Original article

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Fibre development in an intensified mechanical pulping process

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Abstract: Mechanical pulp for printing paper can be produced with a process that involve much less equipment and that require much lower specific energy compared to conventional processes. Even though common evaluation methods, e.g. handsheet testing, have shown that the pulp quality is similar for the simplified and the conventional processes, it is not known how fibre properties, at the microscopic level, is developed with the simplified process. In this mill scale study, the fibre properties attained with an “intensified” mechanical pulping process, consisting of single stage high consistency double disc refining followed by two stage low consistency refining and no reject treatment was investigated. The simplified process was compared to a process with a reject system. The simplified process rendered fibres with higher degree of fibrillation, higher share of axial splits, lower fibre wall thickness but slightly lower length than the conventional process. The fibrillar fines size distribution of the two processes was different. The conventional process generated more of small fibrillar fines which probably explains the higher tensile index at given density for that process. The results show that it is possible to simplify the production process for mechanical pulp and reduce the specific energy with over 700 kWh/adt.

Keywords: double disc refining; energy efficiency; fibre properties; low consistency refining; mechanical pulp; process intensification.

1 Introduction

In this work, a process concept with extreme refining conditions for production of newsprint grade pulp was compared in mill scale to a more conventional process. In

one of the studies of wood defibration by Koran (1967) he wrote: *“In commercial pulping, the optimum temperature is that which provides pulp with a minimum amount of fibre breakage; with fibres possessing high bonding qualities in paper; with no change to their colour due to thermal degradation and at a minimum mechanical energy consumption.”*

Of course, Zoltan did not cover all aspects of mechanical pulping that is important for the performance of the final product. However, the point highlighted by him regarding the pulping (refining) temperature is still relevant and a good starting point of the introduction.

1.1 “Minimum amount of fibre breakage”

The comparably low temperature at fibre separation in the production of stone groundwood and non-pressurised refining (RMP) render pulps with low long fibre content and relatively low strength properties. As refining temperature was increased by the introduction of thermo-mechanical pulping (TMP), a higher share of unbroken fibres, a decreased shives content and higher strength properties were attained (Asplund and Bystedt 1973; Breck et al. 1975; Butcher 1975). Further increased preheating and refining temperature (160–180 °C) leads to almost intact fibres but with the surface covered by middle lamellae which results in poor bonding and optical properties (Atack 1972). There is obviously an optimum temperature for the refining, which depend on the refiner configuration.

One strategy to maintain the low specific energy achieved by increased refining temperature but avoid the lignin covered surfaces has been to simultaneously increase the refining intensity, usually by increasing the refiner rotational speed (Nurminen 1999; Sabourin et al. 1997). The basic thought has been based on the fact that wood to some extent behaves like a viscoelastic material, i.e. the mechanical properties depend on the combination of temperature and strain rate (McCrum et al. 1967). Based on this idea, Sabourin et al. (1997) developed the RTS process in which the wood chips are exposed to high temperature (T) during a short retention time (R) and then refined at elevated refiner disc speed (S). Trials performed

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by Vuorio and Bergquist (2001) also indicated that a reduction of tear index at given freeness attained with feeding segments could be avoided by increased refining temperature (increased housing pressure).

It has been shown that certain type of fibre breakage, along the fibre axis (also called fibre splitting), is beneficial for the surface smoothness of printing paper (Fjerdingen et al. 1997; Nesbakk et al. 2001; Reme et al. 1999). In high consistency (HC) refining of spruce, fibre splitting predominantly occurs on earlywood fibres whereas latewood fibres are peeled (Reme et al. 1999). High intensity refining produces a higher share of split fibres (Kibblewhite et al. 1995; Kure and Dahlqvist 1998; Pöhler and Heikkurinen 2003). The fibre breakage that Koran (1967) refers to is across the fibre which reduces fibre length. In TMP production, the fibre length is usually reduced to some extent depending on the defibration conditions (Heikkurinen et al. 1999). McDonald et al. (2004) claimed that high fibre length and thereby high specific energy is necessary for a good printing paper. However, earlier work has shown that it is not a prerequisite to strive for as high fibre length as possible to produce a high-quality printing paper (Engstrand et al. 1987; Sandberg et al. 2011). The reason why fibre length seems to be of less importance for the performance of pulp from double disc (DD) refiners, especially modern types, is not fully understood but might be an effect of the higher fibre wall development, e.g. the higher degree of fibrillation of DD fibres (Kibblewhite et al. 1995; Reyier Österling et al. 2012). Also, Anderson et al. 2012 showed that the fibre fraction tensile index is around 15% higher for pulp from DD refining compared to SD refining at given whole pulp tensile index.

1.2 “High bonding qualities”

Bonding, in relation to paper structure, is a broad term that is affected both by how large share of the available surfaces that are in close contact (relative bonded area) and the strength of the bond in this contact area (specific bond strength). Generally, the relative bonded area is connected to sheet densification and the specific bond strength to surface properties of the material. Bonding has mainly been associated with strength properties in the out of plane direction, e.g. z-strength, but will naturally affect other mechanical properties such as burst- and tensile strength also. In the end, a paper must have enough strength to withstand the mechanical load in the production and conversion processes as well as in the final application.

