odt). The Fiberized material was primary stage refined at RTS™ conditions (Sabourin et al. 1997) with an energy input of 530 kWh/odt. Sodium bisulphite (3.1% on oven-dry fibre basis, which decreased the pH of the pulp from 5.5-6.0 to 4.7) was applied at the refiner inlet via the refiner dilution water. A portion of the primary stage pulp was further refined using an atmospheric high consistency double disc refiner at four different energy inputs (610-1000 kWh/odt). LC refining of the primary stage ATMP pulp was conducted in two optimized stages at the pilot plant located in the Pulp and Paper Centre, University of British Columbia, Vancouver, Canada. The pulp was disintegrated in 60ºC water for 4 hours prior to refining at low consistency (3.0-3.4%) using a 14” Aikawa low-consistency pilot refiner equipped with 0.41 m (16”) overhung segments and driven by a 110 kW variable frequency motor. Refining conditions were varied by closing the gap of the refiner while the throughput was kept constant. This provided specific energy inputs of 70-180 kWh/odt in the first LC stage and 70-240 kWh/odt in the second LC stage. AFT FineBar segments were installed in the refiner for this work (BEL 5.59 km, groove depth 4.8 mm, groove width 2.4 mm, bar width 1 mm, bar angle 15º). All pulps and handsheets underwent standard testing described elsewhere (Gorski et al. 2012).

Pulp, fibre and fines characterisation

Two LC refined and two HC refined pulps were selected for detailed fibre and fines characterization. The analysis was performed at the Paper and Fibre Research Institute located in Trondheim, Norway. The never-frozen pulps were stored in a cold environment before hot (for assessment of fibre shape also cold) disintegration (ISO 5269:2:2001). Fibres in different fractions were obtained by Bauer McNett fractionation (SCAN M6:69) and stored in wet state in a cold room until analysis. The P200 fraction was collected and allowed to sediment for approximately 48 hours, whereafter the clear supernatant was carefully removed by vacuum suction. The amount of large shives was measured using a Pulmac instrument equipped with a 0.1 mm screen.

The characterisation was performed according to similar procedures as described elsewhere (Gorski et al., 2011a; 2011b). Fibre length, width, coarseness and shape were measured using the FiberMaster instrument for whole pulps and/or suspensions prepared from fractionated fibres (Karlsson et al. 1999). The FiberMaster was also used to assess fibre flexibility. 10 parallel bendability measurements were carried out for each sample, and results (denoted “B3”) were reported for the defined optical length interval from 1.5 to 3.0 mm. The specific surface area (SSA) was assessed from settling tests of long fibre and combined middle fractions based on the principals described by Marton and Robie (1969) and Wakelin (2004). The means of specific surface index (S^3A), bendability and coarseness measurements are presented with their respective confidence interval at 95% level of confidence.

Fibre cross sectional characteristics were determined according to the method described by Reme et al. (2002). Reme et al. (1999) demonstrated that the asymmetric fibre wall thickness distribution could be divided and fitted well by two normal distributions for earlywood and latewood fibres. The authors used the mean of the fitted normal distribution for the whole population to describe alterations in fibre cross sectional characteristics upon refining quantitatively, but emphasized the importance of paying attention to the distribution of the individual fibre cross dimensions in addition to the average (Reme et al., 2002). In this study the distributions of the fibre cross sectional characteristics are interpreted based on box plots, scatter plot regression lines and means of the fitted normal distribution, given with their 95% confidence intervals.

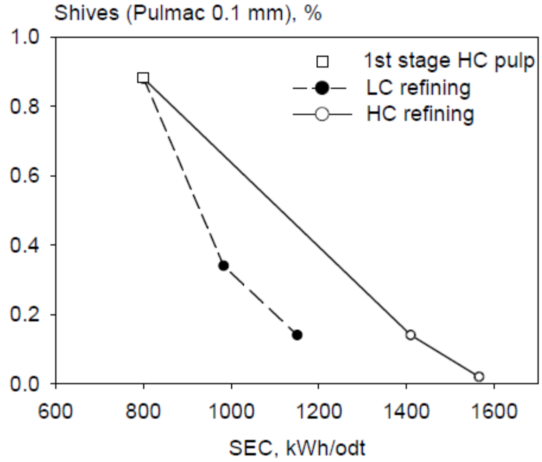

Fig 1. Reduction in Pulmac shives content during HC and LC refining of ATMP with increasing energy input.

Fines turbidity has been shown to reflect their specific surface (Wood, Karnis, 1996). In the current study the turbidity measurements of the P200 fractions were performed at 0.1%, 0.08% and 0.06% consistencies using a HACH 2100AN turbidity meter at 860 nm wave length. Three readings were recorded for each consistency level and the sample turbidity was obtained through interpolation.

In order to examine the development of ATMP fibres upon successive LC and HC refining, measured values of important pulp, fibre and fines properties were plotted versus the accumulated specific energy input (SEC). As the stage specific and total SEC were on different levels for LC and HC refining, the results in this study were rather presented and interpreted as trends than comparisons of absolute values inter/extrapolated to a given SEC. In order to understand the previously described favourable tensile strength development of LC refined mechanical pulp (Gorski et al., 2012), fractional composition and fibre properties of the HC and LC refined ATMP were also compared at equal handsheet tensile index of approximately 40 Nm/g.

Results and discussion

Shives content and fibre size distributions

High consistency ATMP refining is known to efficiently reduce the shive content in pulp, presumably due to the high-intensity primary stage refining conditions and possibly also the influence of added chemicals (Johansson et al. 2011, Gorski et al. 2011a). Both LC and HC treatments following primary stage ATMP refining further decreased the amount of shives in the pulp, *Fig 1*. The chosen LC refining concept performed more energy effectively in terms of shives removal compared to HC refining.

LC refining resulted in a greater reduction in the amount of the long fibre fraction compared to HC refining, *Fig 2*. Especially pronounced is the reduction of the BMN R16 fraction which is coarsest and considered to be harmful to for example surface quality of paper. The reduced long fibre fraction increased the amount of the middle fractions in the LC-refined pulp, which remained rather constant upon HC refining, *Fig 3*.

