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Cut Quality of WFC Paper

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Effect of the Machinery and the Coated Paper Properties

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Contents:

List of used symbols and abbreviations:

WFC: *Wood Free Coated*

SC: *Super Calendered*

LWC: *Light Weight Coated*

UWF: *Uncoated Wood Free*

MD: *Machine Direction (of the paper machine) parallel to the main fibre direction*

CD: *Cross Direction (of the paper machine) perpendicular to the main fibre direction*

LC: *Long Cut (cut performed parallel to the main fibre direction)*

CC: *Cross Cut (cut performed perpendicular to the main fibre direction)*

FTIR: *Fourier Transform InfraRed spectroscopy*

DCM: *Di-Chloromethane*

DSF: *Dynamic Sheet Former*

α_p: *Primary grind angle of a cutting blade in °*

α_s: *Secondary grind angle of a cutting blade in °*

r: *Chord length at the slitter in mm*

δ: *Cutting angle in °*

F: *Cutting force in Newton*

τ: *Shear stress in Pa*

τ_0: *Specific Shear stress in Pa*

S: *Transversal cutting section or main shear plane in mm²*

S_c: *Transversal cutting section or main shear plane in mm² as a function of the clearance*

S_0: *Transversal cutting section or main shear plane in mm² with null clearance*

l: *Thickness of a defined material*

c: *Clearance in mm*

Δl: *Deformation*

γ: *Shear strain (dimensionless quantity)*

ϑ: *Poisson's ratio*

ε_{trans}: *Transverse contraction strain*

$\varepsilon_{longitudinal}$: *Longitudinal extension strain*

G: *Shear modulus in Pa*

n: *Number of webs being cut simultaneously*

e: *Paper thickness of a sheet in µm*

E: *Young's (elastic) modulus in Pa*

w: *Material width in mm*

F_{max}: *Maximal cutting force required to cut a certain amount of paper in N*

Sl_1: *Slope of the cutting curve at the beginning of the measurement*

Sl_2: *Slope of the cutting curve at the end of the measurement*

W_E: *Energy used to reach the plateau of the measurement obtained with the laboratory cutting test (constant process, $F=F_{max}$)*

W_P: *Energy used to cut the full paper width*

W_S: *Energy used to finish the cutting process*

W_T: *Total energy used to cut the sample*

S_X: *Transversal cutting section during the phase x=2, 3 and 4*

F_x: *Maximal cutting force during the phase x=2, 3 and 4*

y_t: *Position of the knife on the y-axis at the instant t*

z_t: *Position of the knife on the z-axis at the instant t*

a: *Semi major axis of the ellipse representing the fibre distribution in a system formed by MD and CD axis*

b: *Semi minor axis of the ellipse representing the fibre distribution in a system formed by MD and CD axis*

θ: *Angle between the knife and the cross direction (fibre orientation) in °*

$P_{L\theta}$: *Weighted Intercepts probability as a function of θ*

x_1: *Position of the upper shear blade centre on the x-axis*

y_1: *Position of the upper shear blade centre on the y-axis*

R_1: *Radius of the upper shear blade in cm*

x_2: *Position of the bottom knife ring centre on the x-axis*

y_2: *Position of the bottom knife ring centre on the y-axis*

R_2: *Radius of the bottom knife ring in cm*

O_d: *Overlap between the two blades*

D: *Distance between the two blades centres*

P: *First contact point between the upper shear blade and the bottom knife ring when looking in the running direction*

Q: *Last contact point between the upper shear blade and the lower knife ring when looking in the running direction*

φ_u: *Angle between the tangent at the upper shear blade in P and the x-axis in °*

φ_b: *Angle between the tangent at the bottom knife ring in P and the x-axis in °*

$|\overrightarrow{S_{ring}}|$: *Magnitude of the initial speed vector*

$|\overrightarrow{S_{upp}}|$: *Magnitude of the speed vector transmitted to the upper shear blade*

$|\overrightarrow{R_{fric}}|$: *Magnitude of the friction forces transmitted to the upper shear blade*

β: *Angle between the knife and the web running direction on the rotary cross device in °*

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Dusting and blanket pollution are of particular interest in offset printing. Papers must be free of dust and loose particles which can reduce drastically the wash interval of the blankets and lead to insufficient print quality. Dust and weakly bound particles are mainly generated during converting operations such as sheeting. Looking at the evolution of the industry, papermakers increasing their productivity by cutting more and more sheets simultaneously and the printers running their machines faster to reduce costs, cut quality has become more and more important over the last years.

For wood free coated papers which present the particularity to have up to three coating layers per side and which are mainly printed with offset process, the cut quality is therefore of high importance. However, most of the studies so far focussed on board or uncoated papers and there is actually no official test method to qualify or to quantify the cut quality of such papers.

To study in detail the influence of the sheeting parameters and paper properties on cut quality, a new test method to quantify the cut quality of wood free coated papers has been developed. In particular, this method takes into consideration the state of the coating layers near the cutting edges which has been found to be an important parameter. A laboratory cutting device was developed to study the effects of various paper properties, such as basis weight, bulk and fibre orientation on cutting forces. Finally, several tests series were performed on commercial sheeters to evaluate the impact of the different process parameters on the cut quality using the test methods developed during this work.

Based on the analysis of the experiments, training materials or even tools to adjust the settings of the sheeters were developed to be used within the mill. All these measures led to a reduction of complaints due to cut quality issues of more than 75% during this project.

This work highlights the importance of the state of the coating layers near the cutting edges and also the main mechanisms which could be linked to the generation of coating cracks. It was seen during this thesis that the paper itself plays a non-negligible role regarding the cut quality obtained. Further research should focus on the composition of the base paper and the coating layers to limit to some extent the generation of those coating cracks.

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Chapter 1

Introduction

In this chapter, the motivation to analyse the cut quality of wood free coated papers as well as the background, the aims and the outline of this thesis are presented

1.1. Cut quality of wood free coated papers

Mainly due to their production process, most materials produced in the world will have to be cut sometimes during their production process. Depending on the material properties, the technique used and the desired product quality, this cutting operation may turn out to be more or less easy. Wood free coated (WFC) papers are produced mainly from chemical pulp and the formed paper is surface coated. For these WFC papers, the cut quality is of outmost importance for several reasons. First of all, most of these papers are commercially printed on sheet fed offset printing presses. In this process, an insufficient cut quality can create runnability problems at the feeding table and a contamination of the blankets leading to loss in production time as the printer has to stop the printing press in order to wash the blankets. The particles accumulating on the surface of the printing blankets can be greater than the millimetre size scale. Running the printing press with such an accumulation of contaminant debris will mark the blankets and make any subsequent print work impossible. Moreover, the cutting dust located nearby the edges can disturb the print quality. A significant amount of WFC papers are used to print high quality magazines displaying luxury items. The visual aspects of the paper and the quality of the edge cut or trim are also important for the paper customers who want to transmit a quality image of their brand or company.

1.2. Influential parameters and background

Over the last decades, the speed of paper machines, printing machines and converting machines have continuously increased and end customers request a high quality product at a lower price. In order to meet these conflicting demands and to stay competitive, paper producers are continuously optimizing the paper composition. More and more pigments and fillers are used instead of fibres. Moreover, coating colour formulations are continuously developed to enhance the final paper properties. This can have an impact on the coated paper properties and mainly on the behaviour of the coated paper during converting and printing. At the same time, the drive for higher productivity at the sheeters has resulted in cutting wider webs at higher speed. Another means of improving productivity is to increase the number of webs cut simultaneously. Nowadays, it is customary to cut several paper webs up to a combined basis weight of 1000 g/m² of paper at once.

A negative consequence of the evolution towards greater productivity has been that cut quality related problems appear to be more and more a significant issue, either at the converting centre (during sheeting) by generation of cutting dust and poor cut quality or at the printer due to the contamination of the blankets. In addition to the development of paper production technology there have also been new developments and new types of printing presses appearing on the market. These novel printing presses now combine several processes such as cutting and printing in one operation to further reduce cost and increase productivity in a competitive market. One such example is the CutStar system from Heidelberg [1]. Cut quality has been the subject to some research in the 70's, mainly regarding the production of board and uncoated papers. However, due to its low importance in the past, cut quality has never really been controlled and monitored meticulously at the production site. This resulted in an uncontrolled process that was not measured and recorded to give a stable and quantified quality.

For all the reasons mentioned before and due to an increase in complaints pertaining to cut quality, Sappi Fine Paper Europe decided in May 2009 to launch a project focussing on this topic. The main objectives were to develop a test method to evaluate the cut quality of wood free coated papers, to study the influence of the machinery parameters and the influence of the coated paper properties on the shear cutting process. A further target was to study the impact of a poor cut quality on the performance in the printing machine.

1.3. Aim of this study

This investigation aims at helping the papermaker to better understand the influential parameters of his process on cut quality and to give him some tools to improve the cut quality either by changing the properties of the materials to be cut and/or the settings of the cutting machinery. The focus is on the shear cutting process of wood free coated papers and the high productivity has to be maintained.

Due to the absence of an official standard test method for wood free coated paper, it is intended to develop both qualitative and quantitative test methods to describe the cut quality of such papers. The developed test methods should help to identify the influential parameters on the cutting and printing process. Studying the cutting process on an industrial scale and trying to find the influence of the paper parameters is a complex problem due to the multitude of parameters influencing the cut quality (see **Appendix A**). Starting with a literature review, the best approaches to meet the needs of industry in terms of cut quality are identified. In order to assess the influence of paper parameters on a laboratory scale, a cutting device was also developed in the framework of this thesis. This device is used to simulate the cutting process and to undertake a parametric study of main paper parameters. In addition, the key parameters of sheeters and their influences on the cut quality are studied in detail on industrial cutting machines. Based on this information and numerous practical tests, some ideas and way to set up the sheeters should be identified.

1.4. Thesis outline

After this introduction a short presentation about paper and paper making is made. The current technologies in converting and cutting of paper are briefly reviewed.

In the second chapter, the methods developed in the course of this thesis to evaluate the cut quality of wood free coated papers are presented.

The theory of the shear cutting mechanism is presented in the third chapter. Experimental data from the laboratory cutting device to show the influence of paper properties on the cutting process are discussed and analyses of commercial sheeter settings and their influence on cut quality are presented.

The drawing of the most important conclusions and an outlook regarding future works is presented in the last chapter.

Chapter 2

Paper and cutting technologies

In this chapter, a brief overview of the paper making process and the different converting operations is made.

2.1. Paper

The word paper comes from the Latin *papyrus* [2] which is the plant used by the ancient Egyptians to make paper. First traces of paper were recorded more than 2000 years ago and its oldest record was discovered on the 9 August 2006 in China [3]. Although in the last decade we have seen the emergence of several new media and technologies, paper still remains as one of the most widely used materials for communication. Its demise has often been announced and forecasted but so far this has proved to be wrong and paper is still being used for printing and as a medium for communication. The speculations regarding the demise of commercial paper printing and converting started with the apparition of TV and were followed by the development of internet. More recently, the same predictions were made with the launch of the e-book (kindle…) and even more recently when the I-pad was introduced on the market. But up to now, the overall consumption of is still growing. Depending on the applications, the production of some paper grades tend to decrease, for example newsprint, but some other paper types such as packaging are still growing. In 2009, over 100 million tons of printing and writing papers were produced worldwide. Considering the worldwide pulp and paper production, more than 370 million tons are produced annually [4]. Across the years, people have realized the usefulness of this material and mainly due to technical advancements in society, the number of application fields where this material is used is numerous: automotive, filtering or health industries are a few examples of use. Many types of papers exist and an extensive list can be found [5].

One way to divide the paper grades is based on their usage and specifications:

- ***Graphic papers*:** newsprint, SC, LWC, WFC, UWF…
- ***Packaging papers*:** corrugated medium, test liner, fluting/Kraft liner, sack paper…
- ***Boards***: folding box board, liquid packaging board, grey board…
- ***Specialty papers*:** cigarette, décor, thermo, filtering, security papers…
- ***Tissue papers:*** toilet paper, hygienic paper…

Each day, new applications for paper materials are being tested and developed. This type of research is mainly driven by the ecological challenges of the 21st century. Indeed paper materials are made from renewable sources contrary to all products made from petrol. Besides that, the development of new fibre based engineering materials (e.g. Nano fibrillated cellulose) during the last few years is leading towards new paper materials which are stronger and lighter with potential for new fields of application. Paper still has an important place in the hearts of people and we even see recent publication written by a journalist as a token of gratitude to this medium [6].

2.1.1. Composition

At the beginning, paper was only composed by fibres or fibre elements mainly coming from vegetal sources [7]. Cellulose fibres constitute the major raw material. Those are about 1 to

2.5 mm long and 20-40 µm wide and form a network where fines (shorter fibres of about 0.5 mm long and 2-10 µm wide) are dispersed. Cellulose fibres can have different origins such as straw, bagasse, wood, hemp or bamboo. Due to issues with productivity and yield, more and more eucalyptus fibres are used in paper industry. The main advantage of eucalyptus is the growing time of the plantation; it takes 7-9 years compared to 15-20 years for other species. Tropical wood species are normally not used for paper making but unfortunately some paper makers in developing countries are still using it. However, several organizations such as Greenpeace are actively denouncing such behaviour [8]. For sustainability and environmental reasons, most of the paper makers are managing their plantation in a sustainable way. For example in Europe, contrary to common thinking, the forest area is growing every year [9]. Finally, for some paper grades such as newspaper, 100% recycled fibres are becoming standard. Specialty papers can be composed with other materials such as synthetic fibres (non-woven). Used paper today is not considered as waste but as a valuable raw material suitable for recycling [10] and there is market trading based on its quality.

Due to economic reasons more and more fillers/pigments are used to fill the space within the fibre structure allowing to a certain extent a reduction of the amount of fibres. This has been pushed to such an extent that in some paper grades fibres are no longer the main constituent of the final paper product. Fillers can come from many sources but are in general mineral particles. Those can be spherical particles such as ground calcium carbonate (d_{50} ~ 0.5-1,5 µm) or platelets such as clay (0.5-10 µm long by 0,02-0,05 µm thick). Several other fillers are used such as titanium dioxide, talcum (magnesium silicate hydrated), satin white (artificial pigment prepared by the action of aluminium sulphate on hydrated lime [11]) to impart specific technical properties to the paper. Most of these mineral particles tend to be abrasive and can cause problems in papermaking since they reduce the lifetime of the wire/blade/felt in the wet section of the paper machine [12]. To ensure a good dispersion and retention of the pigment slurries and sufficient retention of fillers in the fibre network during the papermaking production, dispersants and/or retention aids are normally used. Their chemistry is constantly developing to improve productivity and reduce environmental impact of the papermaking process by allowing a closure of the water circuits. Research concerning paper composition nowadays centres around the reduction of fibre materials while keeping similar paper strength since fibres are so far, one of the most expensive materials in the base paper.

Depending on the purpose of the end product, papers can also be coated. In the coating process, thin layer(s) from few grams up to 15 g/m² of coating colour(s) are applied to the paper surface. The coating layer(s) will enhance some properties such as printability, visual and haptic aspects and resistance against other media such as water. The main components of the coating colour(s) are mineral pigments and synthetic or natural binders. Besides that, several other chemical additives (thickeners, brightening agents, dispersants…) are normally used to:

- *Facilitate the coating application by adjusting the viscosity at low and high shear rates,*
- *Increase the solid content of the coating formulation or the pigment slurry,*
- *Enhance the selected final properties.*

The number of coating layers depends on the paper grade to be produced and can reach seven layers per side for some photo papers. For wood free coated paper the number of coating layers usually varies between 1 and 3 per side.

To further improve the visual aspect of the paper which already depends on the coating recipes used (gloss, silk or matt), it can be calendered. This thesis will focus on double or triple coated papers with different surface finish (gloss, silk or matt).

2.1.2. Manufacture

The underlying technology of paper production has not really changed over the centuries even though the production has considerably evolved going from a hand-made to an industrial product. The basic principle still consists of removing the water from a fibre & filler suspension at low consistency. Until the 19th century paper was made manually. After the French revolution, it was necessary to speed up the fabrication of paper money and Louis Nicolas Robert, working for "*la papeterie de l'Essonne*" was the first to file a patent for a continuously producing paper machine in January 1799. The patent however was not protected well and the first paper machine was manufactured by the English Fourdrinier. This machine produced its first sheets in 1803 [6]. The term Fourdrinier refers to a paper machine that could make continuous paper roll and where the former is composed only with one single horizontal wire.

To improve the productivity paper machine suppliers have mainly concentrated their efforts on increasing the working width and the machine speed. Increasing the working width of a paper machine might appear at first to be an easy task but tremendous efforts and research have been required to ensure a similar quality over the full width. Nowadays, modern paper machines can reach working width of 11.8 meters (Hainan PM2, WFC) [13] and can exceed the speed of 2200 m/min (SCA PM2 tissue machine, 12/03/2010) [14].

To briefly summarize the paper making process, an aqueous suspension (consistency 0,5 - 1%) of fibres, pigments and chemicals additives is applied on a wire or between two wires by the help of a head box. After a first phase where part of the water is removed by filtration (in some machines this is enhanced by a vacuum system), the paper web enters a press section. In this part of the machine the water is removed by pressing the web in a series of nips (contact area formed by two cylinders touching each other). After the press section, the paper web with a dry content of 40 – 55% will enter the drying section. This section can reach a length of hundred meters and is composed of several steam heated cylinders. The remaining water in the paper is evaporated in order to reach the final paper moisture. After a pre-drying section surface sizing and coating operations can also be performed. A schematic representation of a paper making process is shown in **Appendix B**. Coating is applied to the paper either as an in-line process on the paper machine or off-line on a separate coating machine. The coating process consists of applying a coating layer on the paper surface followed by drying. This coating layer is applied to the paper using different technologies such as roll or free jet application. The surplus coating applied is metered to the desired coat weight with the help of a rod or a blade. During the last decades, curtain coating applications have been developed. Here a thin curtain of coating colour is created in a nozzle that falls on the paper surface. This technology allows using special pigments which are contact sensitive. Coated and uncoated papers are sometimes calendered. The calendering process consists of passing the paper web through one to several nips at controlled temperature, moisture, pressure and speed to give a desired surface finish in terms of smoothness and gloss.

2.2. Paper converting – cutting machinery

2.2.1. Introduction

Within a paper mill, the converting process has two main goals:

- Converting reels from 2,5 meters up to 12 meters in width into smaller reels of more suitable width for the customer or further internal converting steps
- Further converting reels into sheets.

Converting also allows the detection and removal of faults in the paper that were not previously removed. In the majority of mills paper is converted using two types of machines:

- Slitter-winders: *Converting the big jumbo reels into smaller easier to handle reels. These reels are sent directly to the customer (converter or printer) or to the sheeter.*
- Sheeters: Current cutting machine are able to handle simultaneously up to 10 reels with a diameter of max 2.4 meters. These reels are then transformed into sheets of the desired size.

Information mentioned in chapter 2 was partly collected from the educational material of Carolina Knife web site [15].

2.2.2. Winders / Slitter-winders:

The main role of winders is to convert wide continuous webs into cylindrical reels by wrapping the web around a core. During this operation, the initial width of the web can be adjusted and the initial roll can be split in several other reels (see **Figure 1**). Winders are used at different steps in the paper making process: at the end of the paper machine, at the end of the off-line coater and at the end of the calender. In the last case a combined slitting and winding operation is carried out since the mother reels from the paper machine are converted in small reels based on the requirement of the customer and also to optimize the production by minimizing trim waste later on at the sheeters. The continuous web from the mother reel is cut along the machine direction at different desired positions and the newly obtained webs are then wrapped around separate cores. Modern winders run at speeds of over 3000 m/min [16].

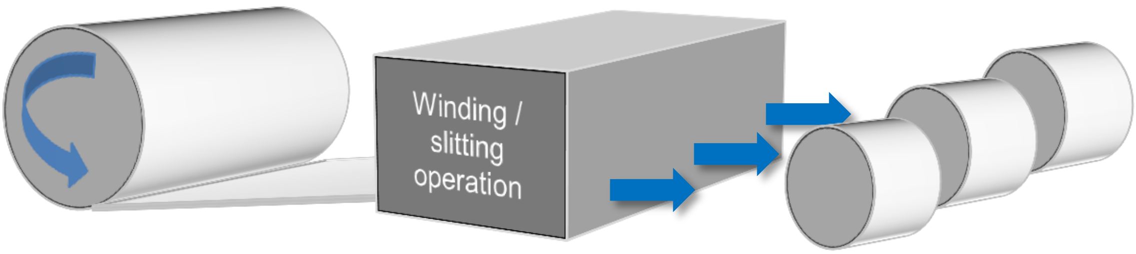


Figure 1: Schematic representation of slitting operation

2.2.3. Sheeter:

A sheeter is a machine converting rolls into sheets. It is composed of two cutting units. The first unit cuts in the grain direction of the paper. The second unit cuts in the cross direction, perpendicular to the main fibre direction. Finally, palletizing operations take place at the end of the sheeter (see **Figure 2**).