The strength properties of a paper sheet made of mechanical pulp are affected by many particle properties such

as size distribution of all particles in the pulp (fibres, fines and shives), fibre wall thickness distribution, fibre wall delamination (internal fibrillation, pore size distribution, splits) as well as surface properties (Corson 1980; Fernando et al. 2011; Kure et al. 2000; Lindholm 1983; Reyier Österling et al. 2012; Rundlöf et al. 1995, 2000). However, the most important factors affecting strength properties seem to be the long fibre conformability and external fibrillation as well as the amount and character of fines (e.g. Corson 1980; Heikkurinen and Hattula 1993; Lindholm 1983; Mohlin 1980; Reyier Österling et al. 2012). The quality of the fibre fraction has been assessed by measuring density or tensile index of the fibre fraction (Corson 1980; Mohlin 1977, 1980). Also, z-strength has been suggested as a good indication of the bonding in a paper based on mechanical pulp (Anderson and Mohlin 1980). In the present work, bonding was assessed mainly by measurement of tensile strength and z-strength.

During the separation and continued mechanical treatment of the fibres, smaller particles are separated from the wood (ray cells) and are also created both from the middle lamellae and by successive peeling of fibre walls. During the initial phase of refining, the created fines originate mainly from the middle-lamellae and primary wall and are more flakes like whereas in latter refining stages, the fines originate from the S_1 and S_2 layers and are more thread like (fibrillar). The bonding ability of released fines (indicated by tensile strength increase when added to a fibre fraction) increases upon successively increased refining energy (Corson 1989; Heikkurinen and Hattula 1993). The character of the fines is also affected by the refining intensity. High intensity primary stage refining seems to produce larger fibrillar fines that contribute less to bonding (Kibblewhite et al. 1995; Mörseburg et al. 2014; Pöhler and Heikkurinen 2003). However, after successive refining stages, the difference diminished (Pöhler and Heikkurinen 2003). The effect of a certain amount of fines in a paper depends on the relative content of flake-like and fibrillar particles and the size distribution of all particles (Brecht and Klem 1953; Luukko and Paulapuro 1999). The smallest fine gives the highest contribution to tensile index (Luukko and Paulapuro 1999; Rundlöf et al. 2000). In mill processes, the quality (optical and strength properties) of fines is also affected by extractives on surfaces (Rundlöf et al. 1995, 2000; Sundberg et al. 2000).

It was early realized that after two stage HC refining there were still fibres with poor bonding properties in the pulp (Jackson and Williams 1979; Kilpper and Baumgartner 1977). This fact led to the development of more or less advanced process concepts for separation and refining of the long fibres (e.g., Engstrand et al. 1987; Nurminen and

Liukkonen 2001; Shagaev and Bergström 2005). However, Corson (1989) pointed out that it is not only poorly developed long fibres that can have a negative effect on paper quality, also poor bonding shorter fractions can be negative. With the same intention, Moqvist et al. (2005) suggested that it is better to refine the whole pulp in the main line in three stages and only have a minimum of reject treatment in order to attain a high quality of all pulp fractions. Studies of the strength properties of fines have indicated that even the released fines develop upon successive refining (Compare strength measurements in e.g. Luukko and Paulapuro [1999]; Rundlöf [2002] and Westermarck and Capretti [1988]).

1.3 “No change to their colour due to thermal degradation”

The colour (i.e. the light absorption in the visible part of the spectrum) of wood is affected by temperature. High temperature, especially in the presence of oxygen and/or transition metals, creates coloured groups (chromophores) in lignin (Gellerstedt 2009). Therefore, for paper products where the brightness is crucial, there is a balance between wood softening and brightness loss in the pulping process.

In addition to the light absorption, the optical properties of paper are also affected by the light scattering ability and, to lesser extent, other factors such as surface structure. The optical properties of paper are commonly evaluated as reflectance factors over the visible spectrum and then expressed as single values such as brightness, luminance, whiteness etc. according to standard methods. These values of reflectance factors are dependent on both scattering and absorption of light by the sample, which can be evaluated as a light scattering coefficient s , and a light absorption coefficient, k calculated using the Kubelka Munk model.

The light scattering coefficient is related to the sheet structure, its ability to scatter light in all directions. This may be described as the specific surface area available for light scattering, which is increased by fines, shorter fibres, fibrillated fibre surfaces etc. However, if particle surfaces are closely bonded to each other, less area is available for light scattering and that will decrease s . This is the reason for the lower contribution to s by chemical pulp fines compared to mechanical pulp fines (Luukko and Paulapuro 1999).

When the preheating and/or refining temperature is increased, the pulp brightness is reduced due to reduced light scattering and increased light absorption (Ahrel and Bäck 1970; Asplund and Bystedt 1973; Higgins et al. 1978; Höglund et al. 1997). To avoid thermal brightness loss, it is important to minimize the time that chips and pulp is

exposed to high temperature (Sabourin et al. 1997). Another way to avoid the brightness loss, even at high refining temperature, is to add a low amount of sodium- or bisulphite to the chips before or in the refiner (Nelsson et al. 2017). Not more than 3 kg sulphite per ton is needed to avoid thermal brightness loss.

In the present work, the only considered optical property was light scattering.