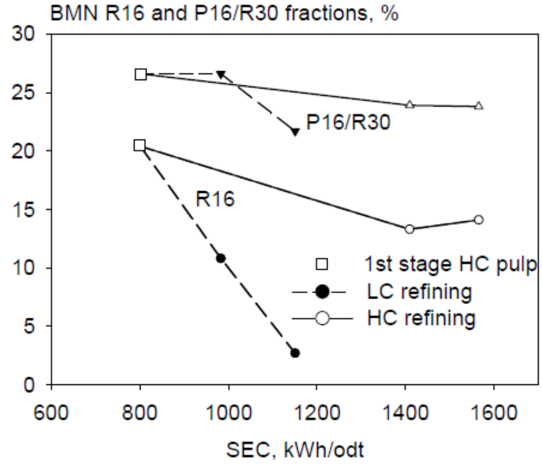

Fig 2. Amount of long fibre fractions (Bauer McNett R16 and P16/R30) in HC and LC refining of primary refined ATMP.

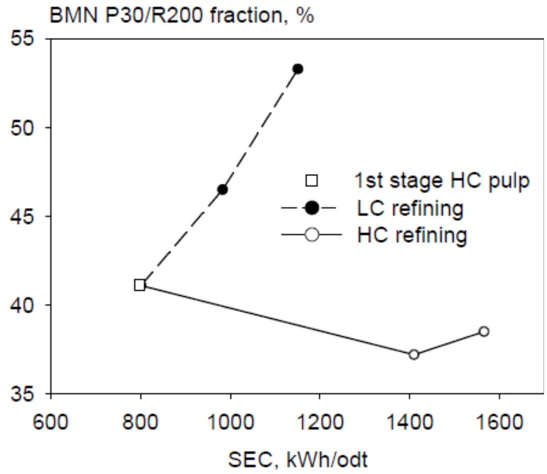

Fig 3. Amount of middle fraction (Bauer McNett P30/R200) in HC and LC refining of primary refined ATMP.

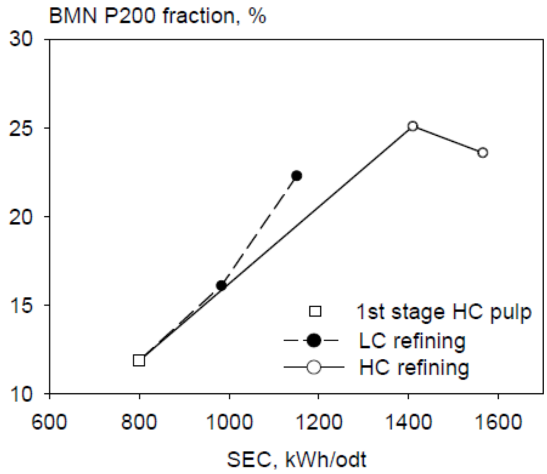

Fig 4. Development of the fines fraction (Bauer McNett P200) in HC and LC refining of primary refined ATMP.

The fines content developed similarly for HC and LC refining, *Fig 4*. The reduced long fibre fraction resulted in a decreased average fibre length with LC refining; however the fibre length distribution was more uniform. The reduction in long fibre content did not result in any significant formation of fines, perhaps due to enhanced softening of the fibres. The differences in fibre length distributions were hypothesized to arise from a different fibre development mode between HC and LC refining.

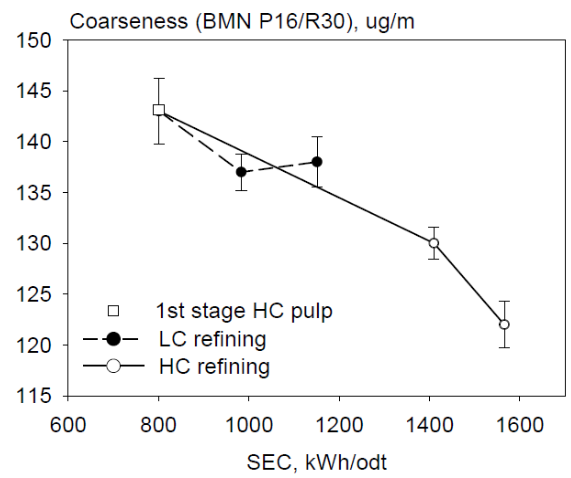

Fig 5. Development of fibre coarseness from HC and LC refining of primary refined ATMP.

Fibre and fines quality development

Both LC and HC refining resulted in a significant and consistent coarseness reduction and an increase in specific surface area of the long fibre fraction, *Figs 5* and *6*. The development of fibre coarseness and fibre specific surface area was proportional to the refining energy input, and progressed at a similar rate for LC and HC conditions. Wakelin (2004) reported that the sedimentation index was influenced by both the degree of external fibrillation and the apparent density of the fibres, but found it difficult to separate the relative influences of the degree of fibrillation and cross sectional dimensions (wall thickness and fibre diameter) on the sedimentation index. In this study, the relative coarseness decrease was much lower than the relative increase in S^3A index for both HC and LC refined ATMP fibres, and the changes in coarseness alone unlikely account for the significant increase in sedimentation specific surface area. These results thus indicate the generation of external fibrils upon both LC and HC refining of ATMP.

The bendability (B3) of the fibre fraction P16/R30 was increased significantly upon both HC and LC refining of ATMP fibres, *Fig 7*. Final bendability levels were significantly higher for the LC compared to the HC refined fibres. From a solid mechanics point of view the fibre stiffness should decrease with reduced cross sectional area and moment of inertia. The minor coarseness reduction upon LC refining (*Fig 5*) is unlikely to account for the observed increase in bendability. It is therefore suggested that the observed bendability increase was predominantly an effect of internal fibrillation and changes to the fibre wall modulus rather than alterations of the fibre cross sectional dimensions. It has been shown that the tensile-bulk relationships were similar for handsheets made of HC and LC refined pulps (Gorski et al. 2012), which suggests the same conclusion.

Changes in fibre shape (introduction of curl termed latency) are a well-known result of HC refining of mechanical pulp. Karnis (1996) described the mechanism of latency creation as a result of lignin and hemicellulose flow introduced by cyclic deformations and compressive

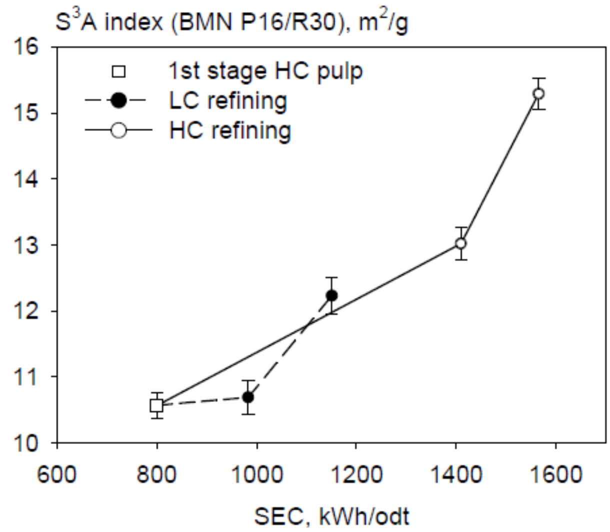

Fig 6. Development of fibre specific surface area (expressed as sedimentation S^3A index) during HC and LC refining of primary refined ATMP.