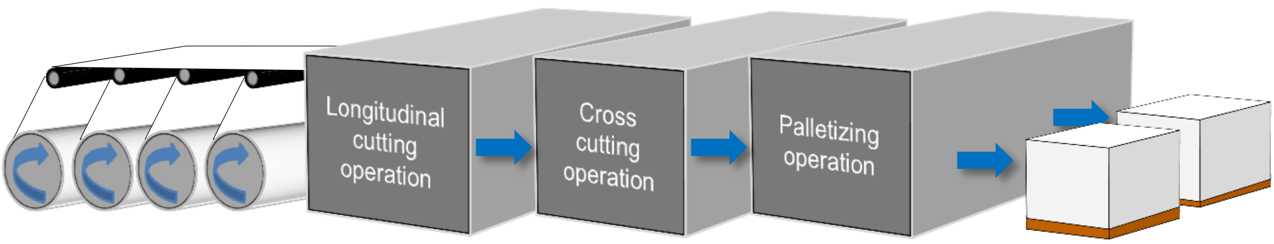


Figure 2: Schematic representation of sheeter operations

Modern sheeters reach speeds of up to 410 m/min. This maximum speed is mainly limited by the cross cutting section. To improve the productivity, some machines are equipped with two slitting units (twin slitter) and even with two rotary cross cutting units (duplex sheeter). A duplex sheeter offers the possibility of cutting two different sheet lengths at the same time, from the same incoming webs. Advantages and disadvantages of such technology are discussed by Ebel [17].

2.2.3.1. Longitudinal cutting system:

Longitudinal cutting systems have been the core subject of research for several years [18]. Schable is a popular speaker in Europe and North America where he regularly presents "*Bladerunners slitting seminars"*. Three major processes are currently used to cut a material in longitudinal direction: Razor cutting, crush cutting and shear slitting cutting (see **Figure 3**).

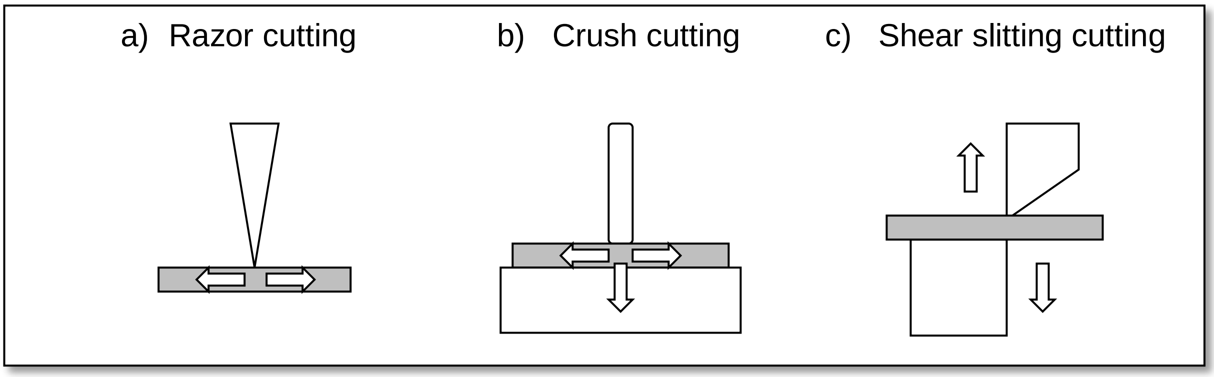


Figure 3: Representation of the main cutting mechanisms: razor, crush and shear cutting

Depending on the material being cut, these systems are more or less efficient. For example, materials such as aluminium sheets which possess a highly sensitive surface cannot be cut properly with a crush cutting system. A material with high elongation such as a non-woven will also not be cut properly with a shear cutting system. It is therefore important to define the most important factors of the cutting process related to the product to be cut in terms of cut quality and productivity. For example, crush cut systems are usually employed when speed of the set-up is more important than the quality of the slit edge. Finally, the abrasiveness of the material being cut is also important to consider because razor cut system are sensitive to this factor. Therefore, it is important to know, when selecting the best cutting system, the mechanical properties of the paper to be cut.

- Razor cutting system:

Razor cutting systems have been widely used in the past and are still employed in many mills. It consists of a razor blade which comes in contact with the paper web. This razor blade creates a tensile stress in the paper higher than its elastic and rupture limit. It is therefore a kind of slicing of the material. The main advantage of this system is its cost. Indeed the original equipment cost, the cost of the knives and the time required to change them make it very competitive compared to the other cutting systems. However, thick or/and abrasive materials cannot be cut with such system. Besides that, close tolerances cannot be guaranteed.

- Crush cutting system:

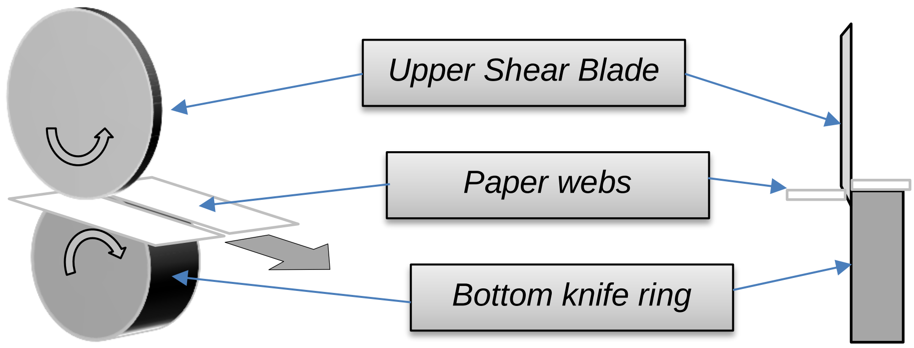
Crush cutting system is the oldest form of cutting technology. With this system, a compressive stress is imposed in the material that will be crushed. Due to this needed compressive stress, special knife geometries have to be used. Very sharp knives are not suitable for such cutting systems as they will be damaged and chip immediately. Hence, the knife used must be dulled depending on the back up material and the material to be cut. To ensure a proper cut, the knife, the paper material and the bed backup must be moving at the same speed. Due to the amount of dust created while compressing the fibre material, this method is nowadays not anymore acceptable for papers which afterwards are printed on high speed printing presses.

- Shear slitter cutting system:

Machines performing such action are usually called shear slitters or shear slitting machines. As mentioned by Schable: “Shear slitting, by definition is the vertical displacement of the material as it enters a shearing nip between two opposing edges” [19]. The opposing edges are usually two rotating disks. It is the first cutting action taking place at the sheeter. Two kinds of shear slitters are widely used:

- Standard slitter: Only the bottom knife ring is driven. The upper shear blade is rotating just due to the friction and contact with the bottom knife ring.
- Top slitter: Both knives are driven. Since it has a higher cutting force this technology has the advantage of allowing cut more paper simultaneously either by increasing the basis weight or the number of sheets. On the other hand, the adjustments of the knives and the control of their speeds are much more sensitive.

The upper rotating disk often called upper shear blade presents a primary grinding angle varying from 15° up to 60° (see **Appendix G**). The bottom rotating disk, often called bottom knife ring has a bigger angle close to 90°. A schematic representation of a standard slitter is shown in **Figure 4**.



a) Perspective view b) Front view

Figure 4: Schematic of a standard slitter unit from different points of view

2.2.3.2. Cross cutting system:

Cross cutters have been developed in order to cut the paper in the cross direction without stopping the paper webs. Originally, cross cutters were composed of one fixed knife and one rotating knife attached to a drum cylinder (see **Figure 5**).

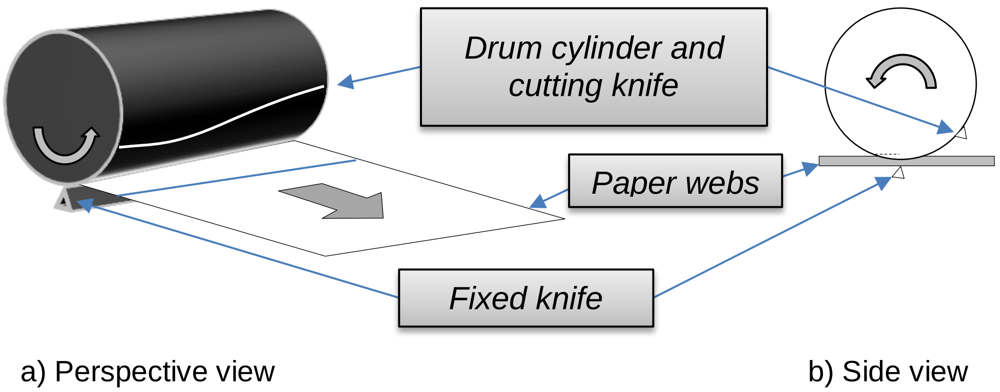


Figure 5: Schematic of a single rotary cross cutter from different points of view

The fixed knife presents an angle to the running direction of the paper webs to ensure that for a given machine speed, the resulting paper sheets present 4 orthogonal angles. To produce different formats, the drum has to run faster/slower and the position of the fixed knife needs to be adjusted accordingly. The main disadvantage of these machines is that the cut quality deteriorates when running out of the working window and with increasing web thickness. To improve cut quality, the single rotary synchronous cutter was developed. It results to an acceleration or deceleration of the drum when the paper webs are not cut, enlarging the working window of the sheeter and avoiding the repositioning of the fixed knife. However, some disadvantages such as the cut quality deterioration due to web thickness still remained. A drawback of these systems is they still force the converter to reduce the speed at long and short cut off lengths. Finally, the double rotary synchronous cutter appeared on the market. With this system, both knives are built on two rotating cylinders (see **Figure 6**).

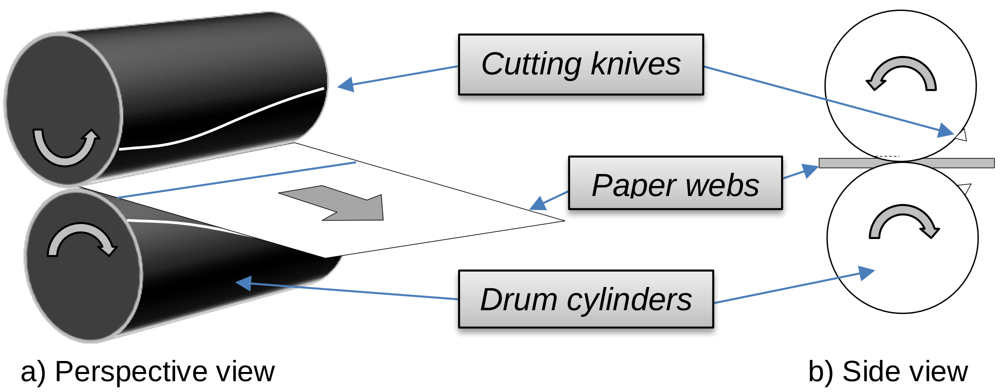


Figure 6: Schematic of a double rotary cross cutter from different points of view

Compared to the single rotary synchronous cutter, its main advantage is a square cut edge over the full paper width (see **Figure 7**), both knives entering perpendicular to the paper surface. This allows the cutting of heavy loads or several webs at once, up to a combined basis weight of 1000 g/m² on modern machines [20]. A further advantage is a longer knives life due to the lower friction between the knives.

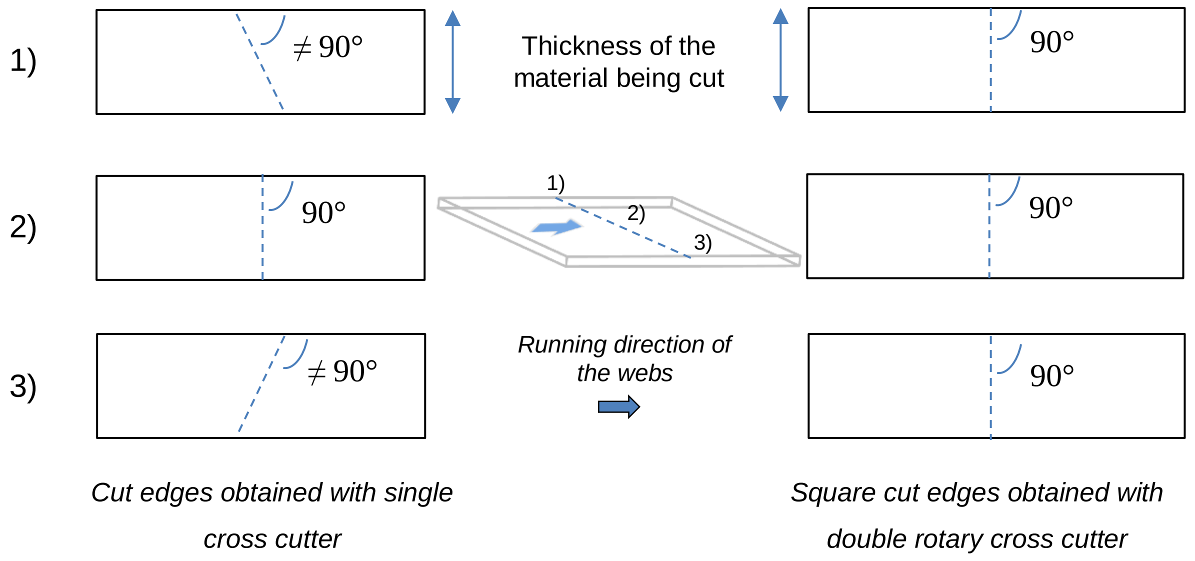


Figure 7: Representation of the cut edge geometry obtained with single and double rotary cross cutter over the full paper width: 1) begin, 2) middle and 3) end of the cut

Nowadays, the main difficulty for the converter is to optimize the replacement and proper settings of new knives (it takes around 4 hours). Finally, the speed stays substantially limited when running long and short cut off lengths. The main advantages and disadvantages of these systems have been described by Wittenberg [21].

2.2.4. Guillotine cutter:

The guillotine cutter (sometimes also called cutter or paper-cutter in the graphic arts industry) is a cutting machine which is processing only sheets. The system is quite close to the *Guillotine* used during the French revolution. It consists of a knife pushed down through the paper stack that is maintained in a fixed position. It is normally used to resize some formats and remove defaults created during the sheeting process. Eventually, it can also be used to produce specific formats which are not achievable with standard sheeters such as very small sizes. The maximum amount of paper being cut is normally around 15 cm. The cut quality delivered by a guillotine is very high even when a much higher number of sheets are cut simultaneously compared to the other cutting machines. This can be attributed to the fact that the paper sheets are locked into position during the cutting process (clamped over the entire surface) and therefore do not have the possibility to tear or break before being cut.

Moreover, contrary to the other cutting machines, no cut quality differences depending on location of the sheet within the stack are noticed.

2.2.5. Liquid jet cutter:

Water jets have been used in the mining industry for erosion purpose. First application in the paper industry may be found in 1935 when the Paper Patents Company in Wisconsin filed a patent with the following title: « Paper metering, cutting, and reeling » [22]. Their invention is a machine that used a diagonally moving water jet nozzle to cut a horizontally moving sheet of paper. Ultra high pressure water jets were later introduced to the market and are used to slit, edge trim and tail cut a variety of materials. A liquid jet cutting system consists of a nozzle ejecting water at ultra-high pressure through a material. It is widely used in the paper industry since 1975. The advantages of water jet cutting include dust free cut and easy positioning. Due to its advantages, water jet cutting system often results in a reduced downtime making the investment very interesting for papermakers. The biggest dissatisfaction when cutting with water jet is the poor quality of the cut edge. As mentioned by Amundsen, cut edge look "*slightly fuzzy and feels soft to the touch*" [23] due to the presence of hanging fibres; it does not have the sharp edge of a blade cut. Therefore application in the paper making process is limited to positions starting from the wet end until the winder.

2.2.6. Laser cutter:

As mentioned by Malmberg and Kujanpää: "*The combination of laser with paper technologies has been studied for more than 30 years*" [24]. Contrary to the current technologies used in paper/board converting processes, laser technology leads to clean and sealed edges. Moreover, it does not affect the properties of the fibre material and any further converting and end use of the paper are normally problem-free. Laser cutter also appears to have no speed limitation and dust problems are avoided. All these advantages make the laser technology very promising for the future. Researchers at the Laboratory of Laser Processing at Lappeenranta University of Technology (Finland) found that a commercial magazine paper can be cut at a speed of 4400 m/min [25].

CO_2 laser technology is used in the cutting of paper. The paper material is vaporized under the action of the laser beam. Inert cutting gas such as nitrogen is used to prevent the combustion of vaporized material.

One of the main commercial industrial applications consists of perforating cigarette filter paper where machines are able to run paper reels at a speed of 800 m/min perforating up to 1 000 000 holes/seconds with a diameter of 50 µm [26]. However the implementation of laser technology in slitting and cutting operations for paper and board manufacturing is limited because of the high investment costs and a lack of basic knowledge and research results.

Workington Mill (Iggesund Paperboard, nowadays part of Holmen Group) was one of the first mills to apply this technology. Their main motivation for this project were cutting dust problems and the target was to deliver to the printer a paperboard suitable for running for several hours without washing the blankets. The Workington project proved that laser slitting was possible and applicable to the paper industry. Slitting speeds of 120 to 245 m/min on Art paper in the thickness range of 114 to 290 µm were reached. The results of the project lead to a patent application and the main findings have been published [27].

One of the main issues with some of the cutting systems presented before is the generation of dust. To reduce this problem, some vacuum systems call “dust extractor system” have been installed on the cutting machinery to suck the dust generated during the cutting process.

Depending on the cutting system used, the reels or sheets have different cut qualities. ***Figure 8*** *shows the cut quality for the same paper obtained by different cutting methods and also shows images of papers cut with laser technology. In this thesis, focus will be hold mainly on shear slitter cutting and rotary cross cutting systems.*

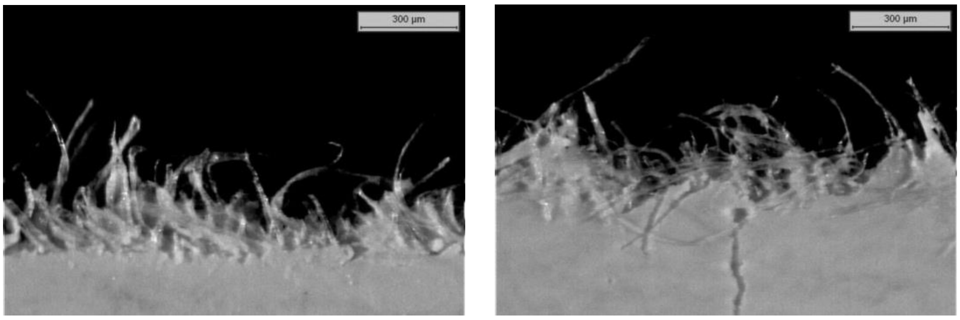
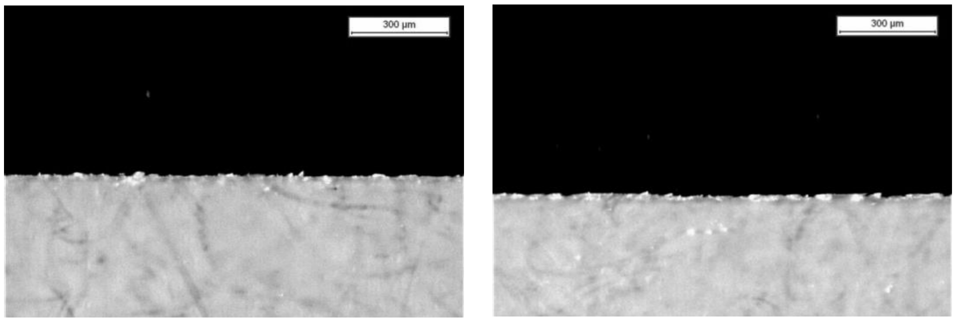
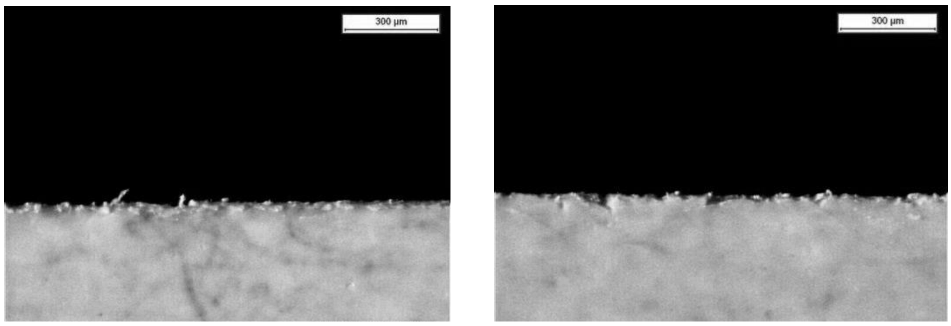
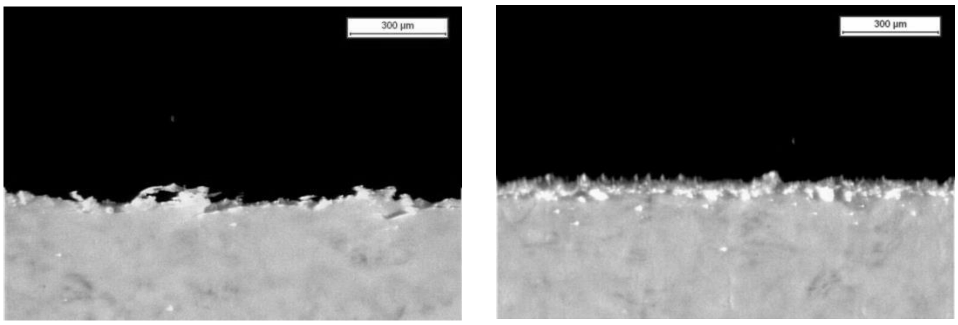
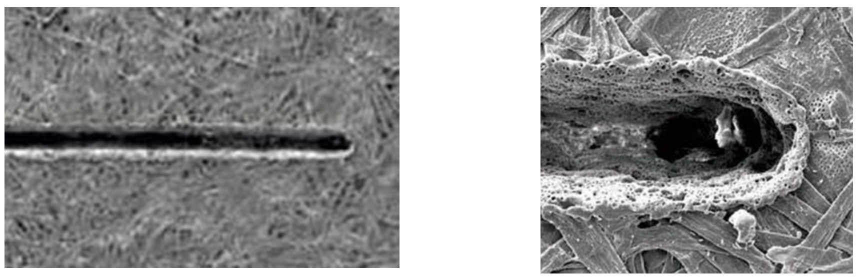
Typical cutting qualities obtained per cutting machine	
*Water jet cutting**	
*Guillotine cutting**	
*Shear Slitter cutting**	
*Rotary cross cutting**	
Laser cutting	 *Source for Laser cutting pictures: Malmberg and Kujanpää* [24], *unfortunately no scaling information was available on the original pictures*

Figure 8: Cut quality obtained with the different cutting processes (*: glossy paper 90 g/m²)

Chapter 3

Development of methods for cut quality evaluation

In this chapter, existing tests methods for the analysis of the cut quality of papers are reviewed. The development and validation of test methods used during this thesis to analyse the cut quality of wood free coated papers are described.