1.4 “Minimum mechanical energy consumption”

Since the specific refining energy for mechanical pulp production is high, a lot of research and development work has been invested in finding ways to reduce it. However, the challenge has always been to attain a large reduction of the specific energy at maintained pulp quality. It is not possible to refer to all work made in the search for improved energy efficiency here, however some work that is related to the present investigation is mentioned.

Chemical treatments before, during or after the refining can reduce the specific refining energy, but can change the pulp property profile if the chemical dose is too large. The by far most utilized chemical used in mechanical pulp production is sulphite (bisulphite/sodium sulphite). A comprehensive overview of chemical treatments in mechanical pulping has been presented by Mackie and Taylor (1988). In addition, some recent research works in the area focused on reduced specific energy can be mentioned; Gorski (2011) investigated the effect of peroxide and sulphite in the advanced TMP (ATMP) process. Nelsson (2016) investigated the effect of low dose sulphite chip pretreatment and Chang et al. (2012) have evaluated oxidizing treatments combined with LC refining.

Low consistency (LC) refining became more common in TMP lines from the mid 1990's, mainly installed as third stage in the main line, as a cost-effective means to reduce the specific energy to given freeness or tensile index (Musselman et al. 1996; Vaughn et al. 1998). LC refiners can be utilized in other positions also, e.g. on reject or as post refiners (Sandberg et al. 2017a). However, pulp properties are not developed in a similar way in LC refiners as in HC refiners, which might limit the applications. Mill scale investigations have shown that in LC refining (up to an applied gross specific energy around 150 kWh/adt), the fibre wall thickness is not reduced by peeling to the same extent as in HC refining and light scattering is only marginally increased (Ferritsius et al. 2020; Sandberg et al. 2017a).

Process complexity has sometimes been increased in the search for improved efficiency. Examples of such

concepts are the Inter Stage Screening (ISS) process (Ferluc et al. 2008), the Noss advanced mechanical pulping (NAMP) process (Shagaev and Bergström 2005) and multistage screen fractionation and refining (Tienvieri and Gummerus 2008). The development towards more complex processes was commented on already in 1977 by Atack (1977), who stated in his concluding remarks of the 1977 International Mechanical Pulping Conference: “Disappointingly, there has been little attempt described this week to simplify flow lines. In fact, it would appear that in many cases systems have tended to become increasingly and, in my view, unnecessarily more complex.”

An approach in line with Atack’s intension was presented by Sandberg et al. (2017a). Their concept is based on an intensified (simplified) process in which almost all fibre development is performed in a single HC DD refining stage. After the HC refiner, the pulp is refined in a LC refiner and subsequently fed directly to the paper machine. This extremely simplified process was evaluated in full scale and paper was successfully produced and printed. However, the effect of the simplified process on detailed fibre properties was not evaluated at that time.

Approaching extreme refining conditions at high production rates makes the refining process very sensitive with small disc gaps and a challenge to keep chip feeding and refiner power stable. Questions that naturally come up are; how far can we go? Is it possible to maintain a proper fibre development with a simplified process, at drastically reduced specific refining energy?

The purpose of this work was to examine the fibre development in an intensified pulping process for production of printing paper and compare it to a TMP process with a reject system.

2 Materials and methods

2.1 A new centre plate for RGP68DD refiners

Recently, Valmet has developed a new centre plate, Supplementary Figure S1, for their RGP68DD refiner, which has turned out to be an important contribution in the work with improved process efficiency.

The new centre plate has totally changed the performance of the DD refiners, enabling over 50% increase in production rate, more stable operation and thereby improved loadability. The idea with the new design is to minimise the free volume in the centre of the refiner and force the chips towards the breaker-bar area. In Supplementary Figure S2, cross-sections of the refiner with the old and the new centre plate is shown.

2.2 Mill trial

Two process configurations for production of TMP pulp for printing paper was evaluated at the Holmen Braviken Mill, Norrköping, Sweden. The raw materials was Norway spruce (*Picea abies*) with a 70/30 mix of roundwood and sawmill chips. In this investigation, the effect of individual process parameters was not studied. The choices of settings were based on experiences from earlier work in the Braviken mill (Andersson et al. 2012; Muhic et al. 2010; Nelsson et al. 2017; Sandberg et al. 2018).

The first configuration, which was used as reference, was a two-stage single disc (SD) PRMP line (i.e. atmospheric chip preheating but pressurised HC refiners) with Twin60 refiners (Andritz), Figure 1. Process data are summarised in Supplementary Table S1. The pulp produced with that configuration is normally utilized for production of newsprint and improved newsprint and is hereafter referred to as the SD-News. After the HC refiners, the pulp is refined in two TwinFlo52 (Andritz) LC refiners operating in series. The refined pulp is fractionated in two parallel Andritz F5 screens. The reject is fed back to the LC refiner feed. The screen accept is fractionated in hydrocyclones (Kadant Noss) and that reject is refined in an RGP262 SD HC refiner (Valmet). The production rate is presented as “air-dry” (10% moisture content) metric tons per hour (adt/h) and was calculated from flow and consistency measurements after the latency chest. The pulp consistency was measured manually in lab (average of seven samples). When the reference sampling was conducted, the production rate was 17 adt/h.

