



Faculty of Technology and Science
Chemical Engineering

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Improvement of the tissue manufacturing process

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Abstract

Increasing competition on the tissue market forces the tissue makers to raise product quality and increase operating efficiency. The creping process and the conditions on the Yankee cylinder continue to be the key factors in the production process. They need to be kept under good control in order to maintain a high and uniform quality. A natural coating always develops on the surface of the Yankee cylinder due to evaporation from dissolved and dispersed substances and to fiber fragments that remain on the surface after creping. Nevertheless, coating chemicals are sprayed onto the Yankee surface in order to modify the adhesion between the paper and the dryer cylinder. To be able to control the process, on-line measurements of coating thickness as well as of the crepe structure of the tissue paper produced would be very valuable.

In the work described in this thesis, the coating layer was analyzed chemically and morphologically to provide information about the coating layer before starting any on-line measurements. The chemicals added and the constituents of the pulps are known to the paper producers, but what is left on the cylinder and whether there are different layers of coating still remain to be investigated. The chemical analysis indicated that the adhesive content was higher in an inner layer of the coating than in the outer layer. The relative amount of polyamide-amine resin calculated on the basis of the nominal nitrogen content in the resin was low indicating that the coating consisted of a significant amount of carbohydrates or other substances. The coating layer could not be considered transparent. It was observed that the coating was thick and appeared patch-wise and that it contained fiber fragments.

Measurements on a laboratory scale, to further be applied on-line on the tissue machine, have been investigated and evaluated in this study. The thickness of the coating layer on a laboratory dryer has been measured. The method was based on fluorescence with an optical brightener added to the coating chemicals sprayed on the Yankee dryer. With a UV-LED (Ultra Violet - Light Emitting Diode) the coating layer was exposed to UV-light and the intensity of the light emitted by the optical brightener in the layer was measured. The intensity in the trials with different thickness of the coating and no coating was scattered and no trend could be seen between the different trial points.

Attempts were made to measure the wavelength of the tissue paper produced with an optical fiber perpendicular to and at an angle to the paper surface. The paper was travelling in a slow speed while the measurements were made. The collected signal to noise ratio was low and it was not possible to detect any representative characteristic wavelength of the tissue.

Papers included in this thesis

I Chemical and Morphological Analyses of the Tissue Yankee Coating

Jonna Boudreau, Holger Hollmark and Luciano Beghello

(Accepted for Nordic Pulp and Paper Research Journal, March 2009)

II A Method of Measuring the Thickness of the Coating on a Dryer Cylinder

Jonna Boudreau and Luciano Beghello

(Submitted to Nordic Pulp and Paper Research Journal)

III Experiments to Find Online Measurements of the Structure of the Tissue Paper Surface

Jonna Boudreau and Luciano Beghello

(To be submitted)

Related presentations and reports by the same author

Ampulski, R., Hollmark, H. and Hedman, J.,

Physical and Tactile Properties of Through Air Dried Tissue

Presented at the 8th Tissue World, Nice, France, March 26-29, 2007

Symbols and abbreviations

Symbols

F_x	Creping force normal to the doctor blade
F_y	Creping force tangential to the doctor blade
T_g	Glass transition temperature

Abbreviations

AC/DC	Alternating current/Direct current
AFM	Atomic Force Microscope
ASE	Amplified Spontaneous Emission
A.U.	Arbitrary Units
CCD	Charge-coupled device
HPAEC-PAD	High Performance Anion-Exchange Chromatography with Pulsed Amperometric Detection
IR	Infrared radiation
NI	National Instruments
PAAE	Polyamidoamine-epichlorohydrin
PAE	Polyamide epichlorohydrin
PVA	Polyvinyl alcohol
SEM	Scanning Electron Microscope
USB	Universal Serial Bus
UV	Ultra violet radiation
UV-LED	Ultra Violet - Light Emitting Diode

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1 Introduction

There are basically four ways of making tissue and towelling products. Three of them produce paper that is creped, i.e. paper that has wrinkles caused by the action of a doctor blade used to remove the paper from a drying cylinder. The dominant technology is the “dry crepe” process. Less common is the “wet crepe” process in which the paper web is creped before it is fully dried. In the wet crepe process, the required adhesion of the web to the drying cylinder is achieved with a thin liquid film. During recent decades, a process called “Through-air-drying (TAD)” has been widely adopted, primarily in the US. In the production of dry creped tissue, the thin paper is dried on a large drying cylinder, called a Yankee cylinder. The paper is scraped off the cylinder by a doctor blade to produce creped tissue. The quality of a paper is very dependent on its structure. A creped paper can resemble a sinus curve with different frequencies and amplitudes depending on many factors; for example the creping blade, coating chemicals and coating thickness on the cylinder. The frequency or period of the paper creping affects the paper quality enormously and it is necessary to measure this on-line to obtain a fast answer to a change in the system. The coating thickness affects the crepe frequency and it is therefore also of interest to measure the thickness of the coating on-line. To produce a product with a high quality and have high production efficiency, the cylinder coating must be controlled.

The aim of this work is to make the tissue process more stable through on-line measurement of the coating thickness on the Yankee cylinder and the crepe frequency of the paper. It is also of interest to determine what is actually on the Yankee cylinder and what the morphology of the coating surface is like. In the first paper, this was studied and compared with industrial experience of the consistency and uniformity of the cylinder coating. For the coating thickness measurement, a study made in 1997 by Lars Granl f at STFI was the cornerstone of the work. The equipment was updated but was based on the same theory. The crepe frequency measurements was built on a simple method using an optical fibre where the light was incident and collected at the same angle while the paper passed at a low speed beneath the optical fibre.

2 Theory

2.1 Dry Crepe Tissue Machine

Tissue production begins with a fibre suspension injected between a wire and a felt or between two wires and transported by a felt to a rotating dryer cylinder called a Yankee dryer. The paper web is pressed onto the cylinder with a pressure roll and the web adheres to the surface. The paper is dried on the cylinder which is heated

internally with steam and with dryer hood over the paper web. The paper is removed by scraping off the paper web with a blade. The scraping produces a wrinkled, creped, paper.

2.1.1 Headbox

The headbox for tissue paper contains stock with a consistency of 0.15 – 0.25 % solids. The pulp is distributed over the machine width by pipes. To produce a multilayer tissue paper, the headbox consists of parallel channels with intermediate separating vanes. The stock is ejected from the headbox and the jet is introduced in the forming section.

2.1.2 Crescent Former

The Crescent Former, see Figure 1, is a felt-wire former and the headbox delivers the pulp between the felt and the wire.

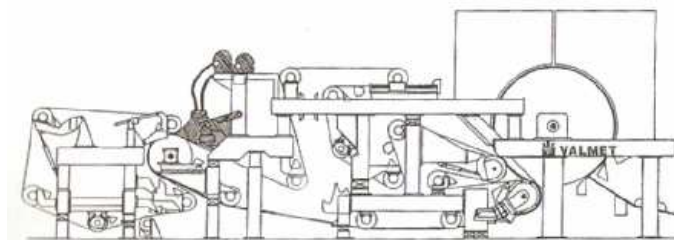


Figure 1. The Crescent former configuration on dry crepe tissue machine (Gavelin, 1999).