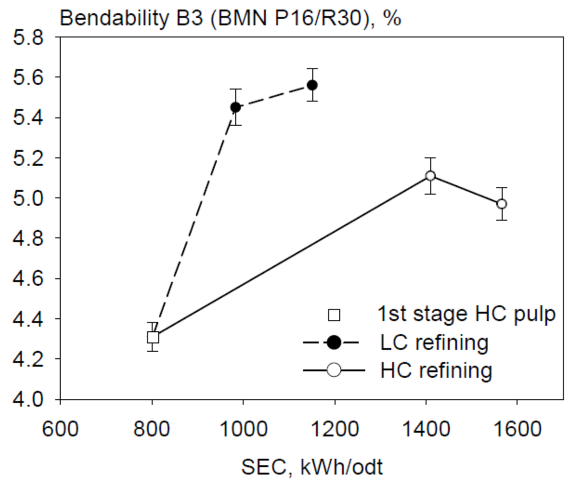

Fig 7. Development of fibre flexibility (expressed as hydrodynamic bendability) in HC and LC refining of ATMP.

tensile and shearing arising from forces on fibres generated by the refiner. In production scale latency is presumed to be removed by high shear agitation at temperatures above the lignin softening point and low consistency in the latency chest. Laboratory hot disintegration routinely performed before fibre quality analysis serves the same purpose and straightens the fibres, thereby possibly masking potential fibre shape alterations introduced upon different processing stages.

Seth (2006) pointed out that the deformations (primarily axial compressions in the fibre wall) could be reversed when fibres in aqueous medium are subjected to tensile forces such as those acting on fibres during LC refining.

Water would enter the pores in the fibre wall and soften it. Fibre straightening upon mechanical pulp LC refining was mentioned by Reyier et al. (2011) and Welch (1999). In this study LC refining and even HC refining of primary stage ATMP resulted in fibre straightening, *Fig 8*. The FiberMaster fibre form factor indicates the average straightness of a fibre population, with 100%

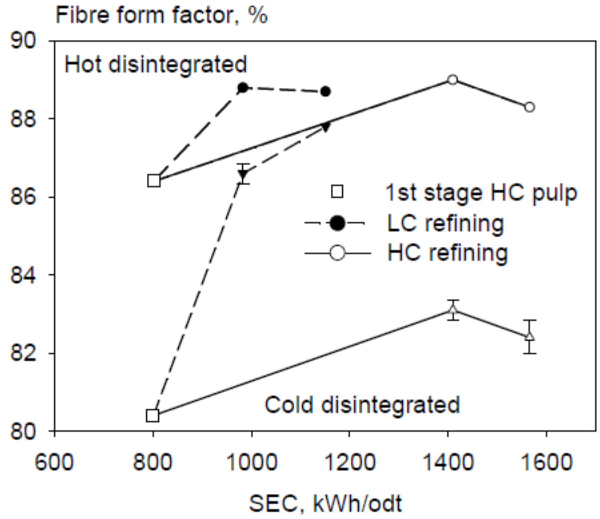

Fig 8. Development of fibre straightness (expressed as fibre form factor) from HC and LC refining of ATMP for hot and cold laboratory disintegrated pulps.

denoting perfectly straight fibres. Measurements of kink and curl using an FQA instrument confirmed this result.

The long fibres (BMN P14/R28) of the latency-removed third stage LC refined ATMP had less kink and curl compared to respective fibres after third stage HC refining. A comparison between laboratory hot- and cold-disintegrated pulps shown in *Fig 8* revealed that the actual straightening effect was greater for LC compared to HC refining, and progressed with greater energy efficiency. Fibre splitting was earlier described as a phenomenon largely linked to the first stage refining (Reme et al. 1999). The level of more than 30% split fibres in the primary refined ATMP used in this study can be considered relatively high, *Fig 9*. Pilot scale ATMP refining of White spruce with addition of hydrogen peroxide was earlier shown to result in approximately 10% split fibres after the primary stage, and there was also a consistent increase in fibre splitting upon the second and third stages of HC refining (Gorski et al., 2011a; 2011b). The fibre split index was approximately similar for all pulps investigated in this study, which indicates that no further fibre splitting was introduced upon neither LC nor HC refining beyond the primary stage. It is possible that the potential for axial splitting was already reached after first stage ATMP refining for the studied fibre population. It should be noted that the difference between the present study and previous findings in both raw material (mixed pine, spruce and fir species used in this study) and ATMP chemistry (addition of bisulphite instead of hydrogen peroxide which gave lower pH) are significant and therefore prevent a direct comparison.

A central question with respect to fibre development in TMP refining is associated with the mechanisms of fines generation and external/internal fibrillation. The mean fibre wall thickness and fibre coarseness have been shown to decrease upon HC refining (Karnis 1994; Kure 1999; Reme 2000). Mechanisms have been described by several researchers as progressive fibre wall peeling and exposure of the S2 layer resulting in generation of bond-

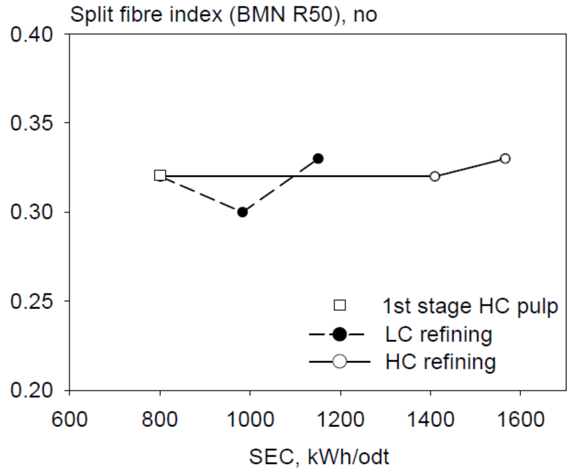

Fig 9. Development of fibre split index in HC and LC refining of ATMP.