Some research was carried out in the 1970-1980’s regarding the cutting process in the paper industry. Modern and highly productive sheeters are designed to cut several paper webs simultaneously, and cutting machine suppliers are exploring the possibility to cut up to a combined basis weight of 1000 g/m² [20]. For WFC papers which are mainly printed in offset, the cut quality is of high importance. Papers must be free of dust and loose particles created during the cutting process as this can drastically reduce the wash interval of the blankets. Research work, experience, and advice on how to operate the sheeters to obtain and maintain the best cut quality have been discussed extensively by Schable [18]. Several factors such as the machinery (knives geometry, blades overlap, over speed, knives quality…) and the coated paper (composition, structure…) have a significant impact on the cut quality. In order to evaluate the influence of these factors, a quantitative and reproducible test method for the evaluation of cut quality is mandatory.

So far, only one method of evaluating the cut quality has been released [28]. The lack of standard test methods to evaluate the cut quality can be attributed to the fact that the standards are strongly dependent on the end use of the product (e.g. medical, food packaging or newsprint) or/and the next converting steps taking place such as offset printing. Indeed, a rough cut quality for a newspaper can be accepted due to its short life time while it will definitely be refused for a high quality magazine due to the printing process but also due to the fact that the end customers expect a high quality product. So depending on the nature of the paper and its end use, the parameters used to describe the cut quality might be completely different. All existing test methods found in literature are mainly designed for uncoated papers or boards. These are essentially focusing on the raggedness of the edges and on the amount of dust collected on the paper.

3.1. Review of existing test methods and selection of the most appropriate methodology

Several ways to evaluate cut quality are discussed in literature and/or used within paper mills (visual, topography, hand feeling, dust measurement…). In this thesis, most of these methods were tried with WFC papers to see which system was the most for use. Their main advantages and disadvantages are discussed in the following paragraphs.

3.1.1. Offline measurements:

In most paper mills, visual and “hand feeling” methods are the commonly applied method and the fastest way to evaluate the cut quality of a sample. As Frye mentioned: “*The best field test for this problem is to shine a flashlight along the edge of the roll or ream, whereby the debris will cast a shadow that is easily seen. Another test is to rub the palm of your hand along the direction of the paper on a roll or a ream. A good slit will feel cool and smooth,* *while any lesser slit quality will feel rough*" [29]. Operators have developed over the years quite a good "feeling" for how a cutting edge should look like. Unfortunately, such visual and touch methods evaluating cut quality turn out to be highly dependent on the person carrying out the test. Only a trained person is able to quantify the cut quality obtained at the sheeter objectively with the naked eye.

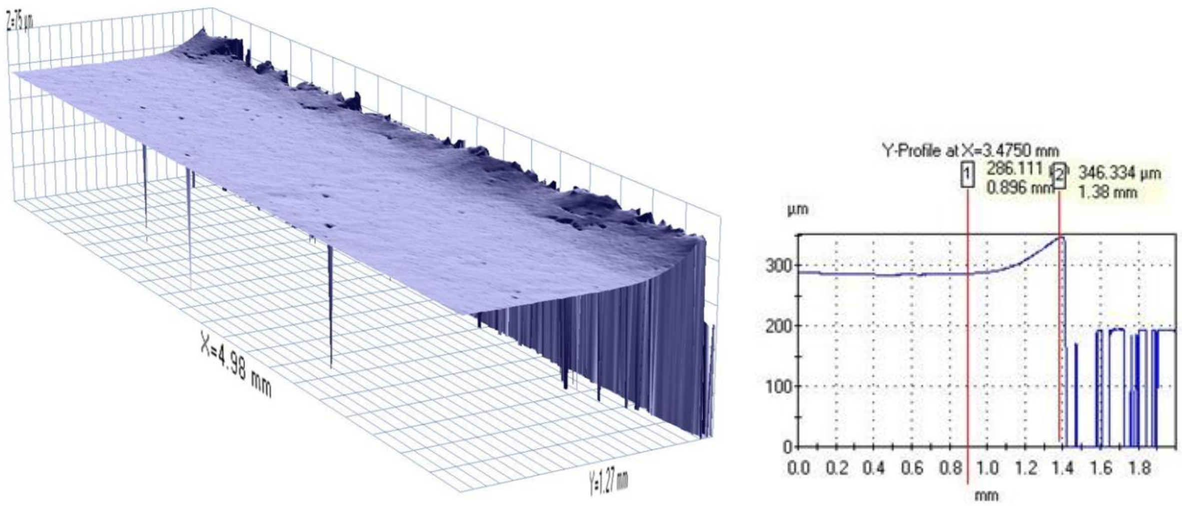
Xerox has been a pioneer in setting up an official test method [28]. This method is based on the visual analysis of the cutting edge with a microscope. Based on the raggedness of the edges, a numerical value is given, with 1 being good to 6 being bad. Since then, offline automated measurement has been developed [30] for sheets up to 28 x 43 cm². It consists of a scanner and image analysis software and informs the operator on cut sharpness, hanging fibre count, sheet size, and the curvature of the cut. This system can be set up to measure in compliance with ISO 22414. Although, the need for standardized measuring method taking the dust into consideration was already mentioned in 1991 [31], the amount of particles released during the cutting process is not considered at all in these methods. Realizing the importance of dust, mainly for the printing process, automatic offline measurements were developed with a focus on it. Basically, the idea consists of placing a stack of samples of freshly cut paper in a hermetic box and sucking up the dust. Through an analyser, the amount of dust is then quantified. PTS also worked on this topic recently [32]. During the cutting process, however, generated dust particles can be projected several centimetres inside the paper sheet surface. So these offline dust measurement systems turned out to be inefficient for WFC paper because they only measure the dust which is located at the outer faces of the pallet, not between the paper stacks. Furthermore, all existing systems found in the market place were for A4 or A3 samples which is definitely not suitable for sheet fed offset paper where the paper formats are strongly varying and can reach up to 2.5 meters in width.

3.1.2. Online measurements:

Online dust measurements systems work at correcting the weaknesses, observed with the offline systems, fairly reliably. With such systems it is possible to continuously monitor the sheeting process. Recently, an online measurement system has been developed [33] that collects and measures unbound dust and debris from the paper web. The result consists of the time required to collect a certain amount of dust. Continuous online dust measurement allows studying the differences between the paper grades and the development of dust formation over time leading to information regarding knife quality. Generally, such dust analysers can be installed on the dust extractor system: a visual detector evaluates the amount of dust passing through the pipe. In this case, it gives an overall information regarding the dust generated at one sheeter which is more than enough to study the paper influences but definitely insufficient to study the machinery influences. Practical experiences have shown that often, the dust is generated at one specific knife, e.g. due to wear of this knife. Besides that, online dust measurement systems turn out to be expensive since they need to be installed on every single machine. To conclude, the main disadvantage of those systems is the high investment costs and the fact that no information regarding the cut quality is obtained such as raggedness or protruding fibres.

3.1.3. Definition of appropriate method

Using a stereomicroscope equipped with a digital camera as used in the ISO test method developed by Xerox appeared to be the cheapest, easiest and most reliable solution to observe the cut quality even if it remains time-consuming. However, the measured parameters must be adapted for WFC papers. One important parameter that is often used as a criterion by the operators on the machine is the presence of a “burr”. This can be defined as the feeling that one might have when passing the finger over the cutting edge. Basically, it is the aspect of the edge in Z-direction. Non-contact optical metrology systems [34] allow to measure precisely the topography profile near the cutting edges (see **Figure 9**) but measurements are highly time-consuming and the data analysis requires some extra time.



a) Perspective view *b) Side view*

Figure 9: Representation of a cutting edge in 3D from perspective (a) and side view (b) (measurement performed with the COTE:M Nanoscope)

Analyses of several cutting samples showed that the higher the deformation of the edge, the more damaged will be the cutting edges (raggedness, fibre pull out the cutting edges, number of cracks). Therefore, the burr is measured only on special cases when a full cut quality analysis is required. In order to perform a complete analysis of the cutting edges; a combination and partial adaptation of the different methods is used in this thesis.

For the standard cut quality, the following conditions have been used during this work:

- The equipment used to analyse the samples consists of stereomicroscope (Leica MZ12, Leica Microsystems; Wetzlar, Germany) equipped with a digital camera (Leica DFC295, Leica Microsystems). The stereomicroscope is equipped with a lens of 10 mm x 21 mm. During the measurement, the surface of the paper sample is illuminated at an incident angle of 20° from two sides using a cold light source (Leica CLS 150 XE, Leica Microsystems). The software used is Leica Application Suite (Leica Microsystems). Standard settings are a microscope magnification of 8.0x, a total magnification of 80x. Illumination at a low angle of incidence is important to reveal the presence of coating cracks near the cutting edges due to the created shadow.

For the burr (if required):

- A *laser topography apparatus* to measure the burr for precise measurement (rough evaluation can be made with the help of oblique illumination, see **Figure 16**).

3.2. Method developed for cut quality analysis of WFC Papers

3.2.1. Sampling and sample preparation

The sample preparation is simple and takes only a few minutes (see **Figure 10**). It consists of cutting out an area of 15 cm x 5 cm at the four edges of the paper stack, defined here as a set of sheets cut simultaneously at the sheeter. Every sheet in the stack needs to be collected and marked (identification of edges, position within the stack and, top and bottom side of the sheet). A sample length of 15 cm is required to get a good representation or average of the cut quality.

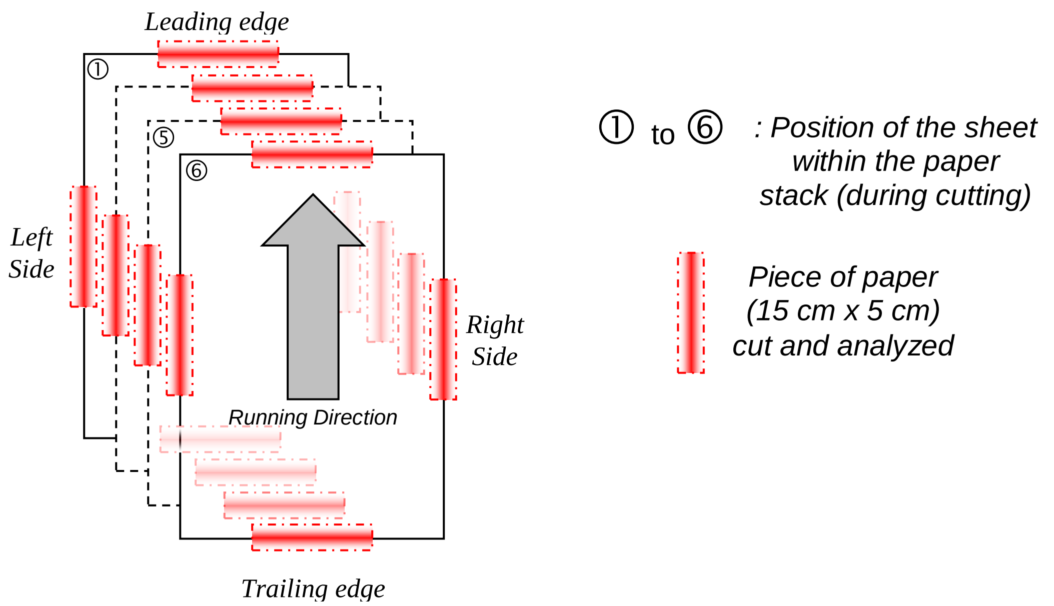


Figure 10: Paper samples collected at the sheeter, areas analysed and identification of the different edges.

Identification of edges is important because, depending on the sheeter configuration, the knife geometry, and the direction of the cut, different cut qualities are obtained. Four types of edges exist.

For the longitudinal cut, the cutting edge will either be supported by the bottom knife ring ("band edge") or not ("blade edge") resulting to different cutting qualities (see **Figure 11**).

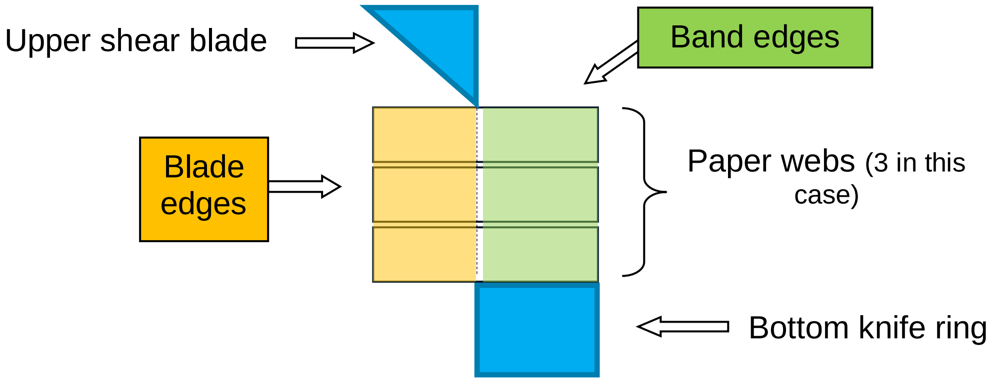


Figure 11: Location of blade and band edges at the sheeter

For the cross cut, looking at a sheet of paper after the cross cutter, the leading edge is the first edge leaving the cutter, the trailing edge, the last one (see **Figure 12).**

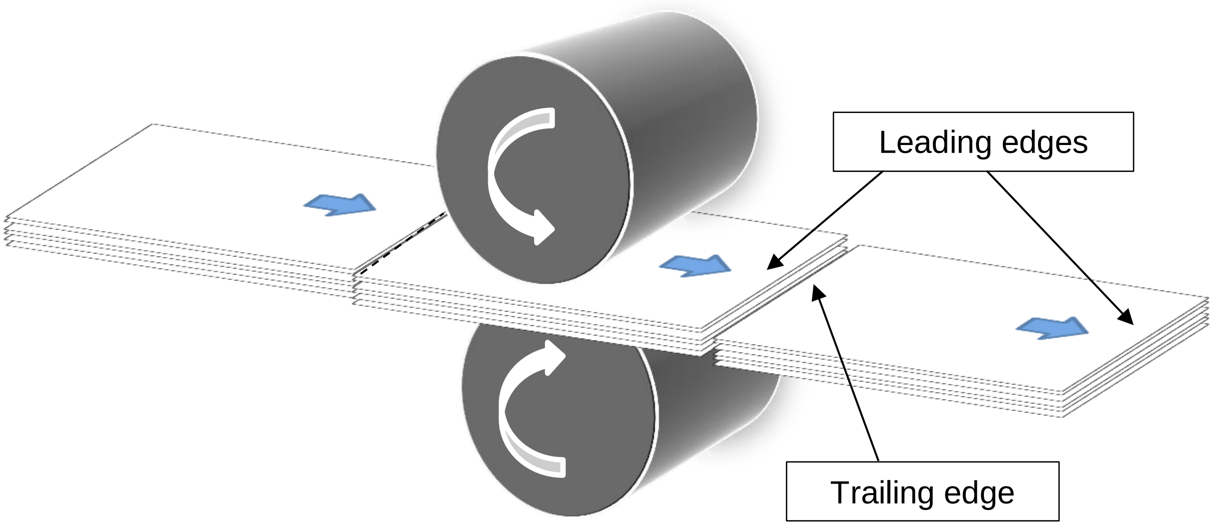


Figure 12: Location of leading and trailing edges at the sheeter

The position of the sheet within the paper stack is important because the cut quality of a sheet strongly depends on its position in the paper stack and the number of sheets cut at once. Therefore, it is very important to collect all the sheets cut at once but also to notice their position within the paper stack. To get a good overview, every single sheet needs to be analysed separately.

Finally, huge differences can be measured on the same paper web when viewing the cutting edge from the top or the bottom side (**Figure 13**). It is therefore very important to measure both sides of each sheet.

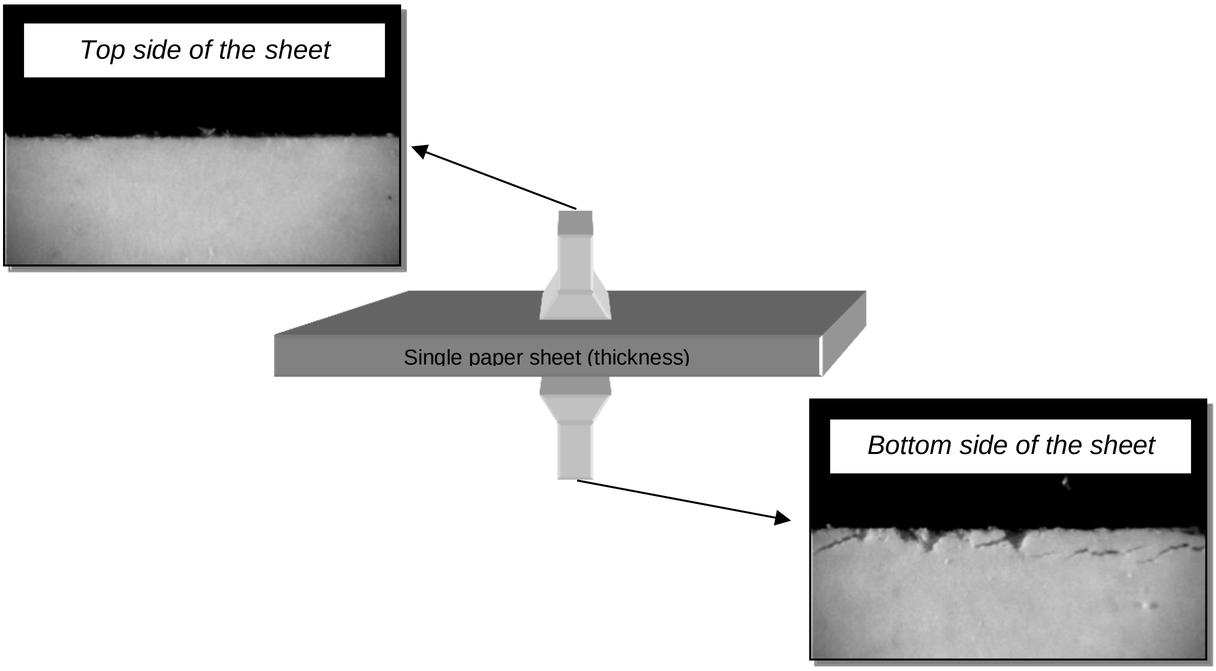


Figure 13: Differences observed when looking at the same edges from two different sides: top and bottom sides

In order to be sure to measure only the cut quality without any external influential parameters, paper clips have to be collected just after the rotary cross cutter and before the palletizing operation. Indeed, and mainly with silk papers, the slowdown (speed reduction) of the paper stack can affect the quality of the paper stack.

3.2.2. Selection of the factors to evaluate cut quality

Detailed analyses of more than 500 samples showed pronounced differences in the quality of the cutting edges between the sheets, depending on their position within the paper stack during the cutting process. The results vary with blade characteristics (e.g. sharpness and geometry) and the paper grade to be cut. As mentioned previously by Frye [35] and Schable [18], the variations can be explained by the fact that the sheets in a paper stack are subjected to different levels of stresses depending on their position in the stack and relative to the blades. Meehan and Burns mentioned in their work that the applied stresses in a web and the material’s response to these stresses dominate the quality of the cut surface. Three parameters proved to be useful to quantify the cut quality (see **Figure 14**):

- *The raggedness of the edges, further called "Raggedness".*
- *The number and size of cracks, further called "Coating cracks".*
- *The amount of fibres pulled out from the cutting edges, further called "Fibre pull".*

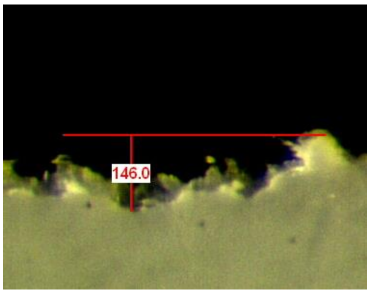
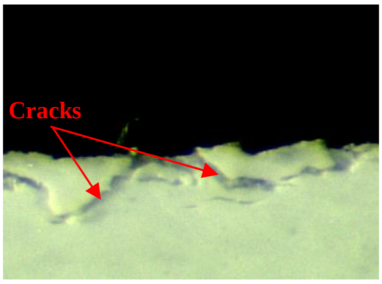
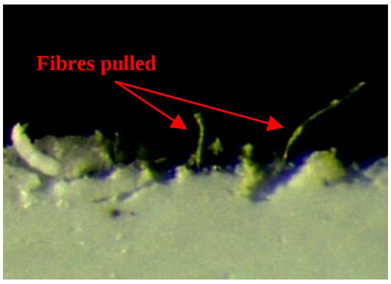
"Raggedness"	**"Coating cracks"**	**"Fibre pull"**
Average amplitude in µm between the highest peak and the lowest valley	*Number of cracks longer than 60 µm over a defined distance*	*Fibres pulled outwards from the cutting edges – visual aspect from 1 (no fibre) to 5 (lot of fibres)*
Error measurement: +/- 5µm	*Error measurement: +/-5 cracks*	-
		

Figure 14: Three factors used to quantify the cut quality of WFC papers
(all images taken with the same camera settings, the width of the picture represents 700µm)

3.2.2.1. Raggedness of the edges:

This measurement corresponds to the amplitude between the highest peak and the lowest valley when looking at the cutting edge in the z-direction (see **Figure 14**). Due to the differences noticed when observing the cutting edge from one side of the paper compared to the other one, it is strongly advised to measure from both sides of the sheet. Depending on the number of webs being cut, on the position of the sheet during the cutting process, on the paper and on the machinery, this value varies between 0 and 200 µm.