The sheet is formed between the wire and felt and dewatered through the wire. The felt is wrapped around the forming cylinder and transports the paper to the nip between the pressure roll and the Yankee cylinder.

2.1.3 C-Former

In the C-Former configuration, the headbox delivers the pulp between two wires under the forming cylinder, as shown in Figure 2, as the paper is transferred to the felt.

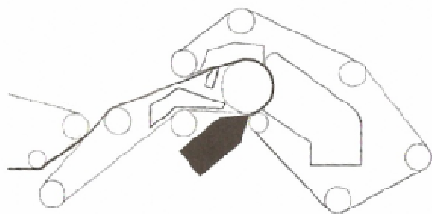


Figure 2. A C-former configuration (Gavelin, 1999).

2.1.4 Yankee cylinder and dryer hoods

The heart of the tissue machine is the Yankee cylinder which dries the paper from 40 % dryness to 90 – 98 % dryness. The heat is provided by steam inside the cylinder which enters the cylinder through the front journal, to the right in Figure 3. The steam is led through the internal shaft and through the nozzles located on the shaft. When the steam condenses on the walls of the inner surface of the cylinder, the condensate is picked up by small pipes dipping into grooves. It is collected in about six transversal headers and led through long bent pipes to the internal shaft and exits the cylinder at the back journal.

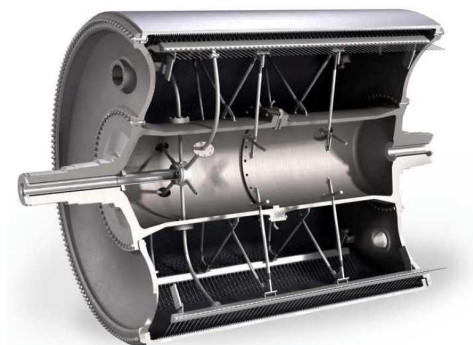


Figure 3. Longitudinal section of a Yankee dryer (Metso Paper).

2.1.5 Coating Spray Application System

Coating chemicals are needed to control the adhesion between the paper web and the cylinder dryer. The coating also protects the surface of the cylinder from corrosion and reduces wear on the doctor blade. The chemicals are sprayed onto

the cylinder through nozzles, as shown in Figure 4, attached to a boom and situated beneath the Yankee cylinder. The boom oscillates to reduce streaks on the surface.

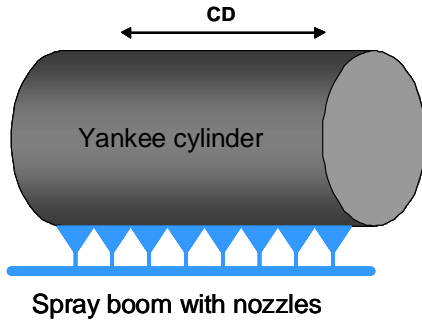


Figure 4. Simplified layout of a Yankee cylinder where chemicals are sprayed onto the cylinder dryer with oscillating nozzles.

2.1.6 Creping doctor and cleaning doctor

A Yankee cylinder for tissue production has space for three doctor blades, although many mills use only two of them. The doctor highest up on the cylinder is the cutting doctor and this is used when the creping doctor has to be moved i.e. when blades are replaced on the other two doctors. The paper scraped off by the cutting doctor goes to broke. Under the cutting doctor is the creping doctor which scrapes off the dried paper from the Yankee cylinder. The construction of the creping doctor is extremely important for the crepe structure and the quality of the paper produced. The doctor blade is 1.0-1.25 mm thick and about 100 mm wide (Gavelin, 1999). Under the creping doctor, the cleaning doctor can be located. The cleaning doctor should, for example, remove thicker patches of coating to make the surface of the coating as even as possible.

2.2 Creping

2.2.1 Creping Mechanism

When the creping doctor scrapes the tissue paper from the Yankee cylinder, the energy from the blade leads to a wrinkling of the paper and breaks the physical structure of the sheet. Microfolds are created and piled up on top of each other on the creping blade. When the pile of microfolds is high enough, the pile falls into a

macrofold. A new pile with microfolds is started to grow and so continues the process. Some authors have made a detailed analysis of the creping process and its dependence on factors such as geometry, adhesion and the presence of a coating layer (Fuxelius, 1967; Oliver, 1980). Other authors have, for the purpose of understanding and teaching the behaviour of various coating chemicals, provided theories on how the chemicals interact with the creping process (Stitt, 2002; Hättich, 1999; Grigoriev, 2005). In section 2.2.2 below, some theoretical statements by some representatives of chemical suppliers are given.

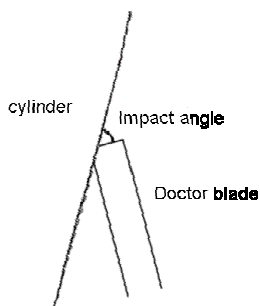


Figure 5. The angle between the Yankee cylinder and the blade. This angle between the top surface of the blade and the cylinder surface is called the impact angle and affects the structure of the tissue paper.

The blade is held against the cylinder at a certain angle, Figure 5. The top surface of the blade can be ground at different angles. The angle between the top surface of the blade and the cylinder surface is called impact angle. This angle affects the distance between the crepes in the paper and therefore also the smoothness of the paper surface (Gavelin, 1999). The larger the impact angle, the fewer micro-crepes in every macro-crepe and the more fine creped is the paper, as shown in Figure 6 and Figure 7.

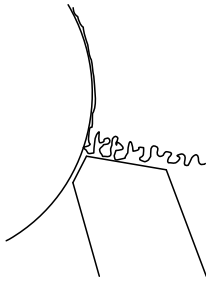


Figure 6. The crepe process with a large impact angle. Only a few micro crepes pile up in each macro crepe. The slope of the blade means that the crepes easily fall off the blade.

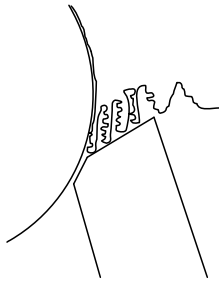


Figure 7. The crepe process with a small impact angle. The number of micro-crepes is larger with a small impact angle because the blade can more easily hold the micro-crepes piled up on the blade.

The blade has to be changed fairly often. It is time to change the blade when the crepe structure becomes too coarse and uneven, and when the coating is building up on the cylinder. The blades are usually made of steel, but ceramic tips are becoming more common.

After the creping process, the paper is wound up and the reel is transported to further treatment. The reel is wound up at a slower speed than the Yankee cylinder is drying the paper in order to keep the paper in a wrinkled structure. If the winder and Yankee had the same speed, the crepes produced would be stretched too much.