The reference process was compared to a simplified process without screening and reject refining. To this end, a trial was performed with one of the RGP68DD HC refiners (Valmet) in another TMP line followed by the two LC refiners described above. The process is shown in Figure 2 and is referred to as the DD-LC process. Process data are summarised in Supplementary Table S2. The DD refiner was equipped with the new centre plate, Supplementary Figure S1, and was operating at 6.5 bar(g) housing pressure. 5 kg/adt sodium sulphite (pH 7.5) was added to the chips right after the plug-screw feeder (approx. 5 s before chips enter the refining zone). The refiner production rate was increased during the trial from the normal 13 adt/h to 17.9 adt/h. The production rate was calculated from pulp consistency and flow measurement after the pulp had been diluted to 7%

Figure 1: One of the TMP lines in Braviken utilized for news, improved news and book paper referred to as the SD-News configuration. Production rate was determined after the latency chest (left red X). Pulp samples for analyses were taken at both red crosses. Process data is summarised in Supplementary Table S1.

Figure 2: Trial configuration with a DD refiner and two stage LC refining referred to as the DD-LC configuration. Production rate was determined after the first dilution, marked with a yellow X. Pulp samples for analyses were taken at the red crosses. Process data is summarised in Supplementary Table S2.

consistency in the standpipe after the refiner. The standpipe consistency was measured (average of seven samples) manually in lab. After the standpipe, the pulp was diluted to 4.8% and refined in the two LC refiners mentioned above. The goal was to produce a pulp after LC refining with tensile index and shives content close to the final pulp of the SD-News process.

At the time of this investigation, it was not possible to feed the paper machine with pulp from the intensified DD-LC process directly. The pulp was treated in a reject system, not shown in Figure 2, before it was fed to the paper machine. In an earlier trial, pulp was produced in a similar intensified process without reject treatment and evaluated on one of the paper machines in Braviken and at printers (Sandberg et al. 2017b). In the present trial, handsheet properties were used to indicate the performance of the pulp.

2.3 Pulp analysis

Pulp samples were taken at the positions shown in Figures 1 and 2. At stable operation, composite pulp samples were collected during a period of 5 min. Pulp from each sampling point was divided into sub-samples and analysed in four laboratories. All samples were hot disintegrated according to (ISO 5263-3:2004) before analysis.

2.3.1 Holmen, Braviken, Sweden: Three sub-samples from each pulp were analysed. Length-weighted fibre length and shives content were measured with a PulpEye (www.pulpeye.com, Örnsköldsvik, Sweden). Shives were defined as particles longer than 300 µm and wider than 75 µm. On each sub-sample two PulpEye measurements were made. Thus, shives and fibre lengths are averages of six measurements and handsheet properties are averages of three measurements.

Handsheets were made with a Rapid Köthen sheet former (ISO 5269-2, DIN 54358) without white water recirculation. The following measurements were made on handsheets: apparent density (ISO 534), tensile index (ISO 1924-2), light scattering coefficient, 550 nm, (ISO 9416). Each tensile index measurement was made on an increased number of 16 strips. Canadian standard freeness (CSF) was measured according to (ISO 5267-2:2001).

2.3.2 Valmet, Sundsvall, Sweden: Pulps were analysed with a Valmet FS5 fibre analyser for particle length – width distribution. Shives content was determined with a Somerville-type equipment according to (Tappi T275 sp-12) using a screen with 0.15 mm slot width.

2.3.3 Stora Enso, Kvarnsveden, Sweden: Handsheets were made according to ISO 5270:2012. The following analyses were made on handsheets: tensile index ISO 1924-2:2008, but on 20 strips, Light scattering coefficient was determined at 550 nm according to ISO

9416:2009. Length-length weighted fibre length, fibre wall thickness, external fibrillation and fibre curl was measured with a FiberLab fibre analyser (Valmet). Determination of length-length weighted fibre length was according to ISO 16065-2:2007. Arithmetic averages (default values from Fiberlab) were used for fibrillation, fibre wall thickness and fibre curl. Shives were measured with a PulpExpert Fibre analyser (Valmet).

2.3.4 RISE PFI, Trondheim, Norway: The samples were fractionated with a Bauer McNett according to SCAN-CM 6:05:2005. Hand sheets were made from the > 50 fraction in a Rapid Köthen sheet former (ISO 5269-2, DIN 54358). On fibre fraction hand sheets, the following measurements were made: apparent density (ISO 534), tensile index (ISO 1924-3), light scattering coefficient (ISO 9416), z-strength (ISO 8791-4). Fibre cross-sectional characteristics were determined from cross-section images produced with high-resolution Scanning Electron Microscopy (SEM and Backscatter Electron Imaging) according to the method of Reme et al. (2002). Approximately 1000 fibres from the Bauer McNett > 50 fraction were analysed. Binarization, filtration and editing of SEM images from fibre cross-sections were performed using a combination of manual and automatic image processing.

3 Results

Two process configurations for production of printing paper were compared in mill scale production regarding hand sheet properties, fibre development and specific energy demand. The first was a two-stage SD HC mainline followed by two stage LC refining and a reject treatment system (denoted SD-News) and the second was a main line with single stage DD HC refining followed by two stage LC refining and no reject system (denoted DD-LC). The pulps from the main line HC refiners are referred to as the SD pulp and the DD pulp respectively (sampled at the left red X in Figures 1 and 2). Process and pulp properties are summarized in Supplementary Table S1–S4.