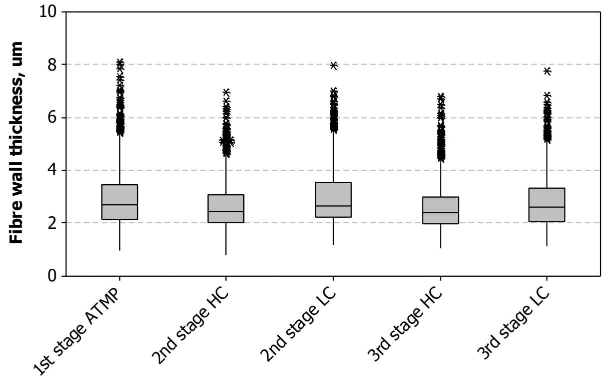

Fig 10. Wall thickness distributions of ATMP fibres before and after two-stage LC and HC Refining (BMN R50).

enhancing attached and detached fibrils (Corson, 1989; Karnis 1994; Johnsen et al., 1995). Fibre wall swelling and increase in thickness and fibre wall area due to loosening of the fibre wall structure was a mechanism earlier proposed for LC refining (Reyier et al., 2011). In this study, the fibre wall thickness distributions were found to be narrowed upon the second and third refining stages, but to a higher extent in the HC than the LC process, *Fig 10*. The right-hand tail was particularly affected, which implies the fibre wall thickness reduction occurred predominantly for the thickest walled fibres. This finding is in agreement with previous studies which demonstrated that fibre wall thickness reduction was greater for latewood than earlywood Norway spruce TMP fibres (Reme et al., 1999).

The mean fibre wall area and thickness were reduced significantly for the intact fibre population from 3.29 µm for the first stage ATMP to 2.89 µm after HC refining and 3.09 µm after LC refining, *Fig 11*. Split fibre mean wall thickness was significantly reduced upon HC refining (from 2.29 µm for the first stage ATMP to 2.07 µm for the third stage HC) but did not change significantly upon LC refining (2.27 µm). Since the proportion of split fibres remained relatively unchanged, this observation indicates that even the relatively thin-walled split ATMP fibres experienced a wall thickness reduction upon HC refining, which was not the case for LC refining.

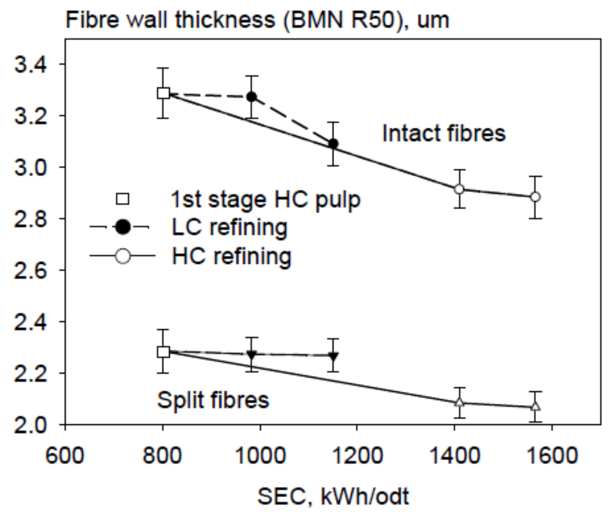

Fig 11. Development of mean fibre wall thickness for intact and split fibre populations in HC and LC refining of ATMP.

Johnsen et al. (1995), Reme (2000) and Reme et al. (2002) demonstrated that the standard deviation of the fibre wall thickness and the degree of particle removal from the fibre surface varied considerably along the length and around the circumference of individual fibres. The authors found that TMP refining reduced the standard deviation of the fibre wall thickness for both earlywood and latewood fibres, but concluded that wall thickness reduction in refining occurred more frequently on the thicker wall areas of the fibre. Johnsen et al. (1995) stated that refining does not remove the outer fibre wall layers one at a time for the whole population, and that the fractional coverage by middle lamella decreases steadily during refining. Based on these findings the individual fibre wall thickness variation was in this study interpreted as an indication of fibre surface heterogeneity.

The mean standard deviation of the wall thickness of the ATMP fibre decreased consistently during HC refining for both intact and split fibres, but only decreased for intact LC refined fibres, *Fig 12*. For the investigated pulps the local wall thickness variation was higher for thin-walled and lower for thick-walled second stage LC refined fibres, when compared to HC refined fibres of equal fibre wall thickness. This observation possibly suggests that LC refining either removed material (e.g. external fibrils) from thick-walled fibres or treated their fibre surfaces more homogeneously in terms of removal and/or exposure of different fibre wall layers than HC refining.

Mean lumen area and mean lumen perimeter of the intact fibre population were not significantly different between the LC or HC refined ATMP samples, and did not deviate significantly from those of the first stage ATMP, *Fig 13*.As the mean fibre wall area remained constant and the lumen area was somewhat reduced upon the first LC refining stage, potential swelling of the fibre wall introduced by LC refining conditions as proposed earlier (Reyier et al., 2011) may possibly have occurred in this study. It is noted that Reyier and co-workers conducted investigations on wet fibres and used a different technique to assess changes to the fibre cross-dimensions.

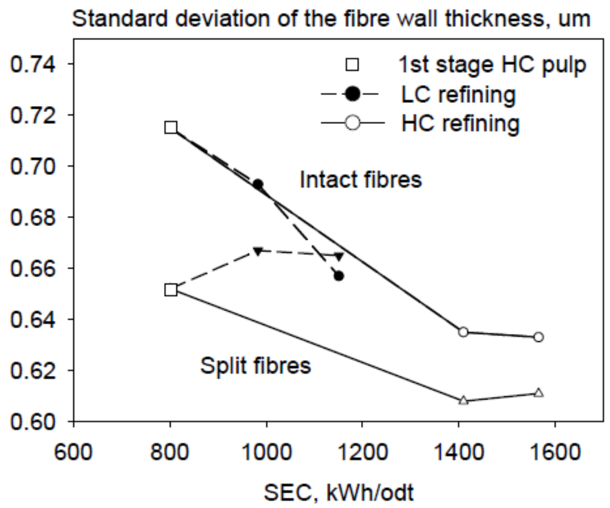

Fig 12. Development of fibre surface homogeneity (expressed as mean standard deviation of the fibre wall thickness) for intact and split fibres from HC and LC refining of ATMP.