2.2.2 Bond Between Sheet and Yankee Dryer

Adhesion is due to the attraction force between the paper sheet and the Yankee cylinder. Some literature says that, in order to achieve the greatest uniformity and the strongest of adhesion, the sheet has to be pressed tightly to the cylinder when the coating is as sticky as possible. The coating is stickiest at its glass transition point (T_g) in the case of cross-linking coatings and at its maximum tack moisture

content in the case of rewettable coatings. If the sheet is pressed to the coating before the coating reaches its T_g , the adhesion is weak when the pressure is released. The coating is too viscous and most of the coating is pressed through the sheet and into the felt by the pressure roll. If the sheet is pressed to the coating too late, then the adhesion is weak because the coating is too hard. If the moisture profile across the machine is not uniform, the coating will set at different times and this will prevent a uniform attachment of the paper web to the cylinder (Stitt, 2002). Figure 8 shows different zones of the cylinder where different steps in the formation take place.

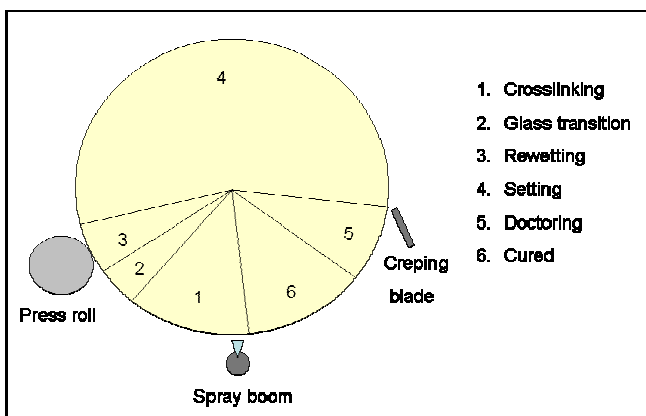


Figure 8. Diagram showing the different zones of coating formation on the Yankee cylinder (Sloan, 1991; Hättich, 1999).

Despite the tackiness of the coating, the surface energies of the different phases that are brought into contact with each other are of great importance for the adhesion. In order to establish molecular contact, an adhesive must, when in a liquid state, wet the surface to which an adhesive bond is to be achieved and the wetting behaviour is controlled by the surface free energies of the phases involved. Spontaneous wetting, or spreading of a liquid on a solid substrate, is favoured by a high surface energy of the solid and a low surface energy of the liquid (Kinloch, 1980).

If the web is pressed tightly onto the coating with good contact, debonding within the sheet will occur when the paper is scraped off the cylinder. Another advantage of good contact is that more fibres are pulled away from the surface of the web when it is separated from the Yankee cylinder, and raised fibres give bulk to the sheet. A higher bulk makes the paper soft and more absorbent.

If the adhesion is too high at the creping doctor, the blade may pick and drag fibres from the surface of the paper and create holes in the web or even cause the web to break. If the adhesion is even stronger, the paper web may simply pass under the blade. If the adhesion is too low, the paper will separate from the cylinder before it reaches the creping doctor and this will lead to a low creping frequency (Oliver, 1980).

2.2.3 Crepe wavelength of tissue paper

The adhesion between the paper and the Yankee cylinder affects the force needed to scrape off the dry tissue paper. Ramasubramanian and Shmagin (2000) showed that an increase in adhesive concentration led to an increase in the creping force, see Figure 9 where F_y is the tangential or creping force and F_x is the normal blade force. These trials were performed on a laboratory scale with polyvinyl alcohol (PVA) as the adhesive.

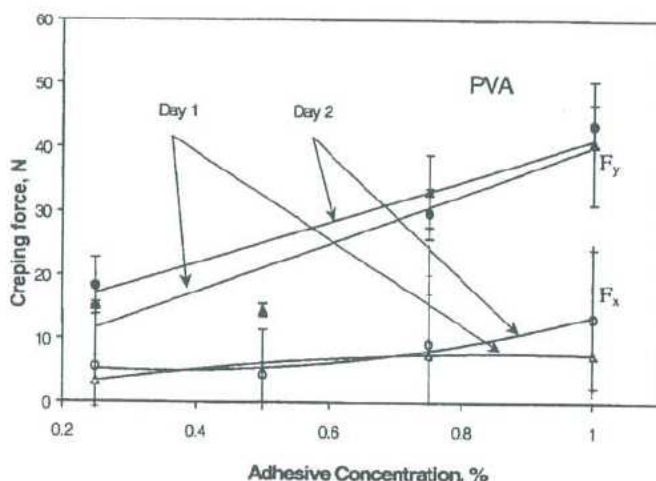


Figure 9. Effect of adhesive concentration on creping force (Ramasubramanian and Shmagin, 2000)

The creping force, F_y , increased significantly when the adhesive concentration was increased.

In this work the relationship between coating thickness and crepe wavelength is important. The thicker the coating layer, the more adhesive is involved in the adhesion of the paper to the cylinder surface. A greater adhesion between the paper and cylinder would give rise to a more finely creped paper with a shorter

wavelength. Ramasubramanian and Shmagin (2000) also stated the effect of adhesive concentration on crepe wavelength on a laboratory scale, see Figure 10.

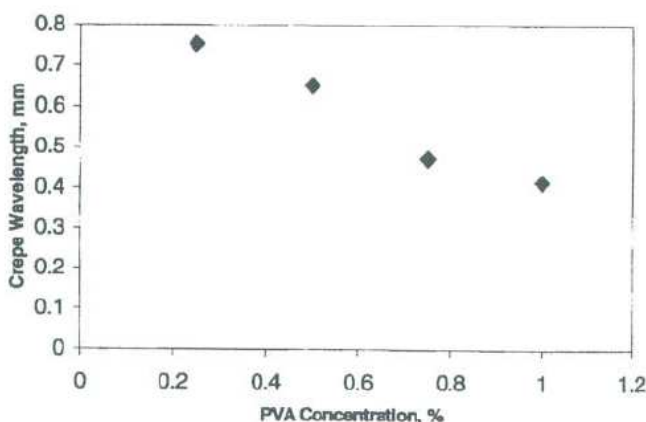


Figure 10. Effect of adhesive concentration on crepe wavelength (Ramasubramanian and Shmagin, 2000).

The plot clearly shows that a higher concentration of adhesive, PVA, gave a shorter crepe wavelength and a more finely creped tissue paper.

2.3 Yankee Cylinder Coating

2.3.1 Natural coating

The cast-iron surface of the cylinder is probably covered by a thin oxide layer with a high surface energy (Kinloch, 1980; Nordman and Uggla, 1978). The process water accompanying the fibre web completely wets the cylinder surface. After being in operation for some time, an evaporation residue is formed on the surface of the cylinder consisting mainly of hemicellulose, fines and wet end additives dissolved in the water. The adhesive properties originate from hemicellulose, which is composed of high molecular weight sugars with branched or straight chains. Pulp and pre-treatment affect the adhesion. For example, an increase in beating increases the adhesion. Beating releases hemicellulose; but the increase in adhesion may be a result of increased fibrillation, which gives more flexible fibres and a greater bonding area (Oliver, 1980). Tissue was made like this in earlier days, when the most frequently used method to control adhesion was to vary the pH of the process water. The adhesion increased with increasing pH.