3.1 Specific energy

The SD-News pulp that was used as reference in this study had a tensile index measured on Rapid Köthen (RK) hand sheets of 57 Nm/g, which is higher than the normal 52 Nm/g of average newsprint pulp in Braviken. The SD-News pulp was closer to improved news, both in terms of tensile index and shives content. The Twin60 line is nowadays the SD lines with lowest specific energy demand to given tensile index in Braviken. The specific energy has been reduced by means of increased production rate, improved segment design, installation of LC refining and separation of screens and hydrocyclones rejects. Thus, the reference process used in this investigation is close to the modern high-intensity Scandinavian TMP lines that were evaluated by Ferritsius

Figure 3: Tensile index, measured on Rapid Köthen (filled) and ISO (open) handsheets, versus specific refining energy for the two studied TMP processes. For comparison, data from a TMP line in Braviken with only SD HC refining, denoted “SD only RK” in the legend, is included (Sandberg et al. 2017a). The lower points are latency pulps and the upper are final pulps.

et al. (2014). In Figure 3, tensile index, measured both on Rapid Köthen (RK) and ISO hand sheets, for the SD-news and DD-LC pulps is shown versus specific refining energy. As a comparison, data from a TMP line (not in operation now) in Braviken with only HC SD refining in the main- and reject lines is included (Sandberg et al. 2017b).

The DD-LC process produced a pulp with tensile index (RK) 53 Nm/g and required a specific refining energy of 1430 kWh/adt as well as an additional 100 kWh/adt of auxiliary energy. The specific refining energy needed to reach the same tensile index for the SD-news process was estimated to 2010 kWh/adt by linear interpolation of the data. The auxiliary specific energy for that process was around 250 kWh/adt, which means that the total specific energy was 730 kWh/adt lower for the DD-LC process. A similar calculation based on tensile index measured on ISO Handsheets gives a difference in total specific energy of 850 kWh/adt. The specific energy difference at freeness 114 ml is similar as to given RK tensile index, Supplementary Table S3.

3.2 Handsheet properties

In Figure 4, tensile index is shown versus apparent density for both ISO and RK handsheets. The drying under pressure and high temperature (93 °C) in the RK sheet former densified the handsheets of all pulps more than in the ISO sheet forming. However, the densification and tensile

Figure 4: Tensile index measured on ISO and Rapid Köthen handsheets versus apparent density for respective handsheets.

index increase was larger (in percent) for the SD-News pulps. The different reaction leads to a switch in tensile index ranking of the two latency pulps and the difference in tensile index of the final pulps is increased.

At given density, tensile index (RK) measured on whole pulps was lower for the DD-pulps but when it was measured on fibre fraction (BMcN > 50) handsheets (RK), it was higher for the DD pulps, Figure 5. These differences will be discussed more below. Earlier studies comparing DD and SD refining have also shown that tensile index measured on whole pulps is lower for DD-pulps at given density (Andersson et al. 2012; Corson et al. 1993; Falk et al. 1987; Ferritsius et al. 1989).

Figure 5: Tensile index (Rapid Köthen) measured on fibre fraction (BMcN > 50) handsheets and whole pulp handsheets. Note that fibre fraction and whole pulp handsheets were not made at the same laboratories.

Z-strength RK BMcN >50 (kPa)

Figure 6: Z-strength versus apparent density for fibre fraction handsheets (BMcN > 50). The z-strength increases less for LC refining than over the reject system even though the apparent density increases more.

The fibre bonding (indicated by z-strength measured on BMcN > 50 handsheets) was higher for the DD pulp than the SD pulp, Figure 6. However, the increase in z-strength over the reject system was higher and thereby, at given density, the final pulps from the two processes had equal fibre fraction z-strength but the tensile index of the fibre fraction was somewhat higher for the DD-LC pulp, Figure 5.

In the following figures pulp and fibre properties are shown versus tensile index measured on ISO handsheets if not else stated.

The light scattering of the DD pulp was around 5 m²/kg higher than the SD pulp at given tensile index, Table 1, which is partly due to the higher content of fines in the DD pulp. However, at certain amount of fines, Figure 7, or at certain fibre length, Figure 8, the light scattering was still higher for the DD-LC pulp. This was due to higher light scattering of the fibre fraction, Supplementary Table S3, which likely was an effect of higher degree of fibrillation and a larger share of axially split fibres, Table 1. An effect of split fibres on light scattering has been shown by (Reme and Helle 2000). The light scattering of the whole pulp was almost unchanged over the LC refining and decreased for the fibre fraction in the DD-LC process whereas it increased over the reject system with HC refining, Supplementary Table S3, which agrees with earlier comparisons of HC and LC refining (Andersson et al. 2012; Ferritsius et al. 2020). The reduced light scattering of the fibre fraction for LC refining might be an effect of the reduced fibrillation, Table 1. A slight reduction of fibrillation over LC refining has been found in an earlier investigation (Ferritsius et al. 2020).

Table 1: Specific refining energy and a selection of pulp properties.