3.2.2.2. Number of cracks near the edges:

The number of cracks near the edges has not been previously considered in the alternative test methods. Those coating cracks will not necessarily result in loose particles and the formation of cutting dust during the converting operations; however, the resulting weakly bound coating particles are likely to be pulled out during further converting operations such as offset printing due to the tack of the ink. The coating cracks can be defined as a fissure / fracture in the coating layer close to the cutting edge (see **Figure 14**). Their number and size vary from one area to the other and they are counted over a distance of 5 cm. Their presence is mainly due to the fact that contrary to the base paper, the coating layers have a much lower elongation capability. During the cutting process, cracks will be generated either due to some compression force or to some elongation forces. Image analyses made with the help of SEM (Scanning Electron Microscopy) have shown that the coating cracks can reach the base paper (see **Figure 15**). Again evaluation of cracks has to be performed for both sides of the sheet (see **Figure 13**). The number of cracks can vary strongly between 0 and up to 150 cracks per 5 cm.

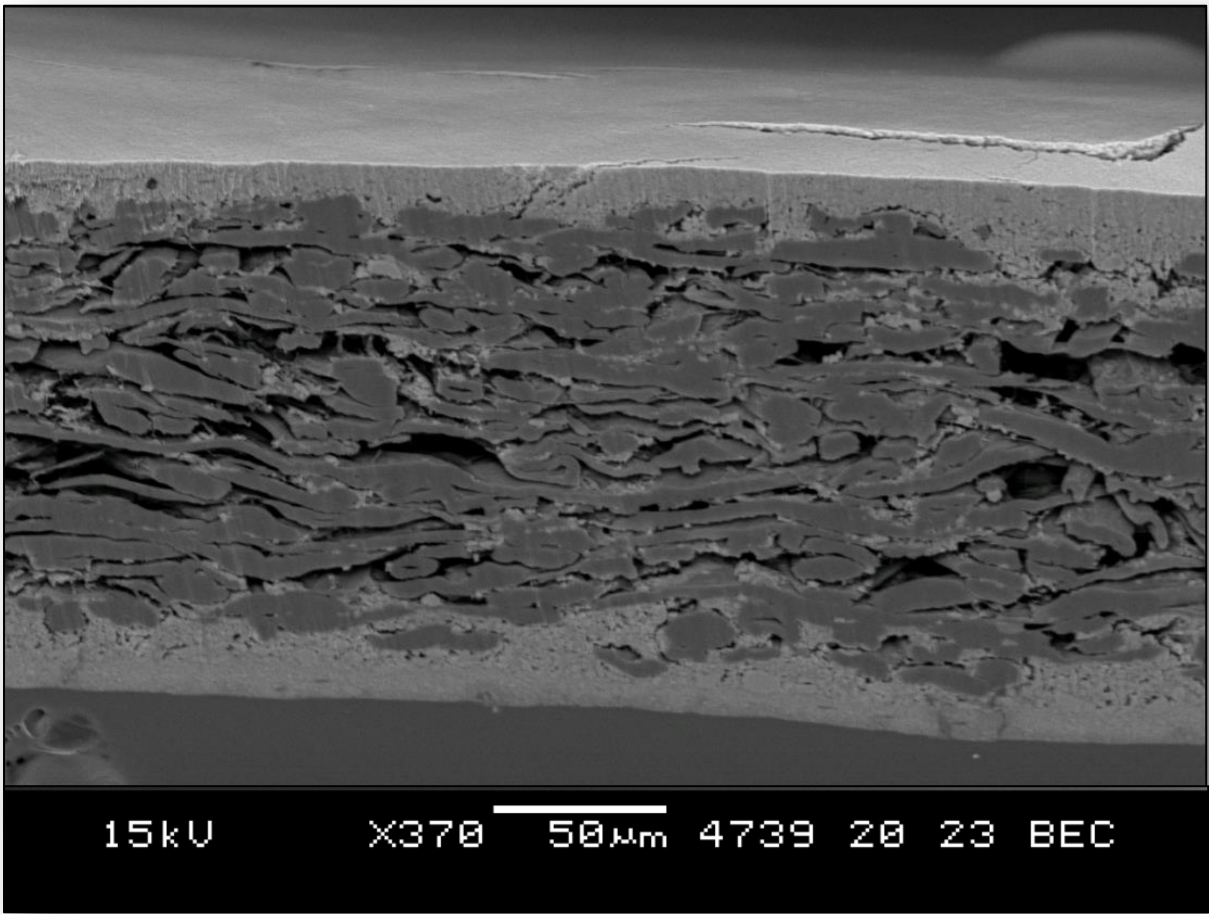


Figure 15: Cross section of a wood free coated paper taken with a Scanning Electron Microscope showing the deepness of the coating cracks

3.2.2.3. Fibre pull outwards from the cutting edges:

This parameter is the most difficult to evaluate accurately. So far, only a visual assessment has been set up. A value from 1 (very good) to 5 (very bad) is given depending on the amount of fibres observed which are pulled outwards from the cutting edge (see **Figure 14**). This parameter is nevertheless important. Bulky papers with a low amount of coating sometimes present a high amount of fibres pulled out from the cutting edges (mainly when the knives are becoming dull) keeping however the raggedness and number of cracks limited. The fibres hanging out can impact the runnability during further converting operations. Underestimating this parameter can therefore lead to wrong conclusions.

3.2.2.4. Burr (evaluated only on special cases):

This term is used to describe an edge which will appear to be rough when passing the finger on it. Looking at the exact definition, it is "*a rough edge or ridge left on an object (especially* *of metal) by the action of a tool or machine*” [36]. It is widely used to say either a cut is good or not. **Figure 16** emphasized the difference between a paper presenting no burr (paper A) and a paper presenting a huge burr (paper B): The burr is emphasized with the help of the oblique illumination creating a shadow on the surface of paper B.

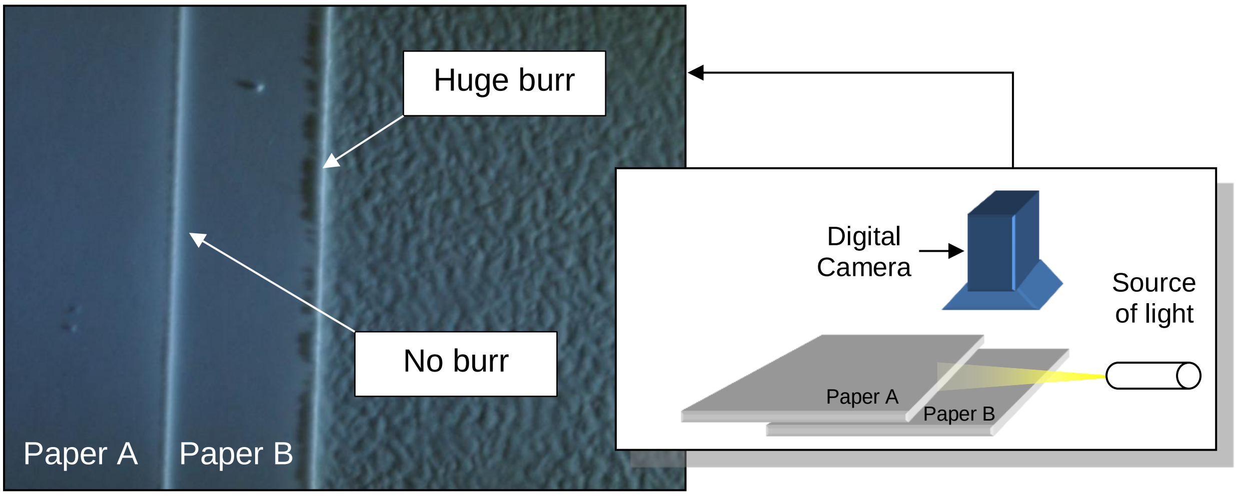
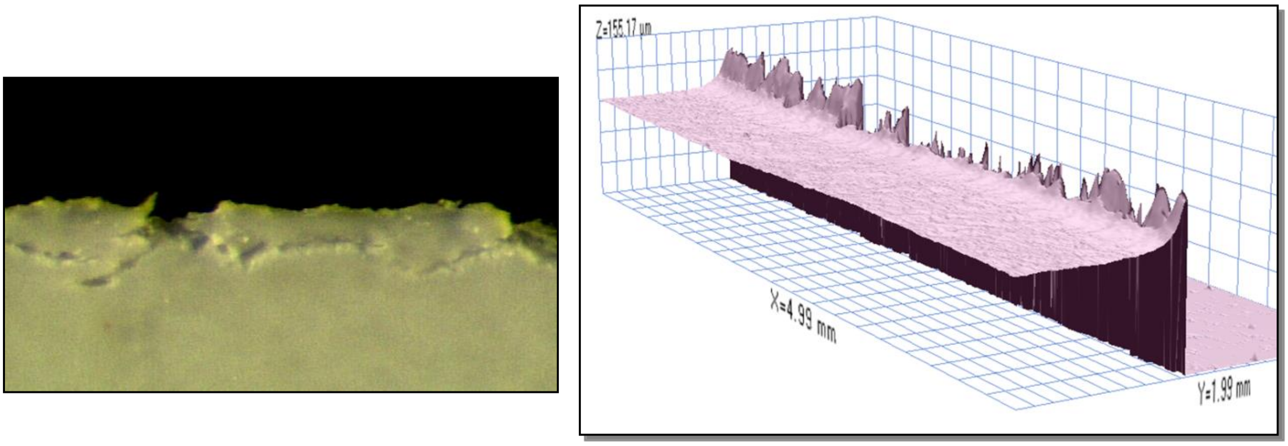


Figure 16: Papers presenting “no burr” (Paper A) and a “strong burr” (Paper B)

For WFC papers, the burr is characterized by coating particles lying on the cutting edges which have been partially pulled apart from the rest of the coating layer. In order to quantify this burr, the microscope is unfortunately insufficient. The best system to measure this burr was found to be the Nanoscope: This is a 3D topography laser measurement system developed by the company Cote-M [34]. Within a few minutes a measurement over a width of a few cm can be obtained (see **Figure 17**).



A) Standard picture microscope **B) 3D topography measurement**

Figure 17: Burr observed on the cross cut (A: with a standard microscope and B: the 3D topography measurement system)

3.2.3. Visual representation of the results

Application of the proposed analysis method results in a large number of data for every single paper stack. For example, when six sheets are cut simultaneously, we obtain 144 data points: six sheets x two paper sides (top and bottom) x four edges x three characteristics. To visualize these data, a system has been implemented to represent the three parameters describing cut quality on both sides of the knives over the whole paper stack for one type of cut (either longitudinal or cross-cut). In **Figure 18**, the raggedness of the cross-cut through the paper stack is shown. A bar chart is used to represent the raggedness measured on both sides of the paper sheet over all sheets of the paper stack. The height of the bar relative to the centre line is a measure for the raggedness with higher values indicating poor raggedness. In **Figure 18**, it can be easily observed that the sheets located in the middle of the paper stack are of poor cut quality in terms of raggedness, while the external sheets show quite a good cut quality (i.e., low values).

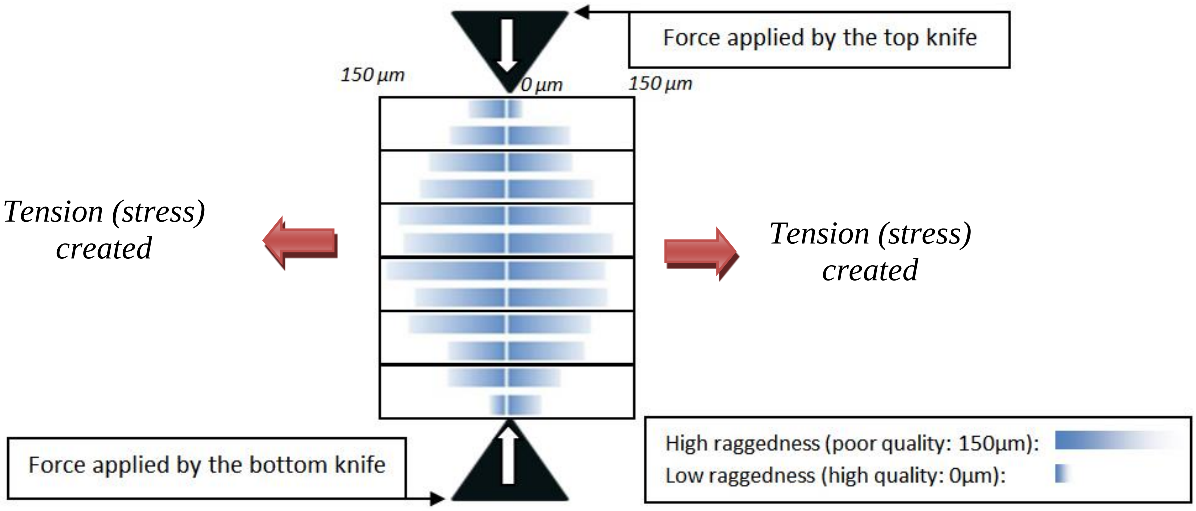


Figure 18: Evolution of raggedness within a paper stack at the rotary cross cutter (6 sheets being cut simultaneously)

Visualisation is easy to understand and very practical in the analysis of the effect of different machinery settings. The number of coating cracks and pulled out fibres may be similarly represented (see **Figure 19** for the number of cracks developed at the twin slitter).

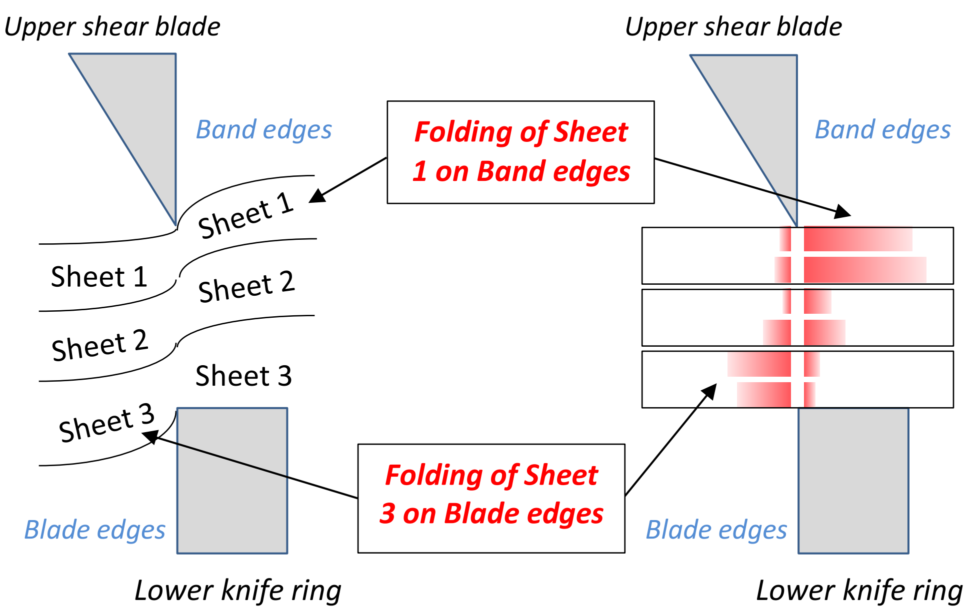


Figure 19: Representation of the cracks developed on the top unit of a twin slitter (3 sheets being cut simultaneously)

3.2.4. Software development for a faster analysis

Based on the first results, the need to develop software for faster analysis of the paper clips which was taking an average of 2 hours became apparent. This software is based on the image analysis of 10 pictures taken from the cutting edges with the aid of a camera and a microscope with a defined zoom and lightning (see section 3.1.3). For this image analysis, *Matlab*® was used.

- Every single picture undergoes the following transformation:
  - In the first step, it is rotated to obtained a “horizontal” cutting edge,
  - Secondly, it is converted into a binary image (only black and white pixel),
  - Afterwards, the average roughness (Ra),
  - Finally, the amount of fibres hanging out from the cutting edges is evaluated in % (amount of pixels above the cutting line).
- The results obtained for every single picture are averaged and summarized (see **Figure 20**). Results are summarized presenting: the standard deviation of the measurements, the averaged raggedness (max-min and Ra), and the fibre pull (Fiber).

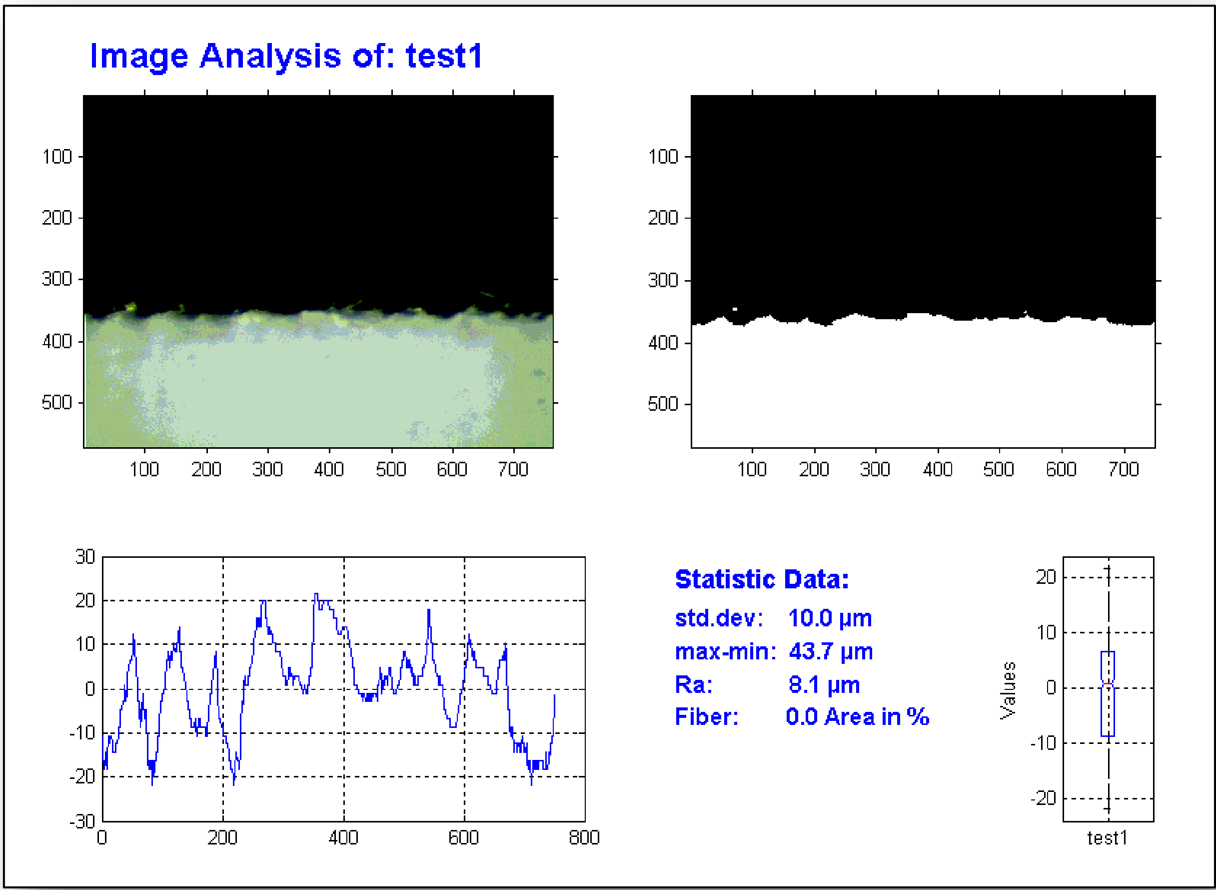


Figure 20: Image analyses, software overview

The number of cracks is still not included in this software. It is mainly due to the fact that the perception of the cracks is strongly influenced by the lighting of the paper samples when the pictures are taken. More image analysis development is required such as taking several pictures from different angle and lighting and combining all results. This final step will require much more investments in terms of time and cost and has not been pursued during this thesis.

3.3. Method developed for dust evaluation at the sheeter

During the cutting process, dust is always being generated. The amount of dust generated mainly depends on the direction of the cut, on the blade characteristics, on the machinery settings and on the material being cut. Despite the high accuracy of the test method described previously, the amount of dust lying on the paper surface is not taken into consideration. However, this is known to have a strong influence on the printing process and needs to be considered and studied. Methods or systems to quantify and/or qualify the dust are mentioned in the literature [33] [31]. Online systems with optical methods of measuring dust were not considered due to the large number of sheeters and the costs involved. We performed several tests in the laboratory to quantify this dust lying on the paper surface nearby the cutting edges such as:

- *Collection of the dust with a transparent adhesive applied later on a black sheet,*
- *Loose and weakly bound paper particle test* [37]*,*
- *Development of test with the Prüfbau apparatus.*

Due to the low amount of dust present on one sheet and due to the volatility of the dust, all evaluated laboratory test methods turned out to be not reproducible and inaccurate. Based on these observations, it was concluded that laboratory methods are not feasible (manipulation error, sample size…) and tests have to be run directly at the sheeter, just after the cutting process. Therefore a new method to evaluate the amount of dust generated at the sheeter was developed. A black rubber roll with a holder has been manufactured. This roll is brought in contact with the paper web with minimal pressure, so just to ensure contact, just after the cutting device during a defined period of time at a defined sheeter speed (see **Figure 21**).