2.3.2 Coating Spray

Today almost all tissue machines are equipped with a chemical spray system in which adhesives and release agents are sprayed onto the surface of the cylinder just before the paper web makes contact. It has been found, by trial and error, that the amount of substance applied and the position of application is critical for good adhesion and creping, indicating that the tackiness of the sprayed coating layer is an important factor controlling the adhesion at the point of creping.

Adhesives

The most commonly used adhesive substance is a polymer in a aqueous solution. The polymers most frequently used today are synthetic polymers: polyaminoamides, polyamines, polyvinyl alcohols, polyvinyl acetates and polyethers (Grigoriev, 2005). Cross-linked polyamide resins with epichlorohydrin (PAE) are the most popular (Grigoriev, 2005). Adhesives have different hardness levels due to the difference in glass transition point (T_g), most commonly between 30°C and 105°C. The cross-linking reaction is dependent on pH. No reaction takes place at low pH and the pH is therefore held low until use. The resins cross-link on the Yankee surface and create a plastic coating layer.

The build-up of the polymer on the surface of the Yankee cylinder is affected by the solubility, molecular weight and chemistry of the polymer sprayed onto the cylinder. If the polymer is easily dissolved in water, it can be dissolved by the humidity of the sheet and build up unevenly on the cylinder surface. A more uniform coating can be achieved if a hydrophobic polymer is used.

The dryer coating can contain more than one adhesive chemical and these are used in different ratios depending on what tissue grade is produced.

Release agent

Release oils are used to reduce the adhesion and release the sheet from the dryer at the creping blade. The adhesive and release oil are mixed together and diluted with water before the mixture is sprayed onto the hot Yankee cylinder. The water evaporates and the mixture of release oil and adhesive forms a tacky coating on the cylinder (Grigoriev, 2005).

Release agents are mostly hydrophobic and can be emulsifiable mineral oils, fatty acid esters, polyphosphates, imidazolines and fatty alcohol ethoxylates. The agent blocks cross-linking sites and therefore prevents a network from being formed (Hättich, 1999).

Release oils soften the coating and delay the setting of the coating. Therefore the release oil has a great influence on the uniformity of the sheet attachment of the paper web to the Yankee cylinder (Stitt, 2002).

In the industry, representing suppliers of chemicals, one thought is that release oil migrates from the Yankee cylinder surface to the surface of the coating, facing the air (Hättich, 1999). The release oil thus has a concentration gradient within the coating layer. The coating layer closest to the cylinder surface is very hard and consists of a completely cured adhesive. The middle layer has emulsified oil that softens the adhesive and the layer on the outside is mainly oil that lubricates the blade.

2.4 Measuring devices

The following ideas have been tested in this work in a laboratory environment to provide the basis for the future development of on-line measurement methods.

2.4.1 Optical fibres

An optical fibre is a glass or plastic fibre that carries light along its length by internal reflection and can also be used as a part of a sensor system. By illuminating the creped paper web at various angles and collecting the reflected light, also at various angles, the crepe wavelength or frequency can be measured.

2.4.2 Fluorescence

Luminescence is the emission of light from electronically excited species, where fluorescence is a particular case, see Figure 11 (Valeur 2002; Lakowicz 2006). When a molecule absorbs a photon, the molecule is brought to an electronically excited state. It returns to the ground state with the emission of a photon. The lifetime of the excited state for fluorescence is 10^{-10} - 10^{-7} s (Valeur, 2002).

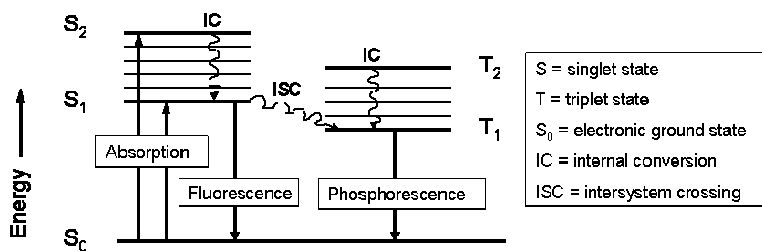


Figure 11. Jablonski diagram, showing a few processes for the molecule to return to the ground state (Valeur, 2002).

If a substance showing fluorescence is introduced into the coating chemical composition, the intensity of fluorescence can be used as a measure of the amount of coating chemicals present on the cylinder surface at any moment.

3 Experimental

3.1 Materials and Methods

3.1.1 Pilot tissue machine and laboratory dryer

Paper I

The tissue machine used in the trial in which the chemical and morphological properties of the coating were studied was a pilot dry crepe tissue machine in a C-Former configuration at Metso Paper in Karlstad (Sweden). The Yankee cylinder was heated up the day before the trial and the old coating layer was removed with sandpaper. The machine was run with a Yankee speed of 1000 m/min and the machine settings were for toilet tissue with a grammage of 18 g/m².

Paper II

The cylinder used to represent the Yankee cylinder was a drying cylinder on a laboratory scale with a diameter of 80 cm and a width of 70 cm. The cylinder was heated to 100°C - 102°C and rotated at a speed of 0.18 m/s.

3.1.2 Pulp

Paper I

The pulp used in this study was Södra Black R a bleached softwood Kraft pulp, supplied by Södra Cell. The fibres in this pulp are strong, slender and shorter than 2 mm. The pulp was refined in a conical refiner, Conflo JC-01 Valmet with MX filling, at Metso Paper with a power of 20 kW/ton.

Paper III

Paper from the trials described in Paper I was used in laboratory studies in which attempts were made to measure the crepe wavelength or frequency using an instrument incorporating optical fibres.

3.1.3 Coating chemicals

Paper I

The coating chemicals used in the trial on the pilot machine were an adhesive called Ekasoft B15 and a release agent called Ekasoft R95. The former is a standard PAAE (polyamidoamine-epichlorohydrin) adhesive and the latter is a mineral-oil-based release agent. The total flow of the diluted coating chemicals was about 4.8 L/min and the flow of the coating chemicals was 118 ml/min.

Paper II

The chemicals used were the adhesive Ekasoft B15 and the optical brightener Blankophor Flüssig 01. The brightener absorbs light between 330-370 nm and fluoresces at 420-470 nm. The coating was sprayed with an air-driven commercial spray nozzle made for spraying paint. The optical brightener was used in three different concentrations, 0.1 g, 0.5 g and 1.0 g, mixed in 500 g distilled water with 13.25 g Ekasoft B15. The dry brightener content was thus 1.7 %, 9.96 % and 14.8 % of the dry coating chemicals sprayed onto the cylinder. The chemicals were mixed just before the trials and were sprayed onto the cylinder in two, four, six and eight layers, each layer consisting of approximately 7.1 g coating/m².

3.1.4 System for making replicas

Paper I

The RepliSet-Gt1 system from Struers was used to make replicas of the Yankee cylinder surface. Based on a fast curing, two-part silicone rubber with good release ability, it was applied to the surface with a dispensing gun. The cartridges contain both polymer and curing agent. These were mixed automatically in a static mixing nozzle during application onto a release paper which was then pressed against the cylinder for a few minutes to allow the silicone to cure. The replicas were then evaluated in a Scanning Electron Microscope (SEM). For more information, see Paper 1.