	DD	DD-LC	SD	SD-News
Specific energy (kWh/adt)	1246	1430	1685	2192
Tensile index, ISO (Nm/g)	39.2	47.7	37.7	48.9
Light scattering coef. ISO (m ² /kg)	52.4	53.4	47.0	50.6
Fibre length ^a , Fiber lab (mm)	2.41	2.34	2.62	2.37
Fibrillation, Fiber lab (%)	5.62	5.33	4.41	4.33
Fibre wall thickness, SEM (μm)	2.38	2.36	2.51	2.52
Share of split fibres, SEM (%)	36.1	34.3	18.7	20.1
Shives sum, Pulp eye (N°/g)	182	83	588	96

More data are presented in Supplementary Table S3. ^aLength-length weighted average.

[Correction added after online publication 06 May 2021: The values of Tensile Index, ISO (Nm/g) have been corrected in Table 1]

Light scat. coef. (m²/kg)

Figure 7: Specific light scattering coefficient versus amount of fines (BMcN < 100). The content of fines is in the pulps, not retained in the sheets.

Light scat. coef. (m²/kg)

Figure 8: Light scattering coefficient versus length-length weighted average fibre length.

3.3 Fibre properties

At given tensile index, the pulp from the DD refiner had lower length-length weighted average fibre length than the pulp after the two stage SD refining, Table 1, which is usually found when DD and SD refining are compared. The fibre length reduction was larger over the reject treatment system in the SD-News process compared to only LC refining in the DD-LC process, which resulted in a similar fibre length at given tensile index for the final pulps. The fibre length reduction over the SD reject system was somewhat higher than normally, most likely due to somewhat too high screen reject rates. Since screen reject is mixed with main line pulp before the LC refiners, a large reject rate can build up the long fibre content around the LC refining system and just a small reduction over the LC refiners can lead to a rather large reduction in fibre length over the LC refining plus screening system.

The DD-refiner produced pulps with higher fibre curl at given tensile index compared to the SD refiners, Table 1. Curl was reduced over the LC refining for the DD-LC process, which agrees well with earlier studies, see Ferritsius et al. (2020) for more discussions of the subject. For the SD-News process with screening and reject refining, fibre curl was unchanged, even though the SD-news process contains third stage LC refining. The HC reject refining most likely re-introduced some curl to the fibres.

The DD pulp had higher degree of fibrillation (FiberLab) than the SD refining at given tensile index, Table 1. The fibrillation did not increase over the reject system in the SD-News line and decreased slightly over the LC refiners in the DD-LC process. The SD-News process has main line LC refining but HC rejects refining which might explain why fibrillation was unchanged. A slight reduction of fibrillation (measured with FiberLab) over LC refining has

been found in an earlier investigation (Ferritsius et al. 2020) which might explain the slight reduction in light scattering of the fibre fraction in the present study, Supplementary Table S3.

Fibre wall thickness was measured both with FiberLab and on SEM images of cross-sections, Table 1 and Supplementary Table S3. Both methods measured lower fibre wall thicknesses for the DD pulps. The two methods show different development of the wall thickness for both processes, but changes are so small that no conclusions can be drawn.

The share of split fibres was considerably higher for the DD refining than SD refining (36.1% compared to 18.7%), Table 1. This agrees with earlier comparisons of DD and SD refiners (Ferritsius et al. 2020) and other high intensity refiners (Kure et al. 2000; Pöhler and Heikkurinen 2003).

3.4 Fines

In Figure 9, tensile index (A) and light scattering coefficient (B) are shown versus the amount of BMcN < 50 fraction in the pulp (not retained in the sheet). The < 50 fraction contributed differently to the pulp quality development in the two processes. Since the middle fraction, BMcN 100-50, was small (<9%) in relation to the < 100 fraction for all pulps, the major part of the difference was likely due to different properties of the fines. For light scattering, the SD and DD fines gave a similar increase when included with the fibre fraction, whereas for tensile index, the SD fines clearly improved the strength more than the DD fines.

The fines were also measured with a Valmet FS5 fibre analyser and classified according to length (40–200 μm , 40 μm steps) and width (1–9 μm , 1 μm step). The limit in

Figure 9: Effect of the < 50 fraction on tensile index (A) and light scattering coefficient (B). SD “fines” improves the tensile index more than DD “fines”. The thick dashed lines connect latency and final pulps. The content of BMcN < 50 is in the pulps, not in the sheets. Note that fibre fraction and whole pulp handsheets were not made at the same laboratories.

width was set to avoid including too many ray-cells, which have a width around 10 μm . The length-width distribution of the fines is found in Supplementary Table S4. For all length classes, the SD-News pulp had a higher number of the thin fibrils (<3 μm) and the DD-LC pulp more of wider fibrils. As an example, in Figure 10, the width distribution for the length class 0.08–0.12 mm is shown for the final pulps of the two processes.

The width distribution of small fibrillar fines (20–40 μm length) before and after LC refining in the DD process as well as before and after the reject system in the SD process is shown in Figure 11. Neither the reject system nor the LC refining had any effect on the size distribution of the fibrillar fines (within the resolution of the FS5 fibre analyser).

Figure 10: Width distributions of fibril-like particles for the length class 0.08–0.12 mm. The distribution is the number of particles relative to the total number of detected particles (0–75 μm width, 0–7 mm length).