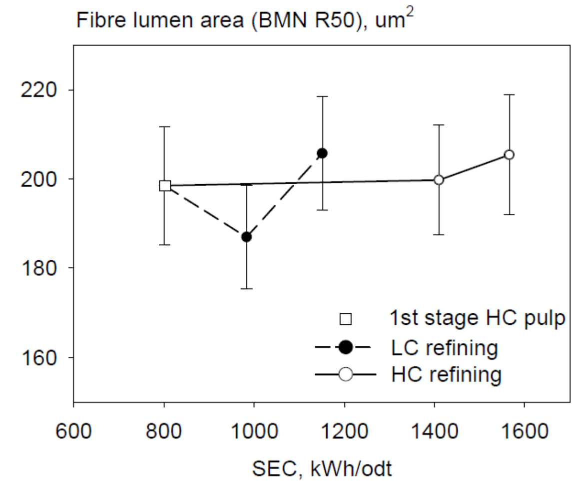

Fig 13. Development of intact fibre lumen area from HC and LC refining of ATMP.

Fibre and lumen form circles are characteristics of the fibre cross-sectional shape (Johnsen et al., 1995). Increasing values of fibre and lumen form circle indicate a more roundish cross-sectional shape with value of one denoting a circular cross-section. Consequently the lower the form circle, the flatter the fibre. In this study the mean lumen form circle showed an opposite development upon further LC and HC refining, *Fig 14*. LC refined ATMP fibres appeared to develop more roundish lumina and a lower collapse index expressed by higher mean lumen form circle values compared to HC refined fibres. The differences in mean lumen shape factors of the third stage HC and LC refined fibres were statistically significant.

It was shown that the stiff latewood fibres respond with minor dimensional and structural changes to multiple compressions and relaxations alike those in TMP refining, while earlywood fibres absorb a large part of the energy and respond with measurable permanent distortions (Salmén et al., 1997).

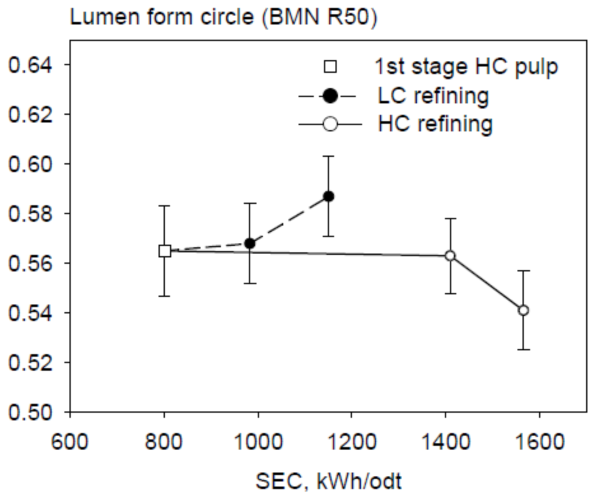

Fig 14. Development of lumen form circle in HC and LC refining of ATMP, intact fibre population BMN R50.

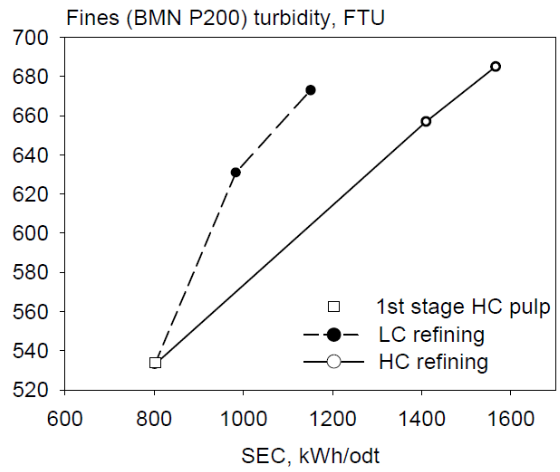

Fig 15. Turbidity of P200 fines formed from HC and LC refining compared at increasing tensile index of handsheets.

Based on distributions of individual fibre characteristics it was observed in this study that at a given fibre wall thickness or cross sectional compactness (z-value) LC refined ATMP fibres had the largest lumen form circle values among the studied pulps. The deviation from the primary stage ATMP was greatest for the third stage LC refined fibres of low fibre wall thickness and z-value. This observation implies that thin-walled earlywood fibres may have experienced a partial fibre de-collapse in LC refining.

It was earlier shown that LC refined fibres were clearly straighter before laboratory latency removal, more flexible and had fewer kinks compared to HC refined fibres. Karnis (1993) documented for various TMP that latency removal resulted in an increase in fibre length by removal of micro-compressions, and an increase in hydrodynamic specific surface area. Johnsen et al. (1995) concluded that latency treatment "…appears to cause fibres to expand from a somewhat collapsed shape established during refining…". These authors also found the effect of latency treatment was most pronounced for thin-walled fibres. Seth (2006) wrote that kraft fibres undergo axial compression in various processing steps, and divided between small scale deformations (dislocations and micro compressions) and large scale deformations (kinks and curl) introduced upon medium and high consistency treatment. It is possible that the observed increase in fibre and lumen form circle upon LC refining of ATMP and partly the increase in specific surface area are a result of similar mechanisms, i.e. due to release of compressive stresses in the fibre wall, introduced upon the first HC refining stage.

Middle fraction and fines properties

Mean length, width and coarseness of the middle fraction (P30/R200) fibres were all reduced upon both HC and LC refining, *Table 1*. LC refined middle fraction fibres were longer and coarser than HC middle fraction constituents. The bendability of the middle fraction fibres was increased upon further refining in both HC and LC concepts, although the development of flexibility seemed to be more energy efficient with LC refining (same trends as for the long fibres).

Table 1. Properties of the combined middle fraction (P30/R200) from the first stage pulp and HC/LC refined pulps.