3.1.5 Scanning Electron Microscope

Paper I

Images of the replicas were taken using a Hitachi low vacuum SEM S3000N in a high vacuum position. The replicas from the pilot trial were studied by SEM without any further treatment. The replica from the commercially operated tissue machine was sputtered with as a different SEM instrument was used.

3.1.6 Sampling of the coating

Paper I

Three samples were collected at each trial point: a paper sample, a coating sample at the cleaning doctor and a coating sample between the cleaning doctor and the spray boom. The coating scrapings were taken from different layers on the cylinder while the machine was in operation.

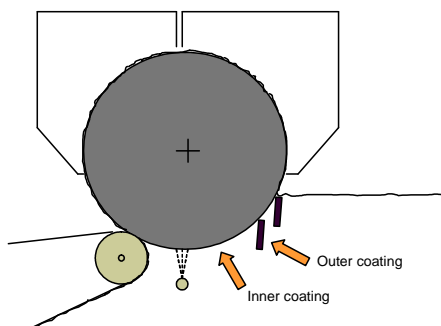


Figure 12. The Yankee cylinder with the sampling positions.

The samples were taken at five different dosages of spray chemicals. The ratio of adhesive to release chemicals was: 1:5, 2:4, 3:3, 4:2 and 5:1. The paper and coating samples were collected 30 minutes after the new coating composition was changed.

3.1.7 Chemical analysis

Paper I

Carbohydrate and nitrogen were determined on the samples of coating taken from the pilot tissue machine and on the paper. The samples were sent to three different laboratories outside the university where the analyses were performed.

The carbohydrate analyses were performed using ion chromatography or gas chromatography on samples that were hydrolyzed in sulphuric acid. To determine the carbohydrate content, Laboratory 1 used the Tappi standard T249, which involves gas/liquid chromatography using alditol formation, Laboratory 2 used HPAEC-PAD (High Performance Anion-Exchange Chromatography with Pulsed Amperometric Detection) after hydrolysis in sulphuric acid, and Laboratory 3 also used ion chromatography with pulsed amperometric detection.

The nitrogen content of the tissue samples was determined by chemiluminescence using a COSA TN1 110 nitrogen analyzer. The nitrogen content was, however, much higher in the coating scrapings so, to improve the accuracy, the Dumas method was used on these samples and a Thermo Flash EA1112 combustion analyzer was employed.

3.1.8 Paper characterisation

Paper I

The surface softness of the tissue paper produced was determined using the surface tester developed by Hollmark (Hollmark and Bolam, 1976; Hollmark, 1983).

The structure of the paper was also analyzed in OptiTopo (Hansson and Johansson, 1999). This is a photometric stereo method for determining the topography of a paper surface where the paper is illuminated from both the left-hand and the right-hand side. Two images are evaluated with a CCD (Charged Coupled Device) camera. The spatial intensity of the reflected light is used to calculate a partial derivate which is integrated to give the surface height. The mean standard deviation of the surface height at different wavelength intervals is then calculated. The surface height differences are indicative of the crepe structure.

3.1.9 UV-LED

Paper II

The equipment for measuring the fluorescence of the coating on a dryer consisted of an UV-LED (boxed into the measuring head) and electronics to emit light pulses, a measuring amplifier and software to log the signal, as shown in Figure 13.

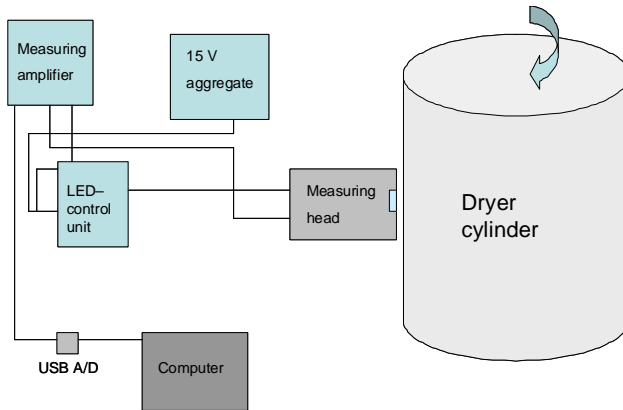


Figure 13. The units composing the fluorescence measurement equipment. The measurement equipment was placed on a table with the measuring head 1.5-2.0 cm from the middle of the cylinder.

The drive electronics for the UV-LED, which was fed by a 15 V direct current, was triggered by the measuring amplifier operating at 220 V. Short light pulses were emitted, synchronous with the reading of the measured signal. The measuring head consisted of a metal box with holes for cables, a connection for industrial air and a window, as shown in Figure 14. In the measuring window, the diode was situated next to a lens that collected the light into a cable that led to the amplifier. The diode emitted ultraviolet radiation at a wavelength of 370 nm.

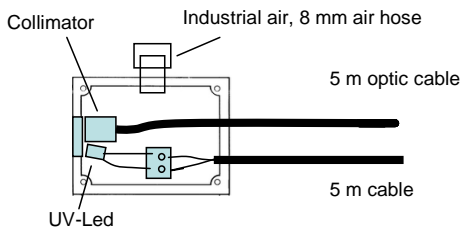


Figure 14. Diagram of the UV-LED captured in its protective box.

The radiation passed through the window and was incident on the brightener in the coating on the cylinder. The particles in the brightener emitted light that passed only through the window but also through another window made of polycarbonate, which absorbs UV-radiation, so that only the visible light generated by the fluorescence was collected and transported via the optical cable. (The box can be pressurized with industrial air to prevent moisture and dust from covering the lens in an industrial situation.) The signal was led to the amplifier and

measurements were made alternately on illuminated non-illuminated objects and the difference between them was recorded, in order to eliminate background light and noise. The outgoing signal was low-pass filtered to obtain a limiting frequency of about 1 Hz. The signal was then converted in an AC/DC converter, an NI USB 6009 from National Instruments, and fed into a computer. The log programme used was a Labview-application that logged the signal to a log file on the computer. The signal was measured at a high frequency. One measuring point is the average of about 1000 data points measured during one second (Granlöf, 2008).

3.1.10 Determination of crepe wavelength

Paper III

The paper was illuminated with a light beam from the optical fibre onto the paper surface. Measurements were made with and without lenses. The measured signal should vary with paper structure when the paper is running by the sensor. The diameter of the beam was a smaller than the expected crepe wavelength of the paper. Figure 15 shows the typical appearance of the structure of the paper.

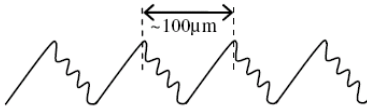


Figure 15. The crepe structure of the tissue paper.