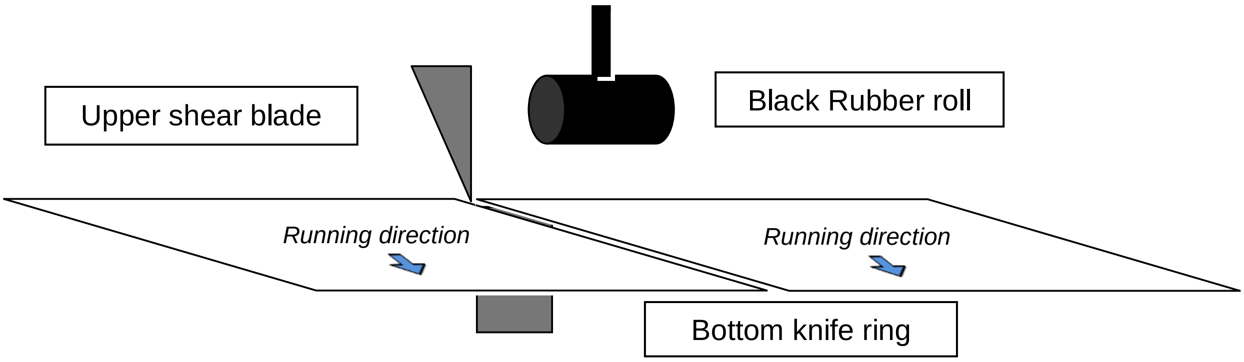


Figure 21: Description of the position of the rubber roll to collect the dust at the sheeter

Due to the material of the roll (Polyurethane), dust particles are sticking to it. At the same time the rubber roll does not create any marks on WFC Papers which is of course of high importance. **Figure 22** presents the results obtained after 1 min of contact at a speed of 150 m/min with a bad (worn knife) and a good (new knife) cut quality.

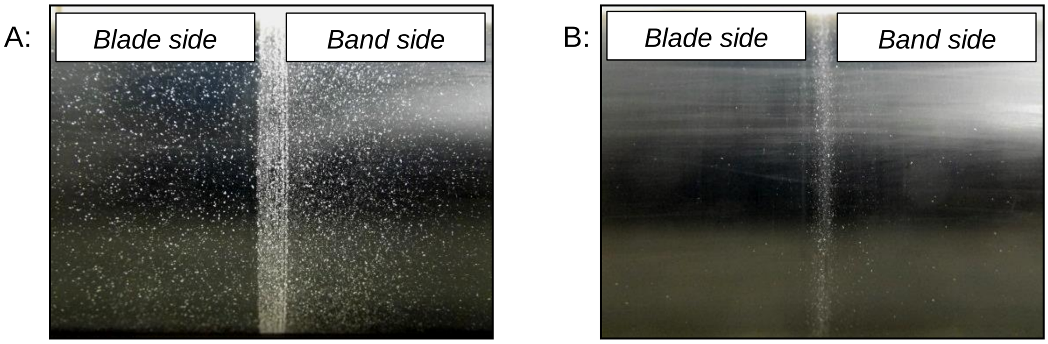


Figure 22: Results obtained with the rubber roll with a worn (A) and new (B) knife

This test method turned out to be simple, fast and easy to implement. It allows evaluating at any time the amount of dust generated by the cutting devices at a defined position. Of course, this test is influenced by several factors such as the presence of dust extractor system, the stability of the web or by the vacuum generated by the edge extractors. As such, this test can only be made on a central position but not on the border of the web. However, its sensitivity provides an excellent and fast procedure to analyse the efficiency of a dust extractor system or the amount of dust generated at the sheeter. The results car either be evaluated visually or by densitometer measurements of the rubber surface after conducting the test: The higher the amount of particles, the less black will be the roll. This method can be used as a detector to evaluate when the knives need to be changed. Tests were run over time and a clear increase of the amount of dust can be noticed (see **Figure 23**).

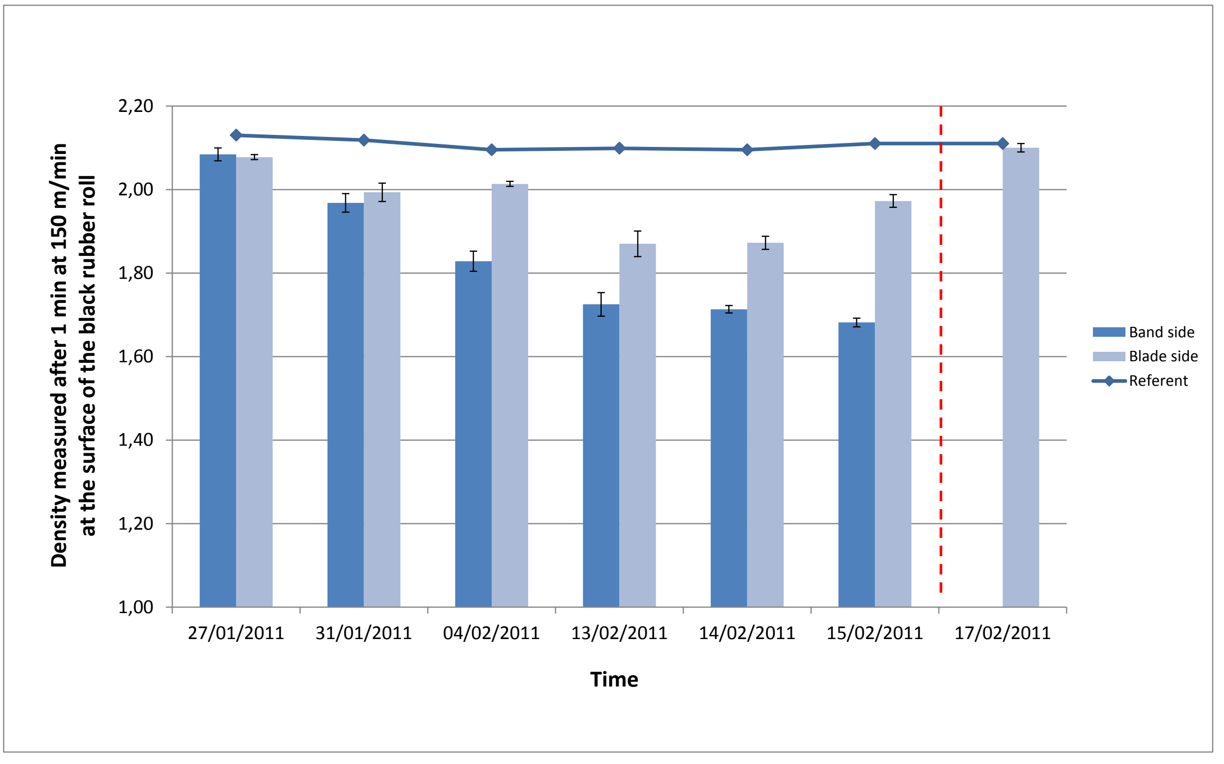


Figure 23: Evolution of the density at the surface of the black rubber roll on band and blade sides as a function of time

This amount of dust correlates very well with the state of the blades and their position (overlapping). Beside the status of the blade, the type of paper being cut will also affect the results to some extent.

It is important to mention that generally significantly more dust is present on the band edges than on the blade edges. Several explanations are foreseen for this phenomenon. The predominance of one of them on the others has not been studied:

- On the band edges, the cutting edges are sheared off when coming in contact with the blade resulting in an important dust generation while on the blade edges, the paper webs are free to deflect and will therefore not be sheared off.
- On the band edges, the paper webs are stable (maintained by the bottom knife ring) whilst on the blade edges, the paper will be bent to some extent (those movements might avoid the deposit of dust particles on the paper surface).
- On the blade edges, there is a higher air displacement during the cutting process. At the exit of the blade, the coating particles might be displaced on the band edge due to the air flow (see **Figure 24**).

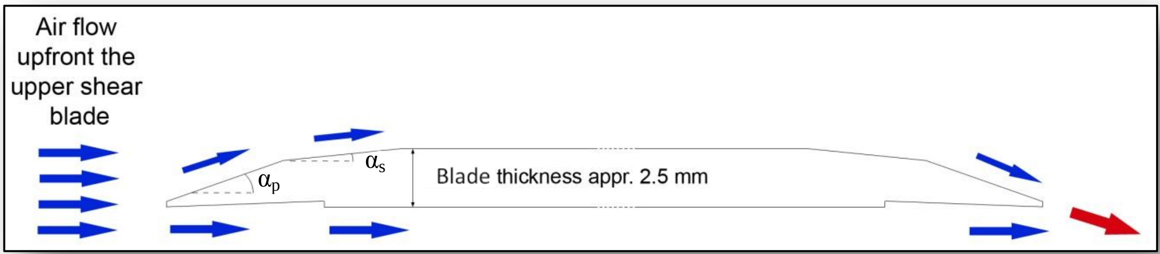


Figure 24: Air flow displacement around the upper shear blade

During the development of this test method, the chemical composition of the dust was also analysed in the laboratory to determine its origin. Methods used were FTIR, ash content and DCM extract. Results have shown that the cutting dust was coming from all paper components (filler, fibre and coating). Compositions were similar to the coated paper itself (fibre vs. filler and coating). It was not possible to distinguish which part of the detected $CaCO_3$ was coming from the filler and which part was coming from the coating layer (same type of pigments are used both cases). This test has been developed later on during this thesis and therefore it is not included in the validation process presented in the next paragraph.

3.4. Validation of the test method developed for cut quality analysis

It is difficult to validate a test method which measuring a parameter which was previously only visually controlled and not recorded. Evaluation and analysis of the results obtained on a daily base during this thesis gives only an indication regarding the significance accuracy of the test methods but this does not qualify. As mentioned previously, the aim of this method is an in-depth analysis of the cut quality of WFC papers to ensure the best cut quality for the printer. To be able to validate the proposed method presented in section 3.2, a series of practical cutting and subsequent printing trials were carried out. The majority of the WFC papers are normally printed on sheet fed offset presses. In this process emulsified ink is transmitted from a plate cylinder to a rubber blanket and finally to the sheets (see **Figure 25**).

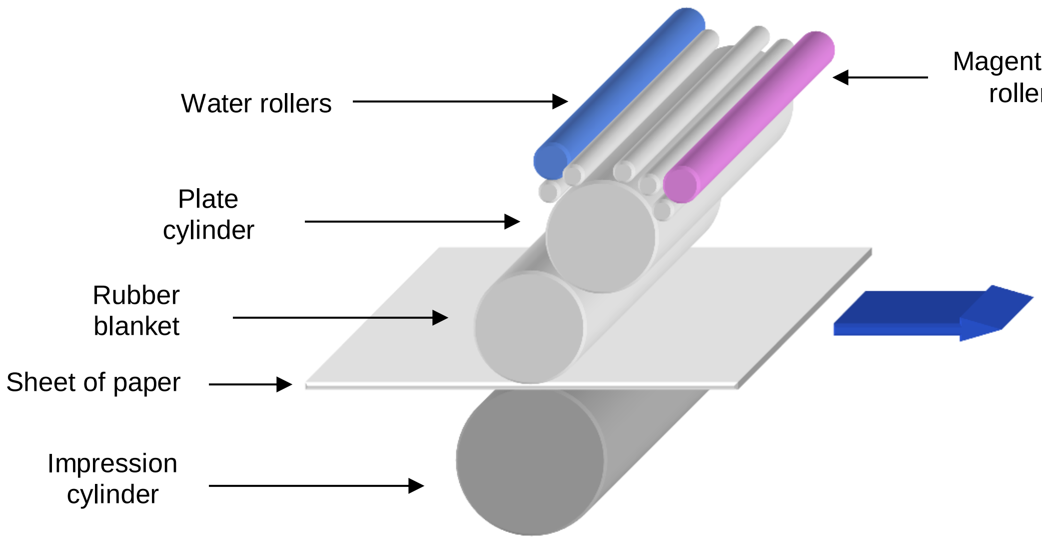


Figure 25: Schematic Sheet-fed offset printing unit

To ensure a homogeneous and thin ink layer, the ink will go through a complex path involving several roller nips. Through the nips, the ink film formed at the surface of the different rolls will be split several times before reaching the plate cylinder. As mentioned previously, the cut quality of the paper is of high importance to the printer because it can have important effects on the printing process. A critical parameter for the printer which can be associated with the cut quality is the accumulation/transfer of dust on the blanket (see **Figure 26**) and the runnability of the paper in the press.

Figure 26: Accumulation of cutting dust on cyan printing blanket (after 5000 cps)

The dust accumulation on the blanket can have several negative effects:

- *Decrease of productivity (due to higher washing frequency).*
- *Decrease of the print quality.*
- *Pollution of the fountain solution.*
- *Lower life time of the blanket.*

One theory to explain the decrease of print quality in terms of presence of black dots on the printing form, is that the dust present on the paper surface, will transfer in a first step to the blanket and then even further on to the plate cylinder. These particles accumulate ink and will then disturb the print quality. Due to this, it is expected that the test methods developed for the evaluation of cut quality should correlate to some extent with observations made at the printer.

3.4.1. Preparation and analysis of the pallets

The same paper grade was cut and twelve pallets of 6000 sheets representing different cutting qualities from very poor to very good were produced (see **Table 1**). To vary the cut quality of the pallet, several settings of the cutting operation were changed:

- *The age of the blade (brand new or old)*
- *The number of sheet cut simultaneously (from 4 to 6)*
- *The sheeter used (top slitter vs. twin slitter)*
- *The type of cutting system (guillotine, twin and top slitter)*

All the pallets were produced with the same paper stock to exclude effects on the test related to paper variability. It is well known that the efficiency of some binders, used to link the pigment particles of the coating layer, can be affected during the printing process (influence of the fountain solution). Therefore even though a paper exhibits similar cut quality, it might behave totally differently during the printing process due to its composition.

Test N°	***Type of sheeter***	***Sheets per paper stack***	***Dust extractor system***	***Comments***
1	Twin slitter	6	Off	Referent
2	Twin slitter	6	Off	Same as referent but with different edges (Band edges)
3	Twin slitter	6	Off	Short grain pallet (all other pallets were cut long grain)
4	Guillotine	~ 1500	Off	Perfect cut quality - Guillotine
5	Twin slitter	4	Off	Good cut quality (4 sheets vs. 6 sheets)
6	Twin slitter	6	Off	Poor cut quality (high overlapping + old knives)
7A	Twin slitter	6	On	Very poor cut quality obtained with old blades & wrong sheeter settings
7B	Twin slitter	6	Off	Same as 7A but without dust extractor system
8	Twin slitter	6	On	Altered knife geometry (60°)
9	Top slitter	6	On	Altered knife geometry (15°)
10A	Twin slitter	6	On	Altered knife geometry
10B	Twin slitter	6	On	Effect of the big asymmetry between top and bottom side of the pallet (upside down)

Table 1: Specifics of sheeting conditions for the commercial print trial

As mentioned in **Table 1**, besides varying the quality of the cut, opportunity was also taken to evaluate the efficiency of the dust extractor systems present on some of the sheeters. Some of the pallets were cut with and without dust extractor system on the same sheeter sequentially one after the other. For all pallets produced, a full cut quality analysis was performed and edges were tracked to be sure of their position during the printing process. As expected, the different factors measured were independent of each other and were varying as follows[1]:

- *Raggedness: from 18 µm to 110 µm in average*
- *Number of cracks: from 0 until 55 per 5 cm*
- *Fibre pull: from 2 until 3.8*

To prove the independency of the factors, linear regression analysis was performed. Results are summarized in **Table 2**. The linear regression coefficient (R^2) does not exceed 0,34.

	Raggedness of the edges	Number of cracks (5cm)	Fibre pull
Raggedness of the edges	1	0,23	0,17
Number of cracks (5cm)	0,23	1	0,34
Fibre pull	0,17	0,34	1

Table 2: R^2 values (linear regression) for evaluation of possible direct interdependence between the three parameters

To evaluate the repeatability of the test method, the measurements were repeated three times for six different papers. The variation coefficients between the values were generally below 3% which is an indication that the developed test method is repeatable and thus suitable for process control. More details about variations between the pallets are given in **Appendix C** (raggedness, cracks and fibre pull per side are mentioned). As expected, the pallets cut with and without dust extractor systems did not show any difference in terms of cut quality (raggedness, number of cracks, fibre pull). The main difference between these pallets was that the pallet produced with dust extractor system was free of cutting dust particles near the cutting edges.

3.4.2. Test conditions for print trial

A special printing test form containing dust-sensitive raster fields (screen area with 50% coverage) near the cutting edges was designed. These have the advantage of being very sensitive to the presence of dust. Dust will appear on the raster as a dark point disturbing its appearance. The naked eye is very sensitive to those variations and therefore, it became

[1] Average value of the pallet

easy to track those changes even during the print run. Due to the printing process, the edges in contact with the gripper do not come in contact with the blanket and due to this, it is not possible to analyse the effect of the cut quality on the printing samples for this side of the sheet (first side in contact with the printing press). **Figure 27** represents the printing form used for the test, the printing direction and the raster used for print quality evaluation. To facilitate the test and analysis of results whilst avoiding any external influence hiding possible correlations, the same kinds of edges were located on the trailing printing edge: blade edges (except for the test 2, 3 and 9). Mixing band and blade edges would have hidden / decreased the correlations between the cut quality and the print quality (different amount of dust is present on both edges as observed previously during the development of the test method for cutting dust evaluation). Surface dust was evaluated on the big rectangular grey raster (40%) located in the middle of the form. The area used to analyse the impact of cut quality on the print quality is the grey raster (50%) located on the trailing printing edges.

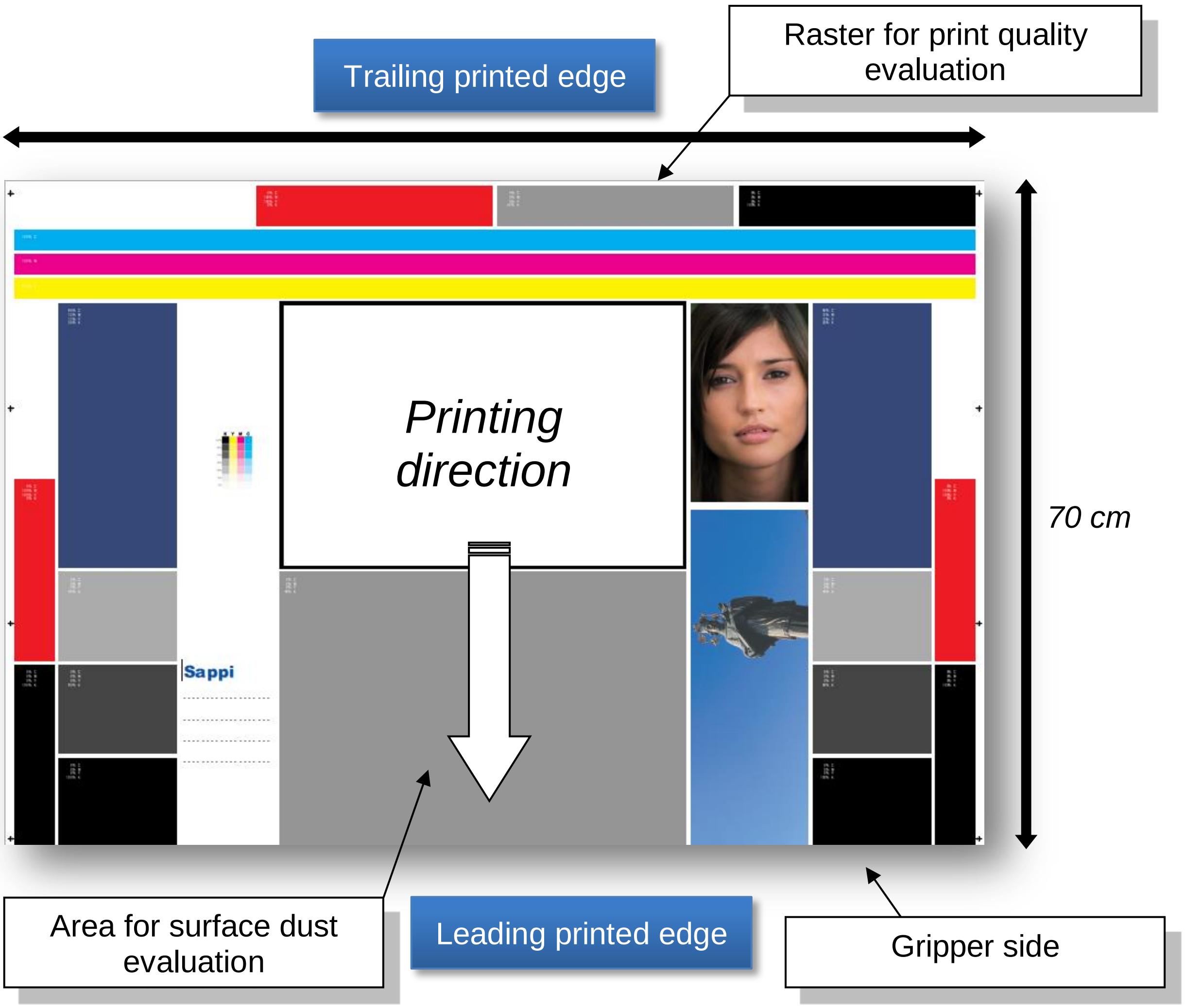


Figure 27: Print form used to evaluate the influence of cut quality on the printing process.