Property	Unit	1st stage HC ATMP	2nd stage HC ATMP	2nd stage LC ATMP
SEC	kWh/odt	801	1566	1151
Av. length	mm	0.66	0.57	0.60
Av. width	µm	31.9	27.9	30.4
Coarseness	ug/m	119	114	113
S^3A index	m2/g	11	35	10
Bendability	%	0.7	1.2	1.1

While the specific surface area index of the middle fraction was increased markedly during the HC refining stage, no significant change was observed with LC refining of ATMP, which indicates a mechanistic difference between HC and LC refining. Since LC refined pulp was found to contain significantly more of the middle fibre fraction compared to the HC refined pulp, it seems that the conditions in LC refining (both the liquid environment and possibly the type and magnitude of forces acting on fibres) resulted in shortening of the long fibres before they experienced surface development. Possible mechanism could be that fibres rather tear apart upon the shearing action between the refiner bars than develop external fibrillation. This would explain the presence of the larger amount of shorter and less developed fibres in LC refined pulp. The difference in surface fibrillation of the middle fraction could also be due to the earlier proposed potential removal of fibrils from the fibre surfaces in LC refining

The fines turbidity (P200) in suspension increased for both HC and LC refining, but more energy efficiently for LC refining, *Fig 15*. An increase in the specific surface area of the fines could be a result of either an increase in the proportion of fibrillar fines and/or a decrease in the size of the fibrillar and flake-like fines, as Reyier et al. (2011) and Andersson (2011) have suggested that LC refining may result in detachment of previously generated fibrils from the fibre surfaces. A quantitative morphological study of the fines formed in LC and HC refining was not included in this study but would help in determining the phenomena involved. The rapid increase in the specific surface area of LC-fines may thus partly be a result of fibrils generated upon first stage refining becoming detached from fibre surfaces in subsequent LC refining. This explanation would be further supported by earlier discussed findings of smoother fibre surfaces of LC refined thick walled fibres. The implications of possible detachment of external fibrils in LC refining for the paper production process requires further study. Retention of the detached fibrils in the paper web during forming should be considered among other things.

Paper quality through fibre properties

Development of pulp and paper properties was published in an earlier paper (Gorski et al. 2012). Handsheets with a tensile index of 40 Nm/g and a light scattering of 59 m^2/kg were produced with HC and LC refining of primary refined ATMP. The HC refining required approximately 1450 kWh/ton, whereas approximately 300 kWh/odt less were required in LC refining. Apparent density of the handsheets developed similarly for both HC and LC refining compared at equal tensile index. The tear index, length weighted average fibre length, and TEA were lower for the LC refined pulp.

The fibre and fines quality profiles differed between handsheets made from HC and LC refined pulp, *Table 2*. Compared at equal tensile index, the shive content was below 0.1% for both concepts and can be considered insignificant. At a given tensile index of 40 Nm/g the LC refined ATMP contained less long fibres and markedly higher proportions of the middle fraction than HC refined ATMP. LC refined fibres were straighter and had thicker fibre walls, but they were also significantly more bendable, while the middle fraction particles were relatively coarse with poorly developed surfaces. HC refined fibres had lower coarseness and fibre wall thickness, and were more collapsed and better externally fibrillated, especially in the middle fibre fraction. LC refined ATMP contained 20% less fines compared to the HC refined reference, but the differences in fines quality were marginal. These results suggest that extensive internal fibrillation of the LC refined fibres compensated for lower fines content and external fibrillation, producing well-bonded sheets with good tensile strength. The high mass fraction of poorly fibrillated middle fraction fibres in LC refined ATMP may have contributed to a sheet structure with a sufficient number of pore sizes and shapes to facilitate equally good light scattering as the more fines-rich HC refined reference pulp.

Gorski et al. (2012) suggested that the energy efficiency in the development of pulp quality in LC refining could be caused by a more uniform fibre size distribution of the resulting pulp compared to HC refining, and that the difference in fractional composition might be the key to the differences in TEA. It was hypothized that shorter fibres would form a stronger, but not as stretchable network. Results of this fibre characterization study underline the importance of flexibility and fibre shape.

The contribution of flexible fibres to an increased relative bonded area and thereby tensile strength is well recognized. The effects of fibre shape and deformations have the subject of extensive studies in the case of chemical pulps.

Table 2. Mean fibre and fines properties interpolated at equal handsheet tensile index (40 Nm/g).

Property	Unit	HC ATMP	LC ATMP
Pulmac shives content	%	0.1	0.2
BMN R16 fraction	%	14	3
BMN P16/R30 fraction	%	24	22
BMN P30/R200 fraction	%	38	53
BMN P200 fraction	%	24	22
S³A index (P16/R30)	m^2/g	8.5	7.7
S³A index (P30/R200)	m^2/g	23	10
Bendability (P16/R30)	%	5.1	5.6
Bendability(P30/R200)	%	1.1	1.1
Mean curl index (P16/R30)	%	0.08	0.10
Coarseness (P16/R30)	ug/m	127	138
Wall thickness (R50)	µm	2.9	3.2
Split fibres (R50)	%	30	30
Fines turbidity (P200)	FTU	660	680

Seth (2006) stated that the stress is uniformly distributed in a network of straight and deformation-free fibres when subjected to in-plane loading, while deformed fibre segments would not fully participate in load-sharing. Deformations create uneven stress distribution and result in a drop of tensile strength and elastic modulus, but would increase the fibre’s stretch potential and the sheet elongation. Karnis (1993) argued that the elastic modulus of paper increased from an increase in effective fibre length upon latency removal and fibre straightening. Strength properties dependent on elastic modulus and fibre flexibility would thus also increase. Page et al. (1979, 1980 and 1991) suggested that the elastic modulus of paper is affected by the elastic modulus of the fibres, bonding degree and the presence of curl, kinks and microcompressions. The presence of curl would decrease the length of fibre segments through which stresses can be transmitted, resulting in a weaker paper structure.

In this study the LC refined ATMP fibres were shown to be straighter and have fewer kinks and less curl compared to the HC refined fibres, even after hot disintegration. Straighter fibres in LC refined mechanical pulp likely have made a major contribution to the documented energy effective development of paper tensile strength, but simultaneously lowered the TEA index compared to the HC refined ATMP.