Figure 16 shows this equipment. The paper was drawn under the sensor head with the help of two metal bars under the paper which were moved with an engine translator at a maximum speed of 0.5 mm/s, which is much slower than a commercial tissue machine which runs at about 30 m/s. The task of the circulator was to lead the light from the light source to the sensor head and any signals from the sensor further to the detector. After the detector, the signal went via an oscilloscope to a computer. The light source used was a broad band Light-Emitting Diode (LED) with a central wavelength of 1300 nm and a band width of about 40 nm.

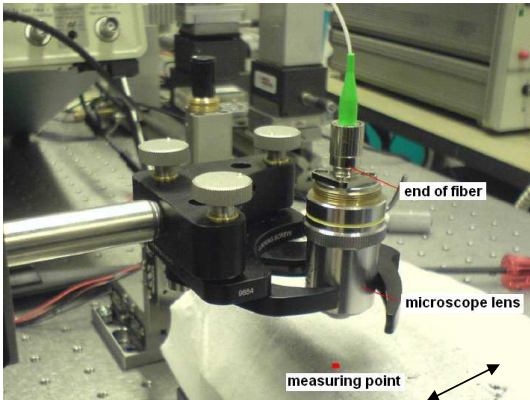


Figure 16. Photograph of the sensor head with the tissue paper moving in the direction of the arrow.

The measurements were made at an angle to the paper web, Figure 17. The paper was moved at a speed of 0.5 mm/s (0.03 m/min) past the measuring equipment. Light from a super luminescent diode with a central wavelength of 1550 nm and a bandwidth of about 40 nm was led through an optical fibre to a lens that focused the light on the paper. The sensor was placed directly at the lens instead of collecting the light through a second optical fibre.

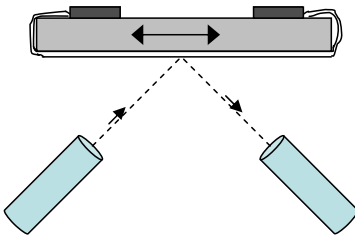


Figure 17. Set up for the angle measurements of the surface structure. The paper was attached to a metal plate by magnets. The plate can be moved in a horizontal direction while the measurements are made by the measuring device to the right.

4 Results and Discussion

4.1 Paper I

- Chemical and Morphological Analyses of the Tissue Yankee Coating

In this study, the coating remains taken from a Yankee cylinder were analyzed chemically and morphologically. The ratio of adhesive to release agent was varied as shown in Table 1.

Table 1. Composition of the coating sprayed on at the trial points.

Trial	Adhesive	Release agent
1	3	3
2	4	2
3	5	1
4	2	4
5	1	5
1:2	3	3

The carbohydrate content and nitrogen content were determined. Nitrogen is a constituent in the spray adhesive used and is therefore of high interest. Replicas of the surface were made when the machine was standing still at trial points 5 and 1:2 and these were studied by SEM.

The carbohydrate values were very sensitive to the sample preparation and analysis procedure and differed a lot between the three laboratories conducting the analyses. Figure 18 shows the result from one of the Laboratories. The left-hand column shows the total amount of carbohydrate, and the other columns show the proportions of the different sugars. The total carbohydrate content was higher in the paper than in the coating samples. Due to the large differences in the carbohydrate content obtained by the different laboratories, the only conclusion that can be drawn is that the coating layers contain almost as much carbohydrate as the paper produced.

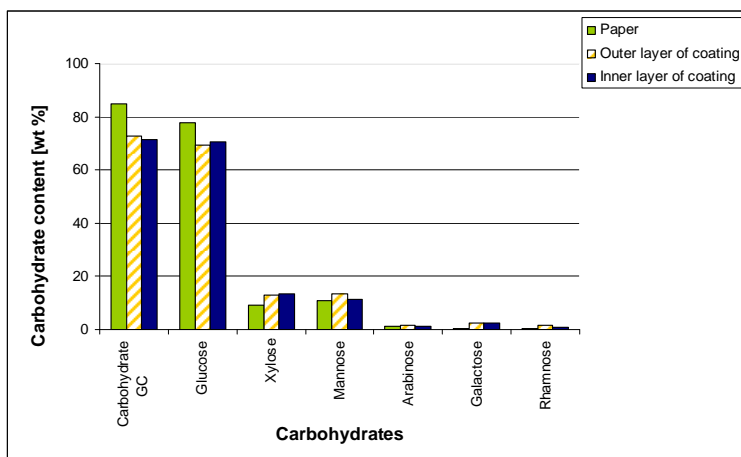


Figure 18. Total carbohydrate content and content of different sugar elements in the paper, in the coating at the cleaning doctor and in the coating after the cleaning doctor.

The nitrogen content increased with increasing amount of applied adhesive. The nitrogen content was higher in the samples taken after the cleaning doctor (the inner layer of the coating) than in the samples collected at the cleaning doctor (the outer layer of the coating) see Figure 19. More adhesive seemed therefore to be present close to the Yankee surface and only a small amount of adhesive was transferred to the paper.

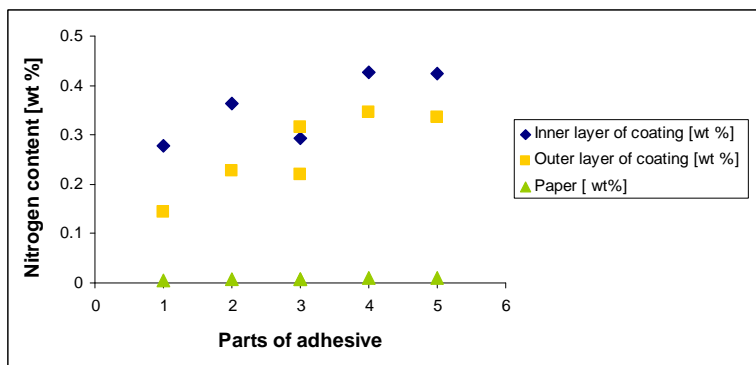


Figure 19. Nitrogen content as function of amount of adhesive applied to the cylinder.

The reason why more adhesive was present in the inner coating layer is presumably related to the cross-linking tendency of the adhesive material, which results in a

cured inner layer, related to the temperature and moisture gradient present in the coating layer. The outer layer of the coating is subject to a cooling effect and a moisturizing effect as the wet web comes into contact with the Yankee surface. Since the doctor blade acts only on the outer layer of the coating, the adhesive should be more cured in the inner layer.

The Yankee coating was patchy with thicker coating layers. After outer layers has been scraped off by the doctor blade, the residual coating contained blade streaks and also contained fibre fragments, Figure 20.

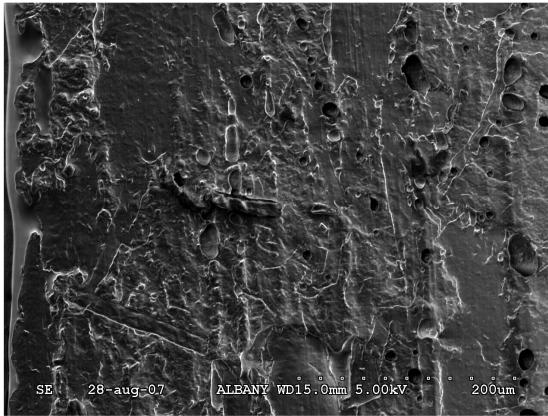


Figure 20. SEM image of a replica of the Yankee cylinder surface. Fibre segments embedded in the coating layer can be seen on both the left-hand and right-hand sides of the picture. The fibre segment in the centre of the picture is probably a loose fibre on the surface of the cylinder, which was transferred to the replica.