3.5 Shives

The shives content was measured with two optical fibre analysers which show similar trends with somewhat lower shives content for the DD-LC pulp compared to the SD-News final pulp after the reject treatment system, Table 1 and Supplementary Table S3. Shives content measured with Somerville (i.e. larger shives, >0.15 mm width) showed a different result, with a somewhat lower shives content of the SD-news final pulp than the DD-LC pulp, Supplementary Table S3. The optical analysers probably measure shives that pass the Sommerville screen and thereby a larger total amount of shives was detected. Generally, there is a rather large scatter in the shives measurements and therefore the conclusion is that the shives content of the final pulps was similar for the two processes and considerably lower than the normal newsprint pulp in Braviken.

The shives reduction was higher for the reject system compared to only LC refining. Therefore, it is important to have a low shives content out from the main line HC refining to attain a final pulp with low enough shives content with the simplified process.

Small shives, that pass the Sommerville screen and that are under the limit of what the optical analysers classify as shives, can still be a problem for print quality (Kartovaara 1990; Zou 2007). Therefore, shive measurements were also made on SEM cross-sections. In Figure 12, examples of measured shives are shown.

In Table 2, the numbers of shives measured on SEM cross-section images are shown. The largest number of detected shives consisted of only two fibres, such as those shown in Figure 12. The SD and DD pulps had a similar amount of small shives (<4 fibres/shive) whereas the number of larger shives was higher for the SD pulp. The final

Figure 11: Width distributions for the 20–40 μm length class for the SD-News process, A, and the DD-LC process B. The distribution is the number of particles relative to the total number of detected particles (0–75 μm width, 0–7 mm length).

Figure 12: Example of cross-sections of shives that were classified according to the numbers of fibres in each shive.

Table 2: Number of shives per 10 mm² fibre wall areas classified by the number of fibres in each shive.

Fibres per shive	Number of shives per 10 mm ² total fibre wall area											
	2	3	4	5	6	7	10	14	25	30	55	60
SD	11	2	1	0	2	1	1	1	0	1	1	0
SD-News	13	2	0	1	1	1	0	0	1	0	0	0
DD	8	2	1	1	0	0	0	0	0	0	0	0
DD-LC	16	1	2	0	0	1	0	0	0	0	0	1

Measured on SEM cross-section images.

pulps of the two process configurations had approximately the same shives content.

As is seen in Table 2, one large shive, containing 60 fibres, was found in the pulp from the DD-LC process. To make sure that the very few large shives doesn't create problem in the paper, it might be necessary to improve the screening operation on the paper machine. Also, it is probably necessary to take care of start and stop pulp from the primary refiner to minimize shive related problems.

4 Discussion

Several earlier studies have pointed out that it is necessary to separate and further refine the long-fibre fraction from a TMP main line (e.g. Corson 1996; Jackson and Williams 1979). However, earlier mill scale work by Sandberg et al. (2017a) has shown that it is possible to produce a pulp for heatset and coldset printing paper, with a simplified process consisting of single stage HC DD refining followed by LC refining and no screening or reject refining. No doubt, it is important to have well developed conformable long fibres to attain good strength properties and print quality, but that can obviously be attained without selective long fibre refining and moreover at a very low total specific energy.

As mentioned above, several earlier studies have shown that DD refiners produce pulps with higher density at certain tensile index. The same trend was found in this study. Corson et al. (1993) suggested that the higher density is due to the lower fibre length that the DD pulp had. However, in this study the final pulps from the SD and DD processes had similar fibre length, therefore it is more probable that the reason for the difference is due to that the DD refiner produces a combination of more conformable long fibres that densifies the network and larger fibrillar fines that gives lower contribution to tensile index. As can be seen in Figure 4, the heat and pressure applied on the sheet during consolidation in the RK sheet former had a larger effect (increase in tensile index and density) on SD pulps than DD pulps. This difference in densification of the two pulp types might also be an indication of higher stiffness of the SD fibres than the DD fibres.

The differences in pulp development over the post treatment systems (LC refining and the reject system) for the DD process and the SD process respectively is also interesting. The fibre length reduction was, in this study, larger over the SD reject system than over the LC refining and despite that, the density increase was higher over the LC refining, Figure 13. Therefore, other changes in fibre properties than fibre length must have a larger effect on the densification upon LC refining, e.g. fibre straightening (Seth 2006) and probably also internal fibrillation (Ferritius et al. 2020). On the other hand, z-strength of the fibre fraction increased more over the SD reject system than over the LC refining, Figure 6. Since there was no significant change in the cross-sectional dimensions of fibres over

Figure 13: Apparent density versus length-length weighted average fibre length. The density increases more over the LC refining than the SD reject system even though the fibre length reduction is lower for the LC refining.

anyone of the two processes, Supplementary Table S3, other factors, such as internal and external fibrillation, must have affected the considerably lower z-strength increase over LC refining.

The single stage chip refiner is of course extremely important in a simplified system and in this study, a large (RGP68DD) double disc refiner was utilised. Earlier investigations have pointed at differences between DD and SD refining (Andersson et al. 2012; Corson et al. 1993; Falk et al. 1987; Ferritsius et al. 1989, 2020; Kibblewhite et al. 1995; Sundholm et al. 1988). These studies come to somewhat different conclusions regarding pulp quality and energy efficiency, however a common observation is that DD refiners produce pulp with lower fibre length, higher density and higher light scattering compared to SD refiners at given tensile index. Similar relationships were found in this study.