Hypothesis on the difference in HC and LC refining mechanisms

A possible reason for the observed differences in fibre development between HC and LC refining could be that the aqueous environment in LC refining promotes internal fibrillation more efficiently and external fibrillation less efficiently compared to HC refining. Mechanical treatment of fibres in liquid environment might be more energy efficient due to their higher degree of softening, and greater refining uniformity due to the lower consistency. The increase in moisture content in wood is known to correlate with the increase in thermal softening, though mainly in the lignin-rich middle lamellae (Salmén, 1987; Salmén, Hagen, 2002). Fibre internal delamination could be hypothized to develop easier upon mechanical impacts delivered in a refiner if the fibre is in a softer state. However, the temperature in HC refining (160ºC) was much higher compared to LC refining (60ºC) which also influenced the degree of softening. The combined effects of temperature and moisture on the softening of individual fibres inside a refiner and the relative importance of these factors are difficult to assess with little published data. Another explanation might originate from the differences in the refining action between LC and HC refiners. It has been proposed that forces exerted on fibres during refining are the key to understanding the refining mechanisms. This has been indirectly confirmed in studies where refiner gap was found to be of high importance to predict the development of pulp properties in a refiner (Mohlin, 2006; Luukkonen, 2011). A study where such variables as forces on fibres in LC and HC refining and average numbers of impacts are calculated for similar raw material, energy inputs and intensity might give new insights in understanding the mechanistic difference in HC and LC refining. Such calculations can be performed using existing approaches (Olender et al., 2007; Kerekes, 2011) which previously indicated that forces acting on fibres during HC refining are larger in magnitude compared to LC refining. This suggests that the difference in the two refining mechanisms originates in the difference in fibre material properties between HC and LC refining, specifically softening of the fibres in the gap.

Conclusions

- Two-stage LC refining of primary ATMP pulp appeared more energy efficient to a given fibre quality development as compared to secondary HC refining. This applied to the reduction of shives and coarse fibres, enhancement of fibre flexibility and the development of specific surface area of long fibres and fines.
- While HC refining reduced the fibre wall thickness and increased external fibrillation of long and middle fibre fractions in an expected manner, LC refining appeared to predominantly affect the structural fibre properties. LC refined fibres were effectively straightened and developed higher flexibility; previously introduced fibre collapse of intact earlywood fibres appeared partially reversed during LC refining. The observed changes to the fibre shape in the LC refiner are suggested to arise from the release of compressive stresses introduced during the primary stage HC refining.
- Quantitative fibre development appeared to deviate between the first and second LC refining stages for many of the assessed fibre characteristics, despite refining at a comparable SEC. Process variables were not investigated in this study. Differences in the inlet pulp properties for each LC refining stage had an impact on the refining effect which warrants further investigation.
- Despite inherent differences in the proportions and properties of specific fibrous constituents, the HC and LC refined pulps formed fibre networks with several similar properties critical for papermaking (tensile index, light scattering etc.). In the case of HC refining, the paper properties were achieved by a larger amount of collapsed longer fibres with a well-developed surface. In the case of LC refining, the fibres were shorter, straighter and more flexible with less developed surfaces.

Acknowledgements

The authors would like to express their gratitude to the staff of UBC Pulp and Paper Centre (especially George Soong and Christine Saville) and the staff of the Andritz pilot plant in Springfield. Berit Leinsvang is especially acknowledged for her thorough fibre characterisation work at the laboratories of PFI. Dr Jens Heymer (AFT) is acknowledged for his advice and support during the LC pilot trials. Norske Skog, Andritz and The Research Council of Norway are acknowledged for financial contribution. Dmitri Gorski would also like to acknowledge the financial support of Gålöstiftelsen, Hans Werthén Fonden and Jansons Legat who all contributed to his post-doc at the University of British Columbia. Dr Marc Sabourin (Andritz Inc.), Dr Lars Johansson (PFI AS) and Jan Hill (QualTech AB) are acknowledged for valuable comments on the manuscript.

Literature

Andersson S. (2011): Low consistency refining of mechanical pulp – process conditions and energy efficiency, Licentiate thesis, Mid Sweden University, ISSN 1652-8948

Braaten K.R. (2000): Fibre and fibril properties versus light scattering and surface smoothness for mechanical pulps, Pulp Paper Can., 101(5), p. 122

Corson S.R. (1989): Aspects of mechanical pulp fibre separation and development in a disc refiner, Paperi ja Puu, 71(8), p. 801

Corson S.R., Flowers A.G., Morgan D.G., Richardson J.D. (2003): Manipulation of paper structure and printability by control of the fibrous elements, Int. Mech. Pulp. Conf., Quebec, Canada, PAPTAC, p. 33

Demler, C. L. (1996): Low consistency refining of secondary fiber: papermill case studies, 1996 Recycling symposium, New Orleans, LA, USA, 3-6 Mar. 1996, pp 381-385

Engstrand, P.O., Hammar, L.-Å., Htun, M.T., Petterson, R.L. and Svensson, B.N. (1988): Framställning av mekanisk og kemimekanisk massa i två steg, Svensk patent 8801731-4, 461 103 (In Swedish)

Eriksen O., Hammar L.-Å. (2007): Refining mechanisms and development of TMP properties in a low-consistency refiner, Int. Mech. Pulp. Conf., Tappi, Minneapolis, Minnesota, USA

Ferluc A., Lanouette R., Bousquet J.-P., Bussiere S. (2010): Optimum refining of TMP pulp by fractionation after the first refining stage, Appita J., 63(4), p. 308

Forseth T., Wiik K., Helle T. (1997): Surface roughening mechanisms for printing paper containing mechanical pulp, Nordic Pulp Paper J., 12(1), p. 67

Gorski D., Mörseburg K., Axelsson P., Engstrand P. (2011a): Peroxide-based ATMP refining of spruce: influence of chemical conditions on energy efficiency, fibre properties and pulp quality, Nord. Pulp Pap. Res. J., 26(1), p. 47

Gorski D., Mörseburg K., Johansson L. (2011b): Role of equipment configuration and process chemicals in peroxide-based ATMP refining of spruce, Nord. Pulp Pap. Res. J., 26(2)

Gorski D. (2011): ATMP process: improved energy efficiency in TMP refining utilizing selective wood disintegration and targeted addition of chemicals, PhD thesis, Sundsvall, Sweden

Gorski D., Olson J., Luukkonen A., Sabourin M. (2012): Two-stage low-consistency refining of mechanical pulp, Appita J., 65(3), p. 1-6

Hammar L.-Å., Salmén L., Sandberg C., Sundström L. (2009): The effect of process conditions on pulp quality development in low consistency refining of mechanical pulp – TMP, Int. Mech. Pulp. Conf., SPCI, Sundsvall, Sweden, pp. 182-185

Hill J., Sabourin M., Aichinger J., Johansson L., Gorski D., Axelsson P. (2010): Combining selective bleaching chemistries and ATMP technology for low energy mechanical pulping at higher brightness, 7th Int. Sem. Fund. Mech. Pulp., Nanjing, China, p. 164