4.2 Paper II

– A Method of Measuring the Thickness of the Coating on a Dryer Cylinder

In this project, an optical method of measuring the coating thickness based on fluorescence measurements was tested on a laboratory scale. An optical brightener was mixed in the coating sprayed onto a metal cylinder and an UV-LED was used to provide ultra violet radiation and to collect the light emitted due to fluorescence.

No significant difference in signal strength could be seen with different amounts of brightener and coating layers, Figure 21. The value for no coating was higher than the values with a coating and the variation was large.

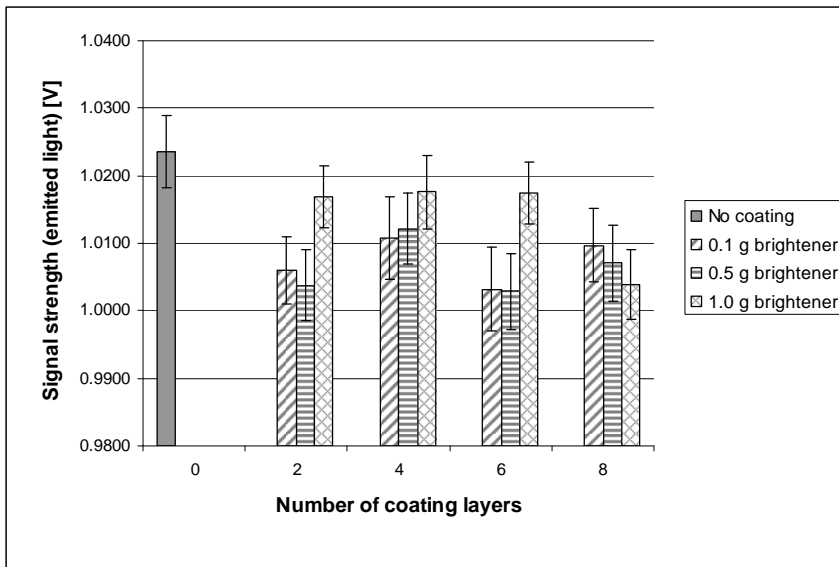


Figure 21. The amount of light emitted due to fluorescence (voltage) for different numbers of coating layers with error bars showing 95% confidence interval.

The results are also given with error bars showing the 95% confidence interval. The average and confidence intervals were calculated after outliers has been removed using a method that employs the quartiles and the differences between the quartiles (Scheaffer and McClare, 1995). The uncertainties are in fact very small, but they overlap each other and there is no significant difference between the points.

One reason for the lack of difference between the points could equipment malfunction, i.e. that the equipment did not respond to the fluorescent substance in the coating. Possible equipment malfunction was therefore tested by comparing two pieces of paper, one fluorescent and one non-fluorescent, that the UV-LED did in fact emit UV radiation. The dryer cylinder used had a more glossy surface than a normal Yankee dryer so, in order to determine whether or not this affected the measuring device, tests were made using a mirror and piece of black fabric. Figure 22 shows the average values obtained for the different surfaces, with error bars showing a 95% confidence interval. The bars for the standard and fluorescent papers differ greatly, suggesting that the equipment is able to detect fluorescence. The difference between the mirror and black fabric was very small. The fact that the response from the mirror was slightly higher than that from the black fabric should not affect the results of the trials using different amounts of brightener and numbers of coating layers.

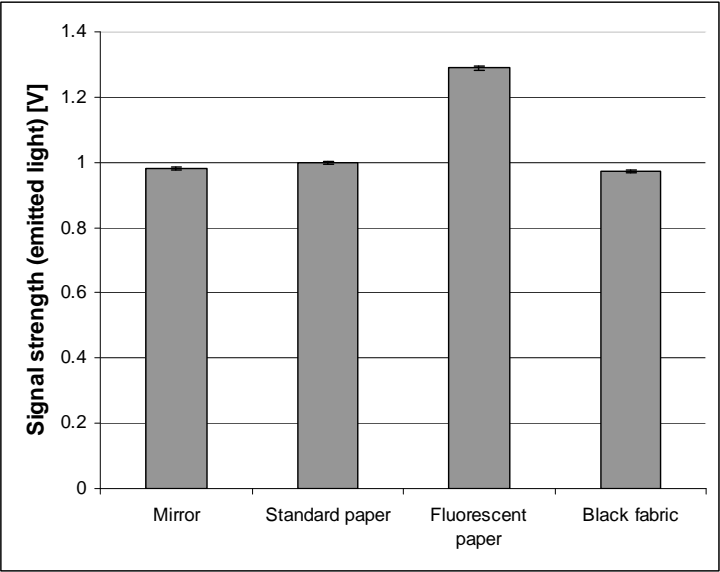


Figure 22. Measurements on different materials with the UV-device.

This technique with fluorescence in the coating requires further development.

4.3 Paper III

- Experiments to find Online Measurements of the Structure of the Tissue Paper Surface

In this project, a simple optical method was used to measure the surface structure of a paper web while the paper was moving. The goal was to obtain a clear signal from the crepe structure to provide a foundation for a future on-line method. The trials were made in cooperation with Acreo AB.

Figure 23 shows data from measurements with a focused beam and without any focusing lens. Raw data have been Fourier transformed to identify the periodicity in the signal (Petermann, April 2008).

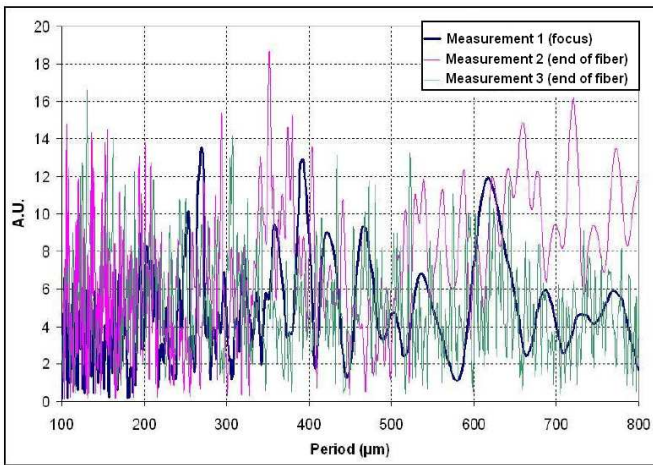


Figure 23. Measurements with a focused light beam and measurements without a focusing lens. The results are shown in Arbitrary Unit (A.U.) based on a voltage measurement.

No clear crepe periodicity was identified. There were a lot of disturbances in the data and no clear period could be extracted. The disturbances in the signal were probably due to information from within the paper confused with that from the crepe structure on the outside of the paper.