All pallets were printed on a 4 colours commercial printing press during two days. At the beginning of each day to ensure similar printing conditions, fountain solution was changed. Between each test point (after each pallet), automatic and manual washing of the blankets were performed on all printing units to ensure every test started under similar conditions. Each pallet was run with a standard speed of 8000 cps / hour and printed samples were collected every 1000 sheets. At the end of each pallet, pollution of the blankets was carefully evaluated (tape collection, pictures, video).

3.4.3. Results and evaluation of the printed samples

As mentioned previously, it is possible to see the impact of a poor cut quality on the print quality. However, to find if there is any correlation between this “raster aspect” and the cut quality, it becomes essential to quantify these decreases in print quality. Therefore, the amount of dust disturbing the print quality in a defined area near the cutting edges has been quantified with the help of a scanner and image analysis software (internally developed under *Matlab*®). In our work, the “50%” rasters located on the trailing printed edges were investigated (see **Figure 27**). The approach was to separate the surface covered by the dust from the standard raster. In a first step the raster are scanned at a resolution of 600 dpi and a filter is applied to remove the moiré effect generated during the scan due to the raster. Afterwards, a black and white picture is made to select only the dust. Finally the percentage of area covers by the particles is calculated. On **Figure 28,** one can see the dust appearing as white spots located on the right side of each sample. To summarize, this program evaluates the surface (% of a defined area) covered with dust: The higher the surface, the worse the print quality. With this procedure, it became possible first to see the development of dust formation on the blanket over time and secondly to rank the pallets according to their impact on the print quality. Results obtained with the different pallets are presented in **Figure 29**.

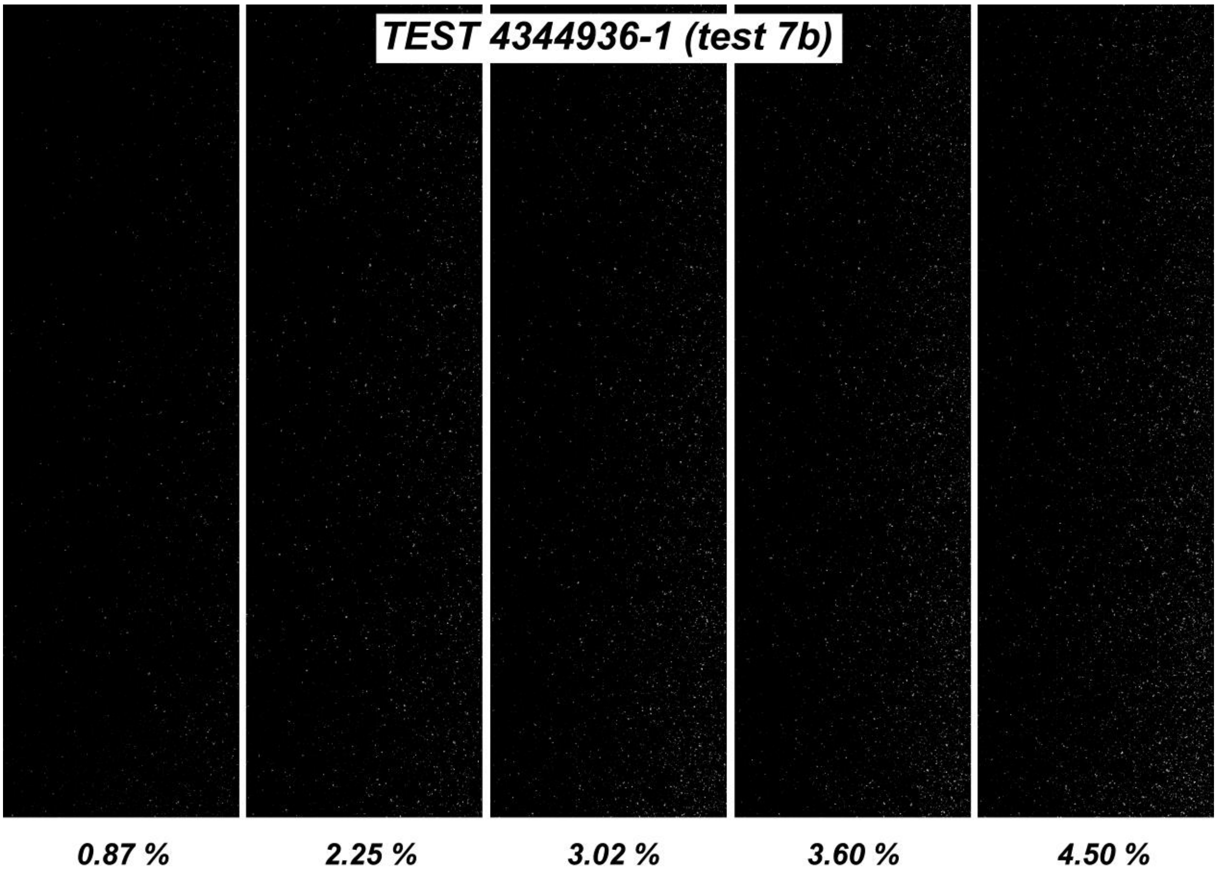
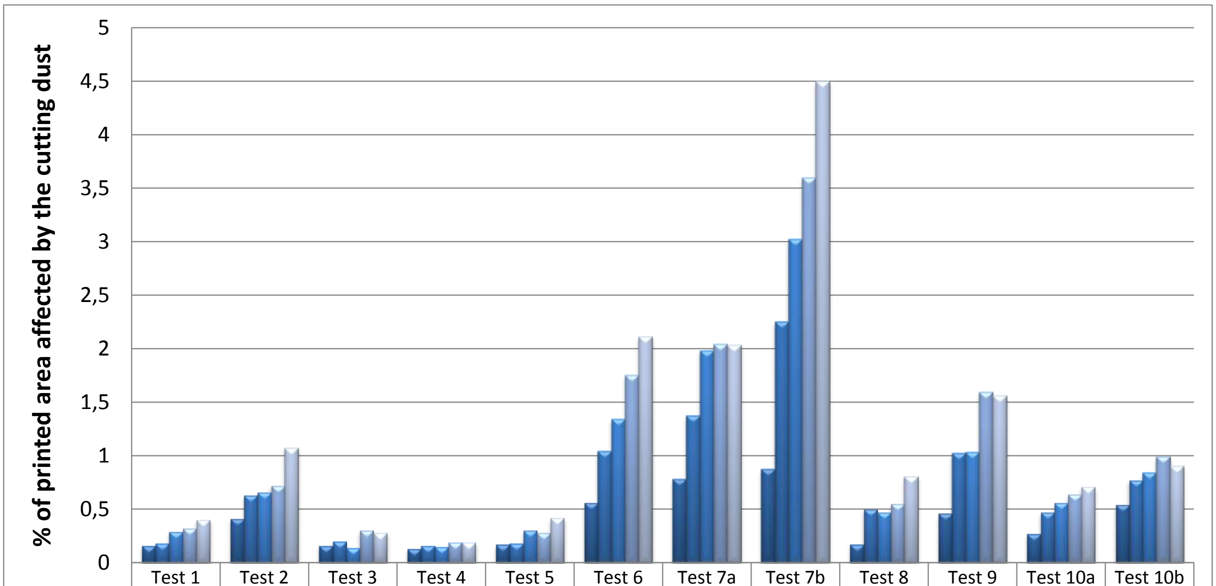


Figure 28: Evolution of the dust after 1000, 2000, 3000, 4000 and 5000 cps (the percentages indicate the area covered by the dust particles)



	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7a	Test 7b	Test 8	Test 9	Test 10a	Test 10b
1000 cps	0,16	0,41	0,16	0,13	0,17	0,56	0,78	0,87	0,17	0,46	0,27	0,54
2000 cps	0,18	0,63	0,2	0,16	0,18	1,04	1,37	2,25	0,5	1,02	0,47	0,77
3000 cps	0,29	0,66	0,14	0,15	0,3	1,34	1,98	3,02	0,47	1,03	0,56	0,84
4000 cps	0,32	0,72	0,3	0,19	0,28	1,75	2,04	3,6	0,55	1,59	0,64	0,99
5000 cps	0,4	1,07	0,28	0,19	0,42	2,11	2,03	4,5	0,8	1,56	0,71	0,9

Figure 29: Impact of cutting dust on the printed samples - Percentage of the printed surface affected by the presence of cutting dust

The main conclusions are:

- First of all, the cut quality has a huge impact on the print quality of the paper when printed on a sheet fed offset press. At a same production rate the amount of dust disturbing the print quality can be up to 11 times worse after only 5000 cps (test1 vs. test7b).
- Difference from one sheeter to the other can be quite large. Although all measures were taken to produce similar cut quality on two sheeters (test1 vs. test7a), big differences were observed between the cut quality obtained and the print quality impact. This shows clear evidence that not only the paper, the cutting knife and position have an impact on the cut quality but also the sheeter itself (e.g. geometry, vibration, stability of the blade holder)
- Band edges are more sensitive to dusting (test1 vs. test2). This point has been clearly pointed out at the sheeter (see section 3.3) but also comes out during the printing test. In average, the amount of dust disturbing the print quality is multiplied by 2.
- The pallet cut at the guillotine was clearly presenting the best print quality over all the tests. Even though this result fits our cut quality evaluation, it was quite a big surprise for the people working in the sheeting department. Most of them thought that this cutting process was creating much more dust. Anyone who tries to pass his hand on the cutting edge of a pallet cut at a guillotine knows that his hand will turn out to be fully covered by white particles. This is simply due to the fact that the contact area in that case is much higher than the contact area obtained with a pallet cut at a standard sheeter due to the lower raggedness of the edges. Hence, the hand will definitely collect more dust but this dust is smaller and specifically located only on the edge. At a sheeter, cutting dust particles are located between the paper stack and up to a several centimetres in the paper sheet.
- Reducing the production rate by decreasing the number of sheets cut simultaneously did not show a significant impact on the print quality in our test (test1 vs. test5). This can be due to the fact that the blades were new and at this stage, the amount of dust or cracks generated during the cutting process is limited.
- The amount of dust in the printed area increases with the number of printed samples (i.e., coating particles accumulating on the blanket surface). This also fits with the experience of the printer as the cutting dust does not simply stay on the paper disturbing the print quality but travels in the printing press, as explained previously, and starts to accumulate in the system until a point where the print quality will not be acceptable anymore. Due to this effect, the printer will stop the printing press and perform a washing of the blankets. This operation is time and money consuming.

- The pallets cut with and without dust extractor system (test 7a vs. test 7b) show a significant difference. After only 5000 cps, conclusions are clear: even though both pallets had strictly the same cut quality, the pallet cut without dust extractor system presents two times more dust in the raster area. Therefore pallets cut with or without dust extractor system have to be compared separately.

In order to see whether the cut quality correlates to the print quality, the different correlations were studied. No correlation was found between the raggedness of the edges or the fibre pull and print quality or printing runnability. However, the number of cracks correlates to some degree with the print quality. To study the correlation between the number of cracks and the percentage of the printed area affected by cutting dust, the data were plotted as two separate series in **Figure 30** where the percentage of the printed area affected by the cutting dust after 5000 cps versus the number of cracks is shown. One series depicts the samples cut with the dust extractor system and the other depicts the samples cut without the dust extractor system. Only the pallets presenting the same type of cutting edges in contact with the blanket (blade edges) have been plotted (tests 2 and 9: band edges and test 3: cross edges).

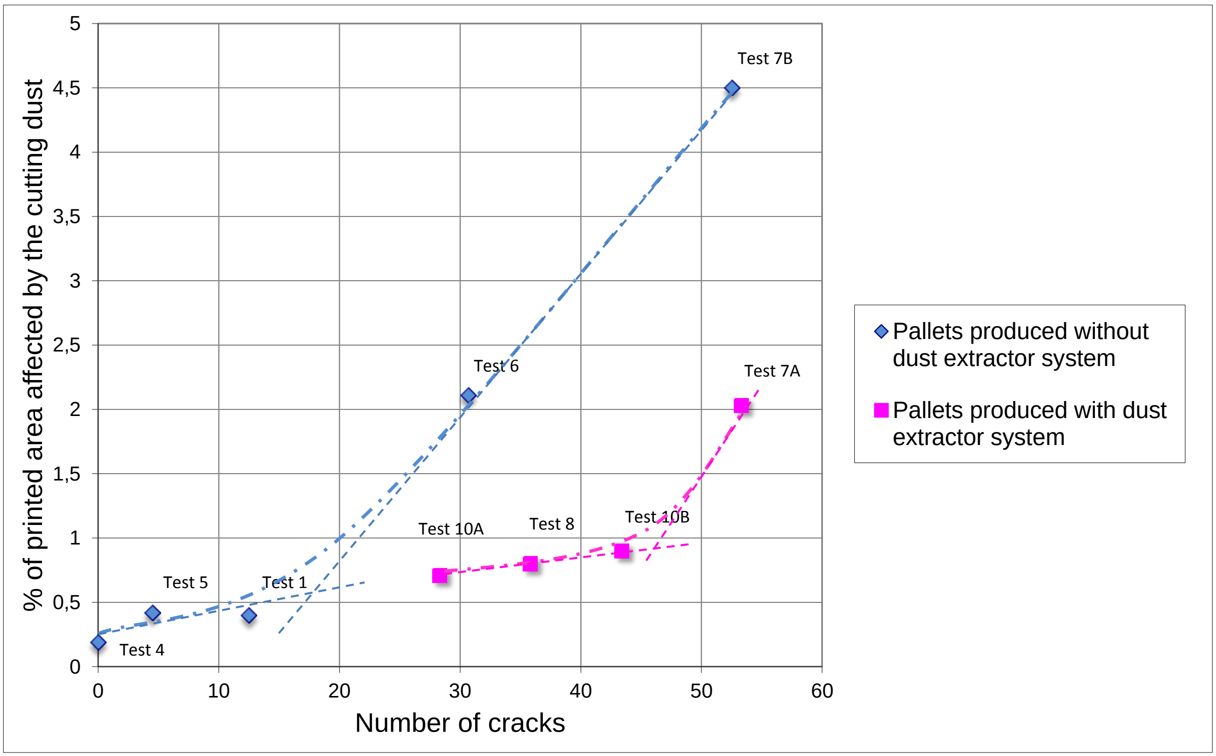


Figure 30: Correlation between the number of cracks per 5 cm and the percentage of printed area affected by the cutting dust

The number of cracks shows a clear correlation to the amount of dust on the printed samples after 5000 copies.

Correlation between the number of coating cracks and the printed area affected by the cutting dust is not surprising because weakly bound coating particles are easily released during the printing process because of the tack of the ink. One way to reproduce this effect is to look at the state of the coated layer before and after applying a simple transparent tape near the cutting edges (see **Figure 31**).

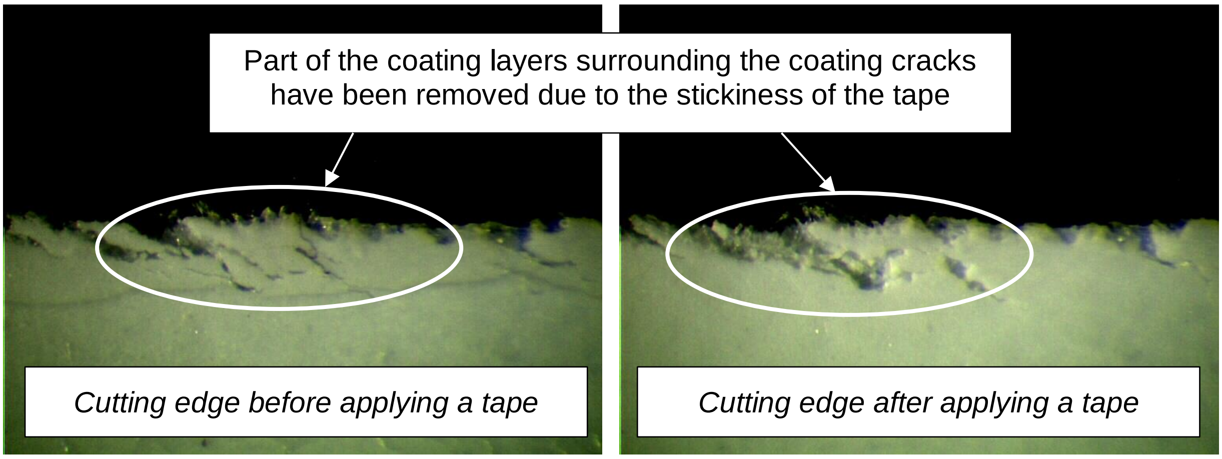


Figure 31: State of the coating layers before and after applying a tape on the surface

For both series, it can be observed that the number of cracks is not creating a major problem until it reaches a certain level: 15 without dust extractor system and 45 with dust extractor system. Above this level, print quality starts to deteriorate rapidly. Our hypothesis to explain this phenomenon is as follows:

- If the number of cracks is low, the strength of the coating layer is not affected significantly and an acceptable amount of dust will be produced.
- If the number of cracks is high, the coating layer will be weakened in several places (where the cracks are linking each other) and more dust will be released during the cutting process. Part of those dust particles, in the absence of a dust extractor system will locate in between the paper stacks on the paper surface near the cutting edges.

This test also illustrates the importance and efficiency of the dust extractor system. For example, pallets 7A and 7B are identical papers (same cut quality) and have been run at the printing press under the same conditions. Still, it can be clearly observed in **Figure 30** that, after 5000 copies, the printed area of sample 7B is significantly more affected by the presence of cutting dust.

It is due to the fact that, for the paper produced with dust extractor system, only the weakly bound particles nearby the cutting edges (where a lot of cracks are present) will be released during printing process. All cutting dust lying on the surface of the paper has been in theory removed by the dust extractor system. For the paper produced without dust extractor system, it will be a combination of the cutting dust lying on the surface of the paper and of the weakly bound particles located nearby the cutting edges.

Even though the printing tests proved that the cracks were a predominant factor to predict the cut quality, the measurement of the other parameters such as the raggedness (visual cutting edge aspect) and the dust amount on the paper surface (influencing the print quality at the printer) is of high importance. These parameters are important to understand the cutting process and what is happening within the paper structure.

To conclude, a quantitative and qualitative test method to evaluate the cut quality of the sheets produced has been implemented and presented in this chapter. The laboratory test method has been used on a daily basis and during all the tests made in the scope of this thesis. During the thesis, this test method has been widely used and turned out to be an efficient tool to follow and analyse the cut quality of WFC papers. This has also been very useful to study in detail the impact of the machinery parameters: results will be presented and discussed in chapter 4. In addition, a fast test to evaluate the dust generated directly at the sheeter has also been developed. This fast test to evaluate the dust at the sheeter was developed later on during this thesis and it is now used on demand by the operator to check the cut quality (for example to check whether it is time to change the cutting blades). Now that these tests have been described, one can analyse the cutting process itself and evaluate the influence of paper and machinery on the cut quality.

Chapter 4

Shearing process: Influence of material properties and sheeter settings on cut quality

In this chapter, the shear cutting process is described. The influences of the main paper properties on the cut quality are studied owing to a laboratory cutting device. Finally the impacts of the machinery settings on the cut quality are investigated.

4.1. Introduction

As Meehan and Burns mentioned in [38], cutting is a "*shearing and fracturing process for creating new surfaces*". The shearing and fracturing process describes the separation of a material due to the application of a shearing force on each side. The shearing force applied is the amount of force required to cut the material through shear. The force applied must create, within the material a shear stress exceeding its shear strength, leading to the fracture and separation of the material. Looking at the cutting methods used for paper, two of them can be classified as a "shear cutting process": the slitter (longitudinal cut) and the rotary cutting devices (cross cut). The slitting process is originally coming from the metal industry. It seems that first traces of slitting mills can be found around 16th century in Belgium. The slitting mill consisted of two pairs of rolls turned by water wheels. Shear cutting is nothing more than what is happening with a pair of scissors while cutting a sheet of material (see **Figure 32**). Indeed the effect of several influential factors on shear cutting can be easily experienced by simple trials using a pair of scissors. For example the effects of the knife angle can be imitated just by regrinding them as required and testing their efficiency on the material. .

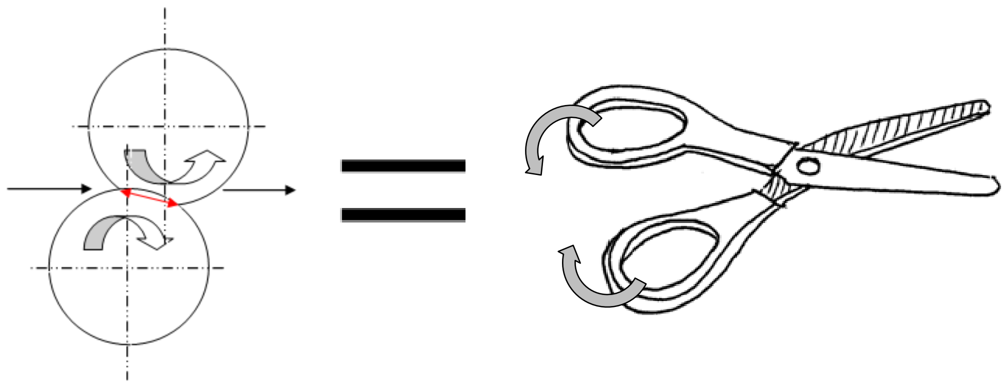


Figure 32: Shear cutting process

Shear cutting has been the subject of research, the majority of which refers to configurative and geometric arrangements of knives to obtain extended effective cutting action.