Johansson L., Hill J., Gorski D., Axelsson P. (2011): Improvement of energy efficiency in TMP process by selective wood disintegration and targeted application of chemicals, Nord. Pulp Pap. Res. J., 26(1), p. 31

Johnsen, P.O., Skinnarland, I., Helle, T., Houen, P.J. (1995): Distribution of lignin and other materials on particle surfaces in mechanical pulps, 1995 International Mechanical Pulping Conference, pp. 95-107

Karlsson H., Fransson P.-I., Mohlin U.-B. (1999): STFI FiberMaster, 6th Int. Conf. New Av. Tech., Stockholm, Sweden, p. 367

Karnis A. (1993): Latency in mechanical pulp fibres, Paperi ja Puu 75(7), pp. 505-511

Karnis A. (1994): The mechanism of fibre development in mechanical pulping, JPPS 20(10), pp. J280-J288

Kure K.-A. (1999): On the relationship between process input variables and fibre characteristics in thermomechanical pulping, PhD thesis, NTNU, Trondheim, Norway

Kure K.-A. and Mosbye K. (2009): Optimisation of TMP fibre properties for SC rotogravure – full scale experiences from Norske Skog Saugbrugs, Int. Mech. Pulp. Conf., SPCI, Sundsvall, Sweden, pp. 11-16

Lundin T., Batchelor W., Fardim P. (2008): Fibre trapping in low consistency refining: new parameters to describe the refining process, Tappi J., 7(7), pp. 14-19

Luukkonen A., Olson J., Martinez D. M. (2010): Low consistency refining of mechanical pulp: a methodology to relate operating conditions to paper properties, J. Pulp Pap. Sci., 36(3-4)

Luukkonen A. (2011): Development of a methodology to optimize low consistency refining of mechanical pulp, PhD thesis, The University of British Columbia, Vancouver, Canada

Marton, R. Robie, J.D. (1969): Characterization of mechanical pulps by a settling technique, TAPPI 52(1969):12, 2400-2406

Mohlin U.-B. (2006): Refining intensity and gap clearance, 9th Pira Int. Conf., Vienna, Austria

Olender D., Wild P., Byrnes P., Ouellet D., Sabourin M. (2007): Forces on bars in high-consistency mill-scale refiners: trends in primary and reject stage refiners, J. Pulp Pap. Sci., 33(3), pp. 163-171

Page D.H., Seth, R.S., De Grace, J.H. (1979): The elastic modulus of paper. I. The controlling mechanisms, TAPPI 62(1979):9, 99-102

Page D.H., Seth, R.S. (1980): The elastic modulus of paper. II. The importance of fibre modulus, bonding and fiber length, TAPPI 63(1980):6, pp. 113-116

Page D.H., Seth, R.S. (1980): The elastic modulus of paper. III. The effect of dislocations, microcompressions, curl, crimps and kinks. TAPPI 63(1980):10, pp. 99-102

Page D. H. (1991): The structure and properties of paper, Wet End Operations Short Course held 5-10 May 1991, Orlando, FL, USA, pp 9-14

Reme P.A., Helle T., Johnsen P.O. (1998): Fibre characteristics of some mechanical pulp grades, Nordic Pulp Paper J., 13(4), p. 263

Reme P.A., Johnsen P.O., Helle T. (1999): Changes induced in early- and latewood fibres by mechanical pulp refining, Nordic Pulp and Paper Research Journal, 14(3):260-266

Reme P.A. (2000): Some effects of wood characteristics and the pulping process on mechanical pulp fibres, PhD thesis, Norwegian University of Science and Technology, 2000, 172pp

Reme P.A. and Helle T. (2000): Quantitative assessment of mechanical fibre dimensions during defibration and fibre development, 86th Annual meeting, Montreal, Quebec, Canada, 1-3 Feb. 2000, Preprints C, pp. C217-C223

Reme P.A., Johnsen P.O., Helle T. (2002): Assessment of fibre transverse dimensions using SEM and image analysis, J. Pulp Pap. Sci., 28(4), p. 122

Reyier S., Ferritsius O. and Ferritsius R. (2011): The development of fibre characteristic distributions in mechanical pulp refining, Int. Mech. Pulp. Conf., Xi`an, China, pp. 40-43

Sabourin, M., Aichinger, J., Wiseman, N. (2003): Effect of increasing wood chip defibration on thermomechanical and chemi-thermomechanical refining efficiency, Int. Mech. Pulp. Conf., Quebec City, Canada, pp. 163-170

Sabourin M., Xu E., Cort B., Boileau I. Waller A. (1997): Optimizing residence time, temperature and speed to improve TMP pulp properties and reduce energy, Pulp Pap. Can., 98(4), T111

Sabourin M., Antensteiner P. and Luukkonen A. (2011): Aggressive low consistency refining in thermomechanical pulping: energy consumption and fibre development, Int. Mech. Pulp. Conf., China Light Industry Press, Xi`an, China, pp. 248-252

Salmén L. (1987): The effect of the frequency of a mechanical deformation on the fatigue of wood, J. Pulp Pap. Sci., 13(1), J23-28

Salmén L. and Hagen R. (2002): Viscoelastic properties, Handbook of Physical Testing of Paper, Vol. 1, R.E. Mark, C.C.J. Habeger, J. Borch, M.B. Lyne and K. Murakami (eds.), Marcel Dekker Inc., New York, USA, p. 77-113

Salmén L., Dumail J.-F., Uhmeier A. (1997): Compression behaviour of wood in relation to mechanical pulping, Int. Mech. Pulp. Conf., pp. 207-211

Seth, R.S. (2006): The importance of fibre straightness for pulp strength. Pulp and Paper Canada 107(1), p. 34-42

Skowronski J. (1990): Surface roughening of pre-calendered basesheets during coating, J. Pulp Paper Sci., 16(3), p. 102

Wakelin, R.F. (2004): Evaluation of pulp quality through sedimentation measurements, 58th Appita conf., Canberra, ACT, Australia, p. 9

Welch, L.V.S. (1999): Low consistency refining of mechanical pulps, PhD thesis, University of British Columbia, Vancouver, Canada

Wild, M. L. (1998): Development of strength of mechanical and deinked pulps with low specific edge load, Wochenbl. Papierfabr., 126(23-24), pp 1218-1222

Wood J., Karnis A. (1996): Determination of specific surface area of mechanical pulp fines from turbidity measurements, Paperi ja Puu, 78(4), pp. 181-186

Manuscript received June 7, 2012

Accepted November 5, 2012