It has been stated that the specific refining energy can only be reduced by a sacrifice of fibre length (McDonald et al. 2004). It could be argued that the fibre length reduction was too large over the reject system in the SD-News process in the present study to be a relevant reference. However, this enabled a comparison of the two processes at a similar fibre length and there was still a large difference in energy demand. Thus, there is no universal relationship between specific energy and fibre length, which also has been shown by Hill et al. (2017).

As mentioned in the introduction, the amount and quality of the fines fraction is also important for the properties of papers based on mechanical pulp. Earlier work has shown that the character of fines is affected by the refining intensity. Fibrillar fines produced at high intensity in primary stage refiners seems to be larger and contributes less to bonding compared to those produced at low intensity (Kibblewhite et al. 1995; Mörseburg et al. 2014; Pöhler and Heikkurinen 2003). However, after additional low intensity refining stages, the difference diminished (Pöhler and Heikkurinen 2003). It is clear that the intensified DD-LC process produced fines with somewhat different size distribution compared to the SD-News process. Kibblewhite et al. (1995) found that fibrillar fines from DD refining are generally larger (not quantified). At a similar mass fraction of fines, smaller fibrils contribute to larger number of particles and thereby a larger area available for bonding. The smaller fibrillar fines produced in the SD-News process probably acted as a better “glue” between the fibres, more like chemical pulp fines (Moss and Retulainen 1997). Rundlöf et al. (2000) have also shown that the smallest fines (all fines types in that case) of mechanical pulps contribute more to both tensile index and light scattering,

and Luukko and Paulapuro (1999) showed that smaller fibrils contribute more to bonding and less to light scattering than larger. This could explain why, even though the DD-LC fibre fraction ($BMcN > 50$) handsheets had higher tensile index at given apparent density, the tensile index at given density for whole pulp (i.e. fibre + fines) handsheets was higher for the SD-News.

Earlier studies have indicated that LC refining might create more small fibrils compared to HC refining (Fernando et al. 2013; Hafrén et al. 2014). That could not be confirmed by the measurement of the length-width distribution of the fines in this study. Fernando et al. (2013) and Hafrén et al. (2014) based their speculations of the differences between HC and LC refining on the same pulps, from a pilot scale LC refiner trial in which the pulp was severely cut (Gorski et al. 2012a, 2012b). The findings they report for LC refining; A large fibre length reduction, poor tensile energy absorption (TEA) development and a relatively large light scattering increase were neither seen in the present mill scale study nor in other mill scale studies (e.g. Andersson et al. 2012; Ferritsius et al. 2020; Sandberg et al. 2017a). Gorski et al. (2012b) suggested that the poor TEA development in LC refining was due to fibre straightening (reduced fibre curl). In the present study, the TEA increase over the LC refining in the DD line was almost as high as over the SD-News reject system even though curl was reduced. Moreover, Fernando et al. (2013) and Hafrén et al. (2014) propose that the small fibrils, that they claim are produced in LC refining, contributes to the light scattering increase and not to the tensile index increase of LC refining. This is the opposite conclusion of the effect of small fibrillar fines that the detailed study by Luukko and Paulapuro (1999) showed, and also, what is indicated by the present work. If LC refining would generate a lot of small fibrils on the fibre surface that contribute to light scattering, the fibre fraction light scattering in the present study should have increased, but it decreased. The rather poor tensile index development of all LC refined pulp fractions and the relatively large light scattering increase reported by Gorski et al. (2012a) and Hafrén et al. (2014) is most likely related to the extreme fibre length reduction in their pilot trial. The large fibre length reduction they got was most likely an effect of too narrow segment bars (1 mm) and low pH (4.7) of the pulp. Kerekes and Meltzer (2018) showed that is unfavourable to use too narrow bars due to high forces on fibres and moreover, Hammar et al. (2010) have shown that low pH is unfavourable for fibre length. In conclusion, their pilot LC refining was not representative for most mill scale installations.

5 Conclusions

Comparison of pulps produced in a process with two stage HC SD main line refining followed by a reject treatment system and a simplified process with single stage HC DD refining and LC refining has shown that:

- It is possible to simplify the production process for mechanical pulp.
- It is not necessary to have a separate treatment of the long fibre fraction to develop the fibres.
- Similar shive contents can be attained with the simplified DD-LC process and a two stage SD HC process with screening and reject refining.
- The simplified DD-LC process required at least 700 kWh/adt lower total specific energy compared to the two stage SD HC process with a reject treatment system.
- The fibre fraction properties of the simplified DD-LC process were at least as good as the final pulp of the SD process.
- The DD refiner produced fibres with higher degree of fibrillation, higher share of axial splits, lower fibre wall thickness and higher z-strength than the two stage SD refining at given whole-pulp tensile index. However, the fibrillar fines size distribution of the two processes was different. The SD process generated more of small fibrillar fines which probably explain the higher tensile index at given apparent density of the SD-News pulp.
- The fibrillar fines length-width distribution changed in a similar way for the low consistency refining in the DD-LC process and the reject system in the SD-News process.
- It is important to reach a high degree of fibre development from the chip refiner in a simplified DD-LC process.

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