In this chapter, more than describing the cutting process, it is intended to link the observations coming from the test methods with the mechanical processes happening during cutting. This is very important because, as mentioned by Meehan and Burns in their work: "*The applied stresses in a web and the material's response to these stresses dominate the quality of the cut surfaces*." [38]. Doing so, it is expected to present a more understandable approach of the cutting process and to emphasize what can be done to improve not only the cut quality but also the productivity at the sheeter. This chapter starts to deal with the theory of shear cutting mechanism before presenting a laboratory cutting device developed to study the effect of WFC paper properties. Finally the influences of sheeter settings are studied in practice.

4.2. Description of the cutting mechanism: shearing process

In most of the literature, the full process is often divided in 3 phases: Deformation, pre shearing and shearing. In their work [38], Meehan and Burns proposed a model to describe the mechanics of cutting. Although their work was on cutting a web of polymer, this can be adapted to the case of a paper web. When cutting a material, most of the actions will happen in the out of plane direction. As mentioned by Stenberg [39]: "*Out-of-plane shear forces combined with high compressive loads are applied to the actual cutting area until the material finally breaks*."

4.2.1. Deformation

This phase starts when the knives come in contact with the paper surface. Depending on the sharpness of the knives and on the paper properties, the material will be compressed more or less between the knives before the knives penetrate in the substrate. This compression phase will take place until the resistance of the paper against deformation is lower than the intrinsic resistance of the material. Therefore the duration of this phase in case of paper will mainly depend on its bulk, its rigidity and of course of the sharpness of the knives because the smaller the area of contact between the knives and the material, the faster the penetration state starts (or the lower the cutting force is). This aspect was studied by Arcona and Dow **[40]**. They proved that the cutting force varies linearly with the blade edge radius. The evolution of the forces as a function of the blade edge radius was also constant and independent of the cutting speed.

4.2.2. Pre-shearing

Just after the compression phase, the knives will penetrate in the paper structure creating a shearing force. It will lead to an elastic/plastic deformation in the profile. The resulting forces/tension in the paper structure can/will result to a tearing of the paper.

4.2.3. Shearing

This is the main phase, the severing of the paper webs between the knives. Paper is a non-continuous material and when a tension is applied, it will have a tendency to break at the weak points. This action results to uncontrolled edges quality, the paper is just breaking due to the tension created within the paper structure. This is mainly influenced by the paper structure. When the paper enters a shearing nip, a stress is created inside the material (stress which is required to sever the paper webs). Meehan and Burns mentioned that: "*The* *mechanics of the material separation is determined by the local stresses near the tip of the cutting knife*" [38]. There are three main fracture mechanisms:

Crack opening (Mode I)
Shearing (Mode II),
Anti-plane shearing (Mode III)

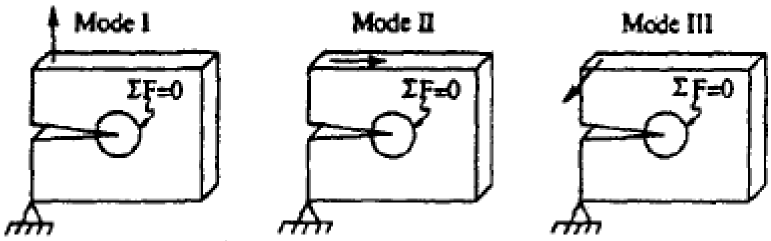


Figure 33: Main separation processes – source: R.R. Meehan and S.J. Burns [38]

Depending on the knives alignment and the web direction, a combination of these shear modes is created. When both knives come in contact with the paper webs, two forces oriented towards each other is generated. Any material will, under a certain strain, undergo a deformation even if this is not always visible with naked eyes (e.g. deformation generated by a car driving on a bridge). In case of paper, this deformation will be higher due to the relatively high compressibility of the material. Therefore both forces created by the sharp knives will create their own stress within the material. These two forces create within the material two "principal" stresses. In the case of a perfect continuous material where a force is applied on both surfaces in one point, a circle is obtained. This is called the Mohr representation of the strain (see **Figure 34**). The sum of the principal components of the stress tensor on the circle is constant. The consequence of having the principal stress components constant is that the shear stress on all planes is identically zero on the circle. The stress state is a two dimensional hydrostatic stress on the circle. This circle is unique and is observable in photo-elastic experiments because photo-elasticity measures the differences between principal stresses. Meehan and Burns measured it during their experience with polymer webs [38]. Interesting is the fact that even if the paper is a non-continuous material, these effects were also measured by Frye [35] with the help of a polariscope (photo elastic stress analysis, see **Figure 35**). In his study, he found that the amount of dust generated mainly on the trailing edge during the cutting process correlated to some extent with the number of fringe areas of stress. However and according to his findings: "limiting those fringes of areas solved part of the problem on the external sheets but not in the middle of the paper stack".

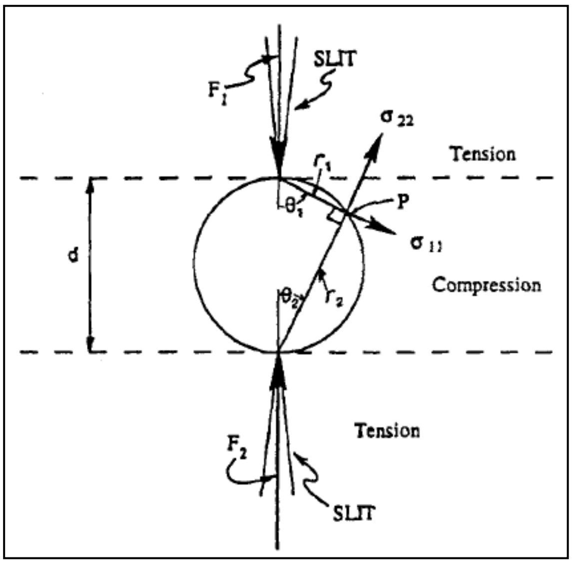


Figure 34: Schematic representation of two forces created when opposing two perfectly aligned sharp knives.

"A circle is drawn through the point of application of both forces. Diametrical compression measures the fracture stress of brittle material." – Source: Meehan and Burns ([38]

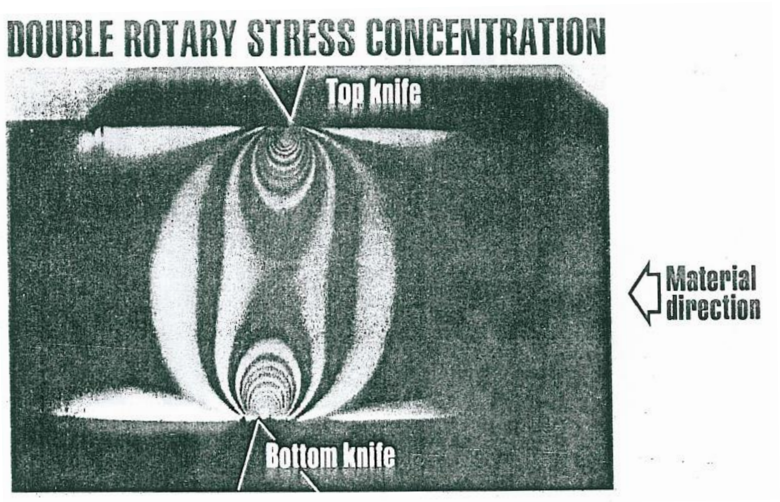


Figure 35: Stress developed during the cutting process within the paper thickness (resulting pictures obtained with a polariscope by Frye [35])

The study of those stresses required special equipment and might be not representative of the practice or at least difficult to link it with the practice due to the variation within the paper material and the very small area analysed with such tests. As we want to keep the outcome of this thesis as useful and practical as possible for the operators, it was decided not to go further on this specific method but to focus on the force required to shear a material under certain conditions.

4.3. Expression of the cutting force in case of shear cutting

Any force $\vec{F_z}$ applied on a material (on a small surface) can be separated in 2 components: a normal stress $\vec{\sigma}_{n,z}$ (equivalent to a pressure) and a tangential stress $\vec{\tau}_{t,z}$ [41] (see **Figure 36**).

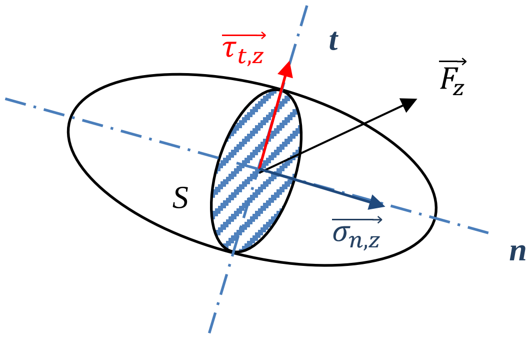


Figure 36: Representation of the vector force on a surface

As mentioned before, the cutting process can be compared to a shearing process: The force $\vec{F_z}$ is applied on the same plane as the surface *S* and the normal component of the force $\vec{F_z}$ is therefore neglected. Besides that, we consider that the force is parallel to the t axis.

$$\vec{F_z} = \vec{\tau}_{t,z}.S$$

Due to the configuration of the blade (length of the blade >> thickness of the blade), we will consider that the shearing occurred only in an orthogonal plane (0;$\vec{x}$,$\vec{z}$) (see **Figure 37**). Considering that the shear stress distribution on the main shear plane is uniform (wherever in the main shear plane, the shear stress is the same), the cutting force (shear force) will be proportional to the shear stress on the main shear plan.

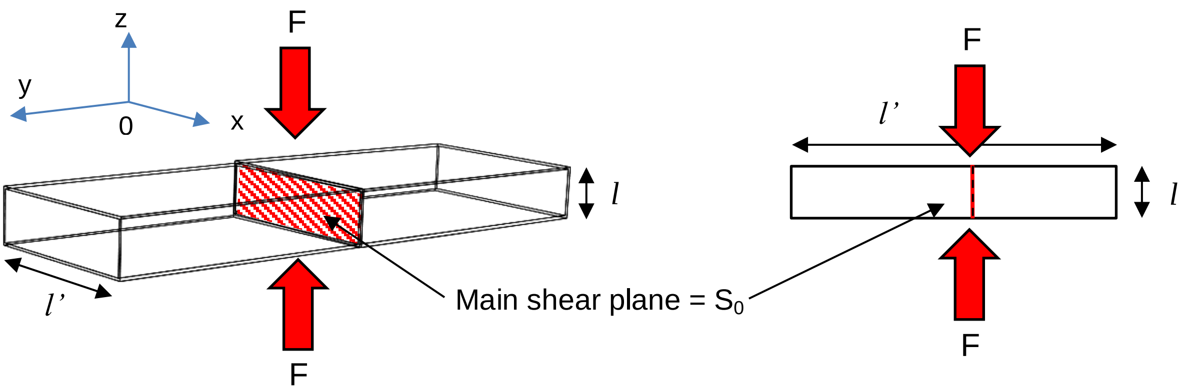


Figure 37: Schematic representations of the shear forces (F) and the main shear plane (S_0) – Perspective (left) and side view (right)

Equation 1: Expression of the shear force as a function of the shear stress and the main shear plane

$$F = \tau.S_0$$

With: F = shear force in N

τ = shear stress in MPa

S_0 = main shear plane in mm² (*l* x *l'*)

In the cutting process, the main shear plane corresponds to the transversal cutting section. The transversal cutting section is defined as the area of paper contained between the two knives (i.e. surface of paper posing a resistance to the knife penetration). In reality, depending on the cutting process, conditions will be slightly different due to the configuration of the cutting machine. For a top slitter and a rotary cross cutter, it can be a small gap between the knives called clearance ("*c*") which clearly modifies the main shear plane (see **Figure 38**) and needs to be considered.

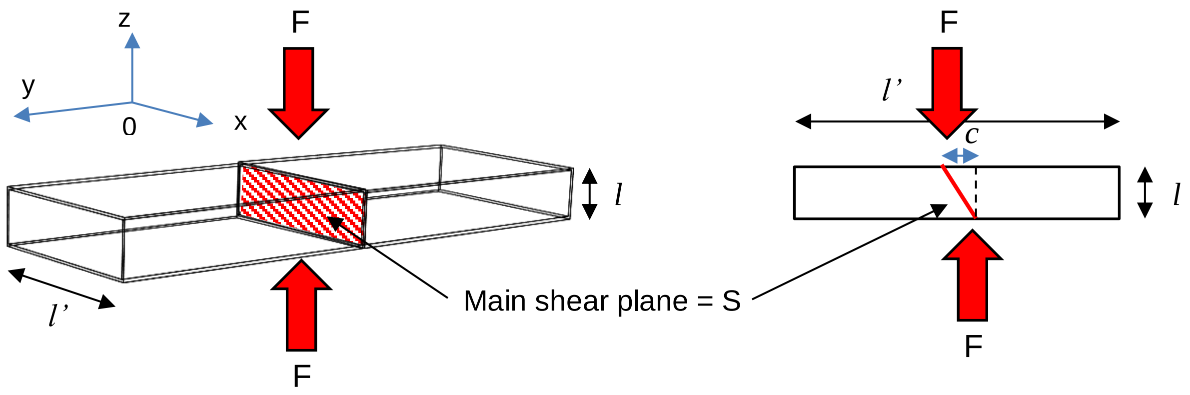


Figure 38: Schematic representations of the shear forces (F) and the main shear plane (S) at the sheeter - Perspective and side view

The main shear plane also called transversal cutting section can be expressed as a function of the clearance and of the ideal situation when both knives are perfectly opposed to each other:

Equation 2: Expression of the transversal cutting section in mm²

$$S_c = \frac{\sqrt{l^2 + c^2}}{l} . S_0$$

With S_c = transversal cutting section in mm² as a function of the clearance

S_0 = transversal cutting section in mm² with a clearance null

l = Thickness of the material being cut in mm

c = clearance in mm

With this formula, it becomes obvious that the higher the clearance, the higher the force required to perform the shearing process. Depending on the material being cut, the expression can be developed as follows [42]:

Equation 3: Expression of the shear force

$$F = k.\tau_0.\frac{\sqrt{l^2 + c^2}}{l}.S_0$$

With F = Cutting force in N

k = constant depending on the material properties (dimensionless)

τ_0 = Specific shear stress depending on the process condition in N/mm²

S = Transversal cutting section in mm²

c = Clearance in mm

l = thickness of the material being cut in mm

The specific shear stress can be expressed as the shear modulus G (also called module of rigidity) multiplied by the shear strain γ [43] .

Equation 4: Expression of the specific shear stress as a function of the shear strain and the shear modulus

$$\tau_0 = \gamma . G$$

With: γ= pure shear strain (dimensionless)

G= Shear modulus in Pa

Strain is normally defined as the deformation of a solid due to stress and can be expressed as the change of length divided by the initial length.

Equation 5: Strain expression

$$\gamma = \frac{\Delta l}{l}$$

With: γ= strain (dimensionless)

Δl = Change of length in mm

l= Initial length of the sample

Two kinds of “shearing” can be distinguished (see **Figure 39**):

- Pure shearing: It is a three dimensional homogenous flattening of a body. The forces applied by the knives are exactly opposite to each other. The paper material is shortened in one direction while being elongated perpendicularly.
- Simple shearing: It consists of a pure shearing process plus a rotation.

In both cases, the shear stress always creates in the material a shear strain. This shear strain corresponds to the deformation of the material. Experiences have shown that this shear strain is proportional to the initial thickness of the material.

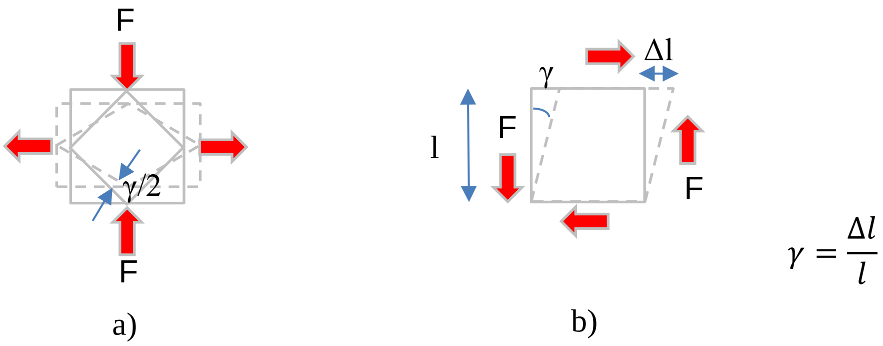


Figure 39: Comparison of (a) pure shear and (b) simple shear [44]

The shear strain is calculated in both cases as a function of the initial length. In case of simple shear, the calculation of the strain is very easy. In case of pure shear (a), it is a bit more complex but the development of the calculation leads to the following formula:

Equation 6: Expression of pure shear strain as a function of *l* and Δ*l*

$$\gamma = 2.\frac{l.\Delta l - \Delta l^2}{l^2 + 2.\Delta l^2 - 2.l.\Delta l} = f\left(\frac{\Delta l}{l}\right)$$

<u>Remarks:</u> *Calculations and hypothesis to reach this formula are detailed in **Appendix D**.*

So for both cases, γ can be expressed as a function of $\left({}^{\Delta l}/_{l}\right)$. To conclude, the force required to cut a paper materials depends on the resistance opposed by the paper itself to the penetration of the knives and of course of the sharpness of the knives (which directly influence the surface area where the forces are going to be applied). So the cutting force is expressed as:

Equation 7: Expression of the cutting force as a function of the shear strain, shear modulus and main shear plane

$$F = k.G.\frac{\sqrt{l^2 + c^2}}{l}.S_0.f\left(\frac{\Delta l}{l}\right)$$

In case of pure shearing, the shear modulus is expressed with the Poisson's ratio and the Young's Modulus. Under the assumption that the paper is considered as an isotropic material then:

Equation 8 : Expression of the shear modulus as a function of the Young modulus and Poisson's coefficient

$$G = \frac{E}{2.(1 + \vartheta)}$$

With ϑ, Poisson's ratio

E, Young's modulus in Pa

Poisson's ratio is defined as the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio contains a minus sign so that normal materials have a positive ratio (Positive Poisson's ratio: Material contracts when stretched and Negative Poisson's ratio: Material expands when stretched).

Equation 9: Expression of the Poisson's ratio [41]

$$\vartheta = -\frac{\varepsilon_{trans}}{\varepsilon_{longitudinal}} \qquad \& \qquad \varepsilon = \frac{\Delta l}{l}$$

With WFC papers, different Poisson's ratios exist depending on the position considered (pre-coating layer, top coating layer, base paper…). In average, coated papers have been reported to show negative Poisson's ratio values in the thickness direction [45]. FEM model for simulating slitting and guillotining were developed [46]. However any forces applied on a material cause further deformations which themselves are creating forces. These forces are difficult to calculate and to predict with inhomogeneous materials such as papers. Moreover in our case, we deal with triple coated paper which comprises a material composed of seven layers presenting different properties. Even though the technology and power of new computers allows billion of operations per seconds, the simple simulation of a cutting process is still time consuming and delivers results which are still questionable regarding their correlation with reality. Due to all the reasons mentioned above it was decided to consider the force given in equation 7 and to focus on practical tests and observations which can result in practical solutions directly applicable for the papermakers.

4.4. Laboratory measurements to study paper properties

Studying the influence of the paper properties in practice (at a commercial sheeter) is not realist for different reasons such as the costs involved to produce the needed paper reels, the time required and also the repeatability of the measurement. Therefore, a laboratory cutting device was designed and built in order to simulate the cutting process. The main target was to get a reliable and accurate cutting device to enable the study the cutting process and the influence of paper parameters such as fibre composition. Obviously, the expectation of getting similar cut quality in the laboratory on a small paper sample compared to practical conditions might appear impossible or even a fantasy. However, if we are able to record the development of the cutting force, then we could draw some conclusions on the cut quality at the sheeter. Indeed, there are some correlations between the applied stresses, the material properties and the cut quality. This was also observed by Meehan and Burns in their work: "*The applied stresses in a web and the material's response to these stresses dominate the quality of the cut surfaces*." [38]. The development of this apparatus was made within Sappi Fine Paper Europe S.A. by Penaso [47]. It is very important to have a clear view of the process and which kinds of influences are applied due to our actions to understand and properly interpret the results of the experiments. During the cutting process, the paper material is cut by two knives. In one case, the knives are fixed and the paper is transported through the nip (long cut) and in the second case, the paper is fixed and the knives pass through it (cross cut). In both cases, the paper material reacts to an external strain. With the laboratory cutting device, we are measuring this resistance of the paper. The force required to cut the paper is linked to the knives geometry and to the paper properties. As mentioned before, the shearing force applied is the amount of force required to cut the material through shear. The force applied must create, within the material a shear stress which exceed its shear strength, leading to the fracture and separation of the material. As illustrated in **Figure 40**, the fact that the resistance and deformation of the paper during the cutting process influences the process parameters makes the total process very complex. Therefore, being able to record this force is of high importance to understand the process. In order to take all possible parameters in account, a 5M approach has been used (see **Appendix A**).