Figure 24 shows the result of the trial in which measurements were made as a function of time with a focusing lens at different angles to the paper web. The angles used were 10° and 40° . At 40° measurements were also made when the paper was stationary as a reference, to assess the noise.

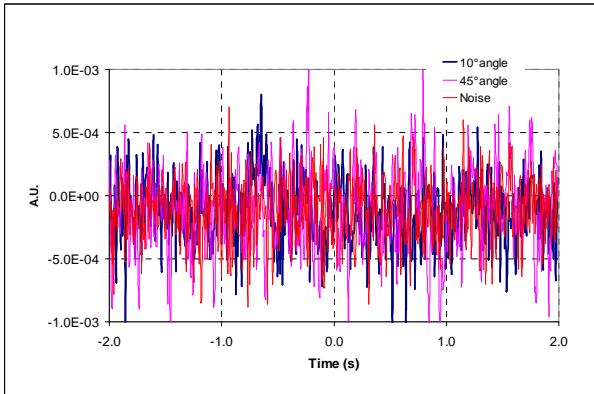


Figure 24. The signal from the paper sample at two different angles and one measurement when the paper web was stationary. The Arbitrary Unit (A.U.) is here a measurement of the voltage.

Figure 25 shows the Fourier transform of the measuring data from Figure 24. With a creeping period of about $100\ \mu\text{m}$, a peak would be expected at about 5 Hz in the Fourier transformed diagram (Petermann, September 2008). The peak around 5 Hz is not constant with time and is therefore just noise. The reference with the stationary paper gives about the same structure as the moving paper. This is due to light scattered within the paper instead of merely being reflected at the surface of the paper.

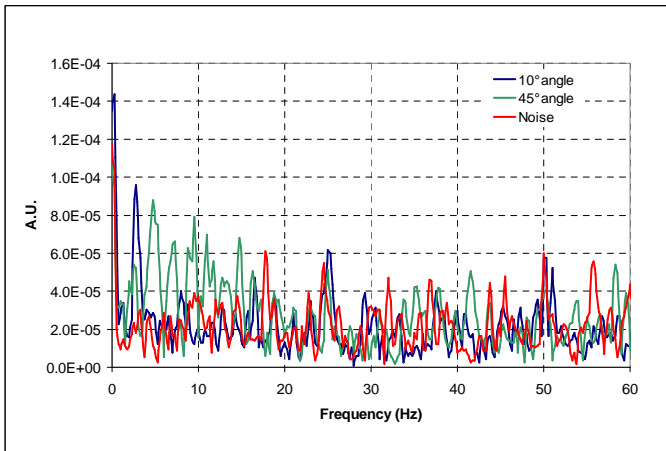


Figure 25. Fourier transform of the data in Figure 25.

5 Conclusions

The chemical compositions of the coating layer and of the tissue paper produced have been studied together with morphological investigations of the Yankee coating surface. Since the adhesive was a polyamidamine polymer, the nitrogen content in the samples was considered to be an indication of the amount of adhesive left in the coating. The nitrogen content was significantly higher in the samples of the inner coating layer than in these of the outer coating layer. This suggests a gradient in the coating layer, where more adhesive is present deeper in the coating. The nitrogen content also increased significantly with increasing amount of adhesive added in the spray composition. There was no obvious variation in the carbohydrate values when the ratio of adhesive to release agent in the spray was varied. The relative amount of polyamide-amine resin calculated on the basis of the nominal nitrogen content in the resin was low. The conclusion is therefore that the coating consists of a significant amount of carbohydrates and other substances.

The coating layer was patchy, and had imprints of fibres and fibre fragments embedded in the coating. The blade streaks in the coating show that only the higher layers of the patchy coating touch the blade.

Equipment intended for making on-line measurements of the coating thickness on a Yankee cylinder was studied on a laboratory scale. A fluorescent optical brightener was added to the coating chemicals and the intensity of the light emitted as a result of UV radiation was measured using UV-LED. UV radiation was emitted at a wavelength of 370 nm; the light emitted as a result of fluorescence was subsequently collected and sent to a detector. The signal from the trial was scattered and no correlation between the amount of brightener and the intensity of the emitted light could be detected. The technique requires further investigation before it can be used on a tissue machine for measuring the thickness of the coating that has accumulated on the drying cylinder. The optical brightener used in the coating must be better suited to the equipment and the amount of brightener added to the coating should also be examined.

Measurements of the crepe wavelength of the tissue paper have been made with a simple probe using an optical fibre at the surface of the paper. The probe has been used alone, with a focusing lens perpendicular to and at an angle to the paper and also with collimated light. The tests showed that the signal was not sufficiently distinct to enable the structure of the paper to be measured. IR-radiation penetrates into the paper structure and the light collected and led to the detector

came from all the layers in the paper, both with measurements made perpendicular and at angle to the paper surface, and not just from the surface that was sought.

The easiest way to continue experiments to find a technique for measuring the crepe wavelength would perhaps be to conduct an optical Fourier transform. The paper could be illuminated with a laser and the diffraction picture could be collected by a video camera after transmission through the paper.

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Improvement of the tissue manufacturing process

The creping process and the conditions on the Yankee cylinder are the key factors in the production process. They need to be kept under good control in order to maintain a high and uniform quality. A natural coating always develops on the surface of the Yankee cylinder due to evaporation from dissolved and dispersed substances and to fiber fragments that remain on the surface after creping. Nevertheless, coating chemicals are sprayed onto the Yankee surface in order to modify the adhesion between the paper and the dryer cylinder. To be able to control the process, on-line measurements of coating thickness as well as of the crepe structure of the tissue paper produced would be very valuable.

In the work described in this thesis, the coating layer was analyzed chemically and morphologically to provide information about the coating layer before starting any on-line measurements. The chemicals added and the constituents of the pulps are known to the paper producers, but what is left on the cylinder and whether there are different layers of coating still remain to be investigated. The chemical analysis indicated that the adhesive content was higher in an inner layer of the coating than in the outer layer. The relative amount of polyamide-amine resin calculated on the basis of the nominal nitrogen content in the resin was low indicating that the coating consisted of a significant amount of carbohydrates or other substances. The coating layer could not be considered transparent. It was observed that the coating was thick and appeared patch-wise and that it contained fiber fragments.

Measurements on a laboratory scale, to further be applied on-line on the tissue machine, have been investigated and evaluated in this study. The thickness of the coating layer on a laboratory dryer has been measured. The method was based on fluorescence with an optical brightener added to the coating chemicals sprayed on the Yankee dryer. With a UV-LED (Ultra Violet - Light Emitting Diode) the coating layer was exposed to UV-light and the intensity of the light emitted by the optical brightener in the layer was measured. The intensity in the trials with different thickness of the coating and no coating was scattered and no trend could be seen between the different trial points.

Attempts were made to measure the wavelength of the tissue paper produced with an optical fiber perpendicular to and at an angle to the paper surface. The paper was travelling in a slow speed while the measurements were made. The collected signal to noise ratio was low and it was not possible to detect any representative characteristic wavelength of the tissue.