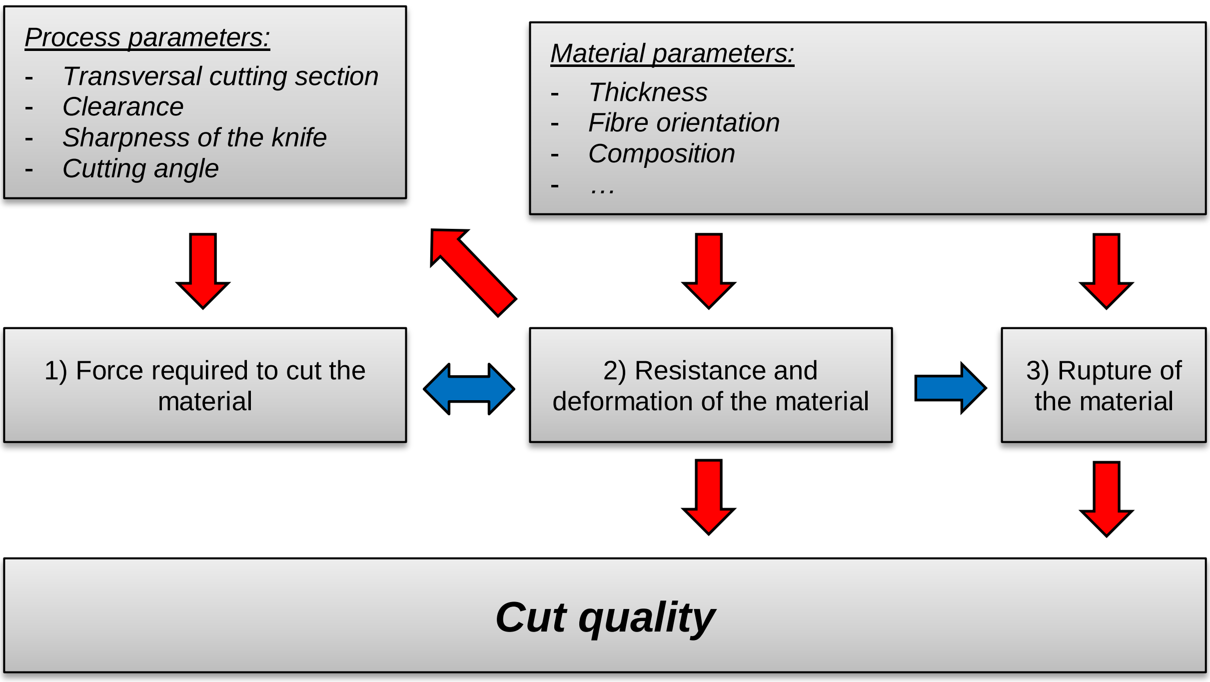


Figure 40: Schematic representation of the interactions between the different steps of the cutting process (1, 2 & 3), their influencing parameters and their influence on cut quality.

For given process conditions, it is important to keep the resistance and the deformation of the paper as low as possible to ensure the best cut quality

4.4.1. Description of the apparatus (developed by Penaso [47])

The main target was to design and implement a laboratory cutting device allowing the testing of paper properties in a fast and reproducible way. To reach this target, the Zwick device which is a laboratory apparatus to test the mechanical resistance of the materials has been used as a starting point. The Zwick creasing module (used to study the pre-folding of the paper) has been modified to receive a cutting knife (see **Figure 41**). The bottom knife ring was simulated by using the largest standard groove supplied with the creasing module. Those are perfectly ground with a 90° angle (see **Figure 42**). Maintaining contact of the upper shear blade with this “bottom knife ring” ensures the presence of a supported edge and an unsupported edge which is free to deflect.

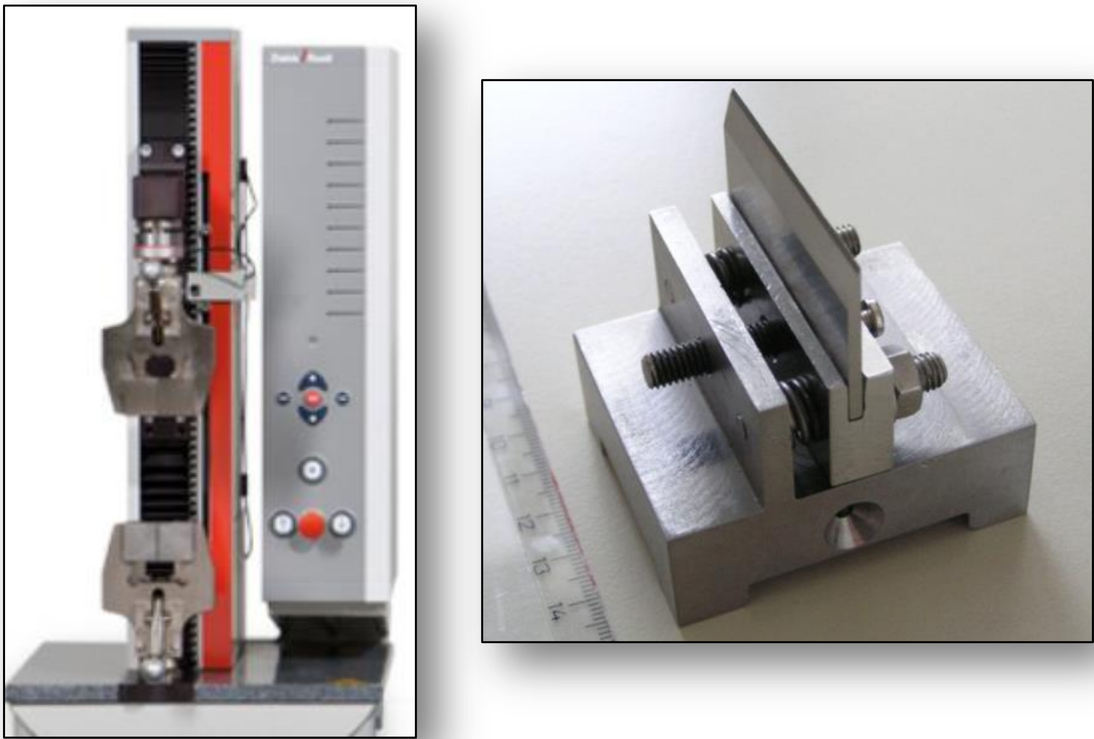


Figure 41: Zwick line testing machine, knife and knife holder designed for the laboratory cutting device. ***(Pictures from Penaso*** **[47]*)***

The general principle is quite simple: the upper shear blade is linked to a pressure sensor and its displacement can be accurately recorded. So, the force as a function of the knife displacement can be plotted. The paper sample (composed by x sheets) is placed on the bottom unit of the Zwick and its stability is ensured by the presence of 2 clamps. Holding the paper sample fixed during the process is important. Indeed, during the real production process, the tension of the paper web is controlled and maintained constant. All angles and geometries were adjusted and calculated in order to reproduce as well as possible the cutting process occurring at the commercial sheeter. During a cutting test, the upper unit of the Zwick will first reach a “0” position at low speed and after waiting few seconds to ensure a perfect stability of the system, the upper unit will go down at a constant speed until reaching a "end" position where all the paper material has been cut (shear between both blades).

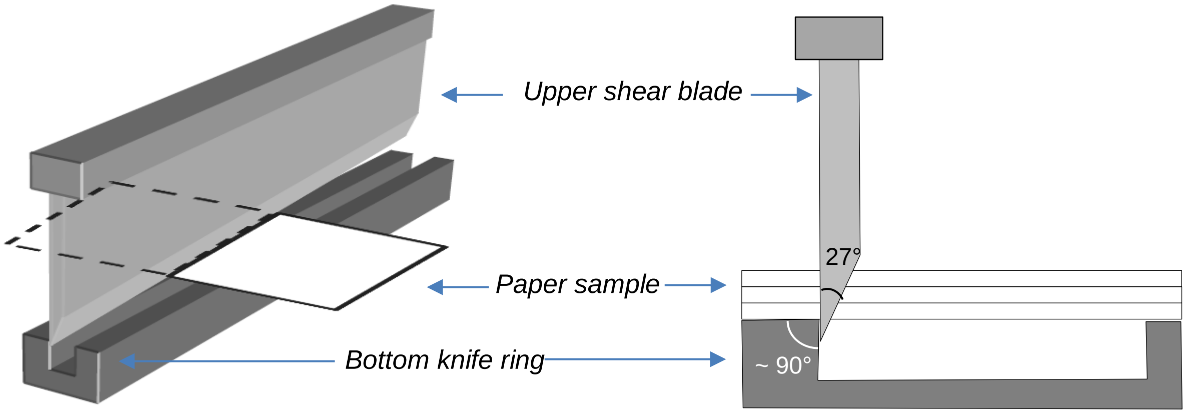


Figure 42: Perspective and front representations of the main parts of the laboratory cutting device: upper shear blade, bottom knife ring and paper sample at the beginning of the cutting action

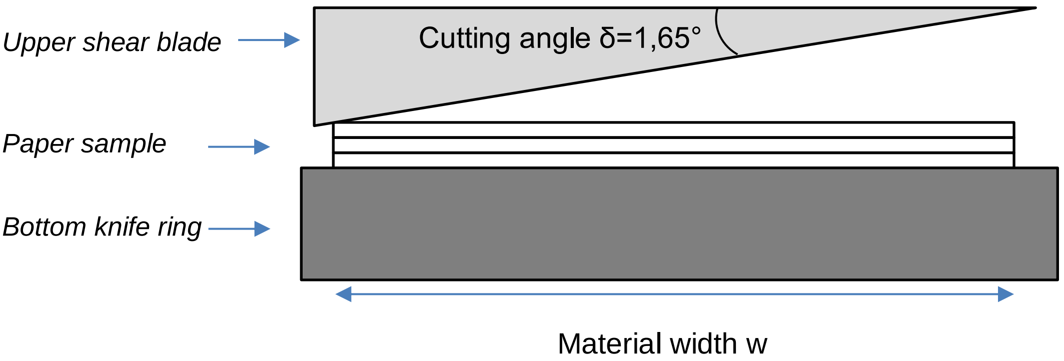


Figure 43: Side view of the laboratory cutting device and paper samples.

As mentioned in the first part of this thesis, the position of the blade plays a major role in the cut quality and as expected, it is also found to be the case in the laboratory. Therefore, special attention was given to position the knives. Strain gauges were used to ensure a perfect alignment of the blades (see **Figure 44**).

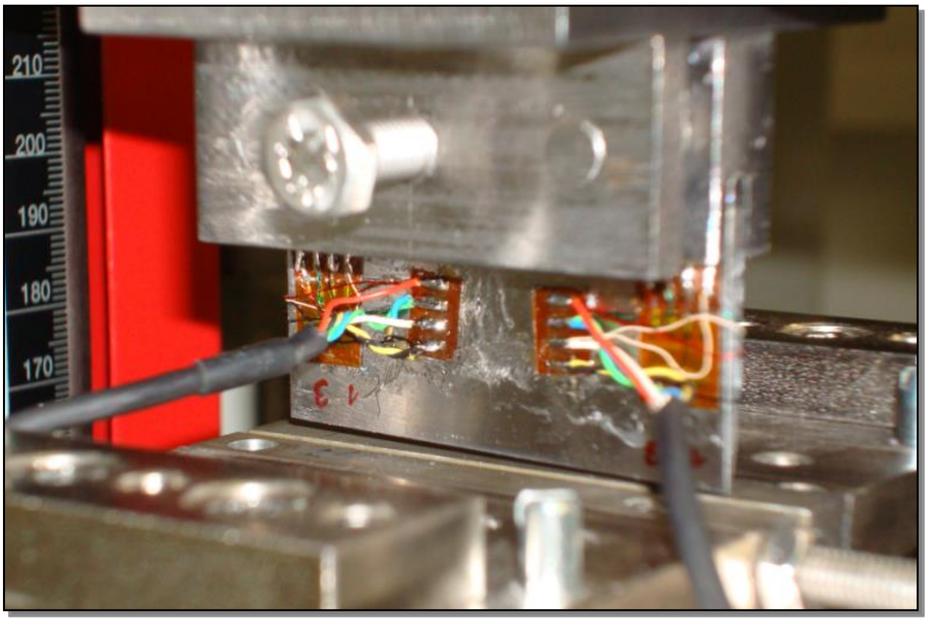


Figure 44: Strain gauges used to ensure perfect alignment of the blade
Source: Picture from Penaso [47]

The choice of the blade material was also carefully made and similar material as on the sheeters was used to produce the cutting knives: Alloy steel S790 from the company Böhler Miller [48]. The penetration speed (speed in the z-axis) of the blade in the paper material was performed at 0,8 m/min. During the cutting process, the paper strips were clamped on both sides to ensure their stability during the cutting process and to reproduce the tension of the web at the commercial sheeter. One side is maintained by the so called “bottom knife ring” and one side is free to deflect as it is in practice. All those efforts have resulted to the development of a highly accurate device allowing reproducible measurements. More information about the device can be found in the thesis of Penaso [47].

This system allows recording the cutting forces during the full cutting process as a function of the penetration of the knife in z-direction. Several phases can be observed when looking at the curve (see **Figure 45**):

1: *The knife is going down until reaching the paper surface (cutting force = 0).*

2: *The knife is in contact with the paper surface and starts the cutting process (compression in a first step followed by the cutting). The amount of paper being cut is increasing until the knife reaches the bottom side of the last layer being cut. The duration of this phase is clearly linked with the thickness of the paper stack. Based on the material structure and composition, the forces will increase more or less.*

3: The amount of material being cut is now constant and the cutting point is moving along the paper sheet (the cutting force is constant).

4: The first layer of paper has been completely cut and therefore the amount of paper being cut is slightly decreasing (It results of course in a decrease of the cutting force).

5: The cutting process is finished; all the paper material has been cut (cutting force = 0).

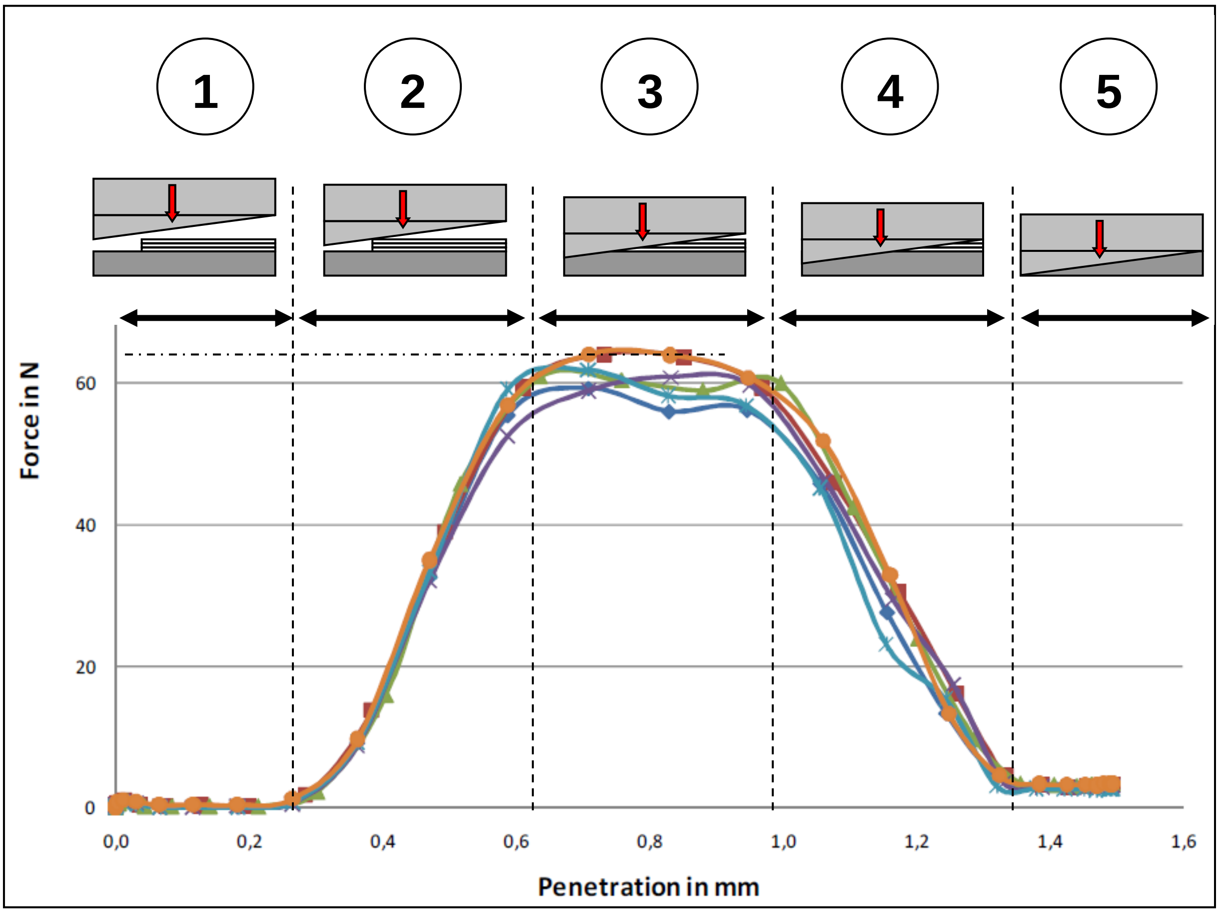


Figure 45: Evolution of the force during the cutting process and schematic representation of the cutting steps (six measurements are performed to ensure repeatable average values)

Finally, to check the validity of the assumptions regarding the phases occurring during the cutting process, several tests were performed where the cutting process was stopped within the different phases. By doing so, it was possible to check the state of the paper layers to confirm our results. Observations of the paper layers in the different phases of the cutting process are summarized in **Table 3**.

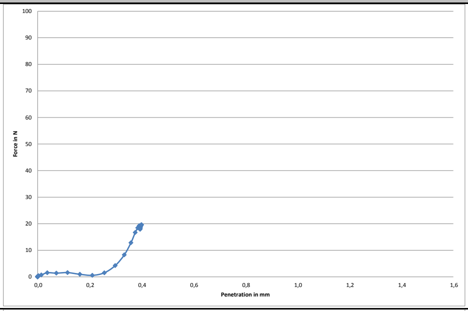
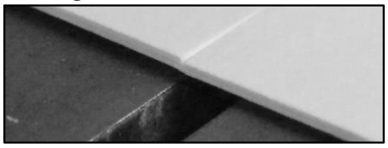
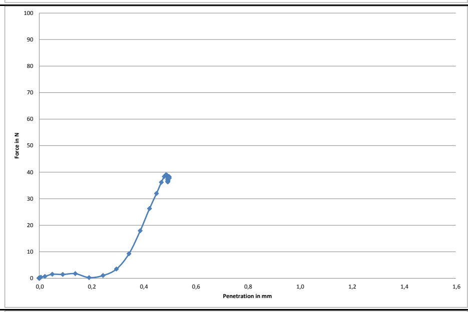
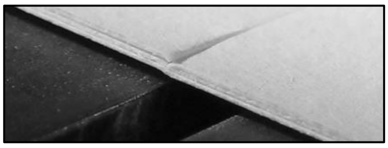
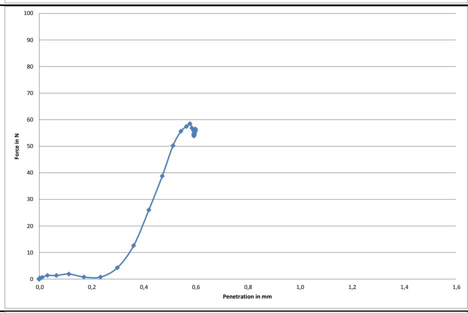
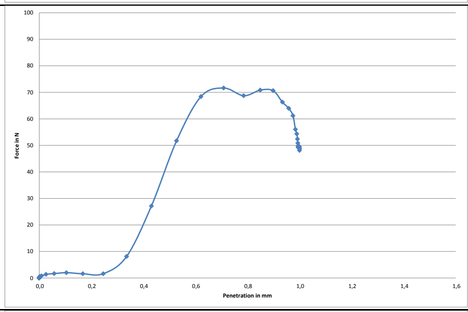
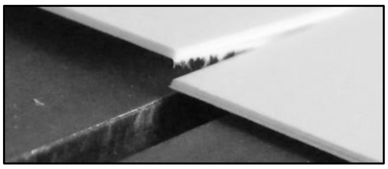
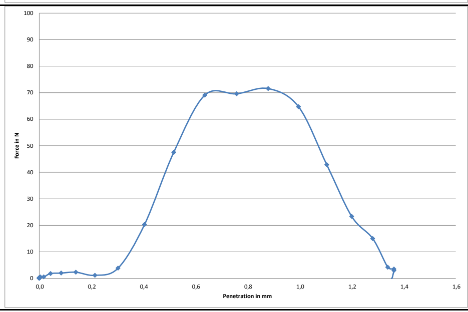
Test settings	***Curve obtained***	***State of the paper layers***
Test 1 (stop after 0.4 mm)		The first layer has undergone a stress but is not cut (only strongly folded). Other sheets present just a folding mark: 
Test 2 (stop after 0.5 mm)		The knife has now clearly cut part of the first layer, the second layer is partly cut and the third only embossed: 
Test 3 (stop after 0.6 mm)		The knife has penetrated the 3 layers and is now going through them: 
Test 4 (stop after 1 mm)		All layers are now clearly being cut (only the last one is not yet fully cut): 
Test 5 (full test: stop after 1.4 mm)		All layers have been cut

Table 3: Description of the paper states during the cutting process

From this curve, several pieces of information are obtained (see **Figure 46**):

- *The maximum force required to cut the material (F_{max} also called cutting force), it depends on the material being cut and on the surface below the cutting blade,*
- *The energy required to reach F_{max}, (W_E),*
- *The energy to close the cutting process (W_S),*
- *The energy required to cut the full piece when F = F_{max} (W_P): this energy is directly related to F_{max} and on the total width of the sample,*
- *The total energy, $W_T = W_E + W_P + W_S$, required to perform the cutting process,*
- *The slope of the curve at the beginning of the measurement and at the end,*
- *The start and finish measurement points, depending on the thickness of the paper and on its width,*
- *The width of the plateau (when F = F_{max}): it depends on the width of the sample, the thickness of the paper stack and the cutting angle. Indeed, the lower the cutting angle, the smaller the plateau for a defined sample width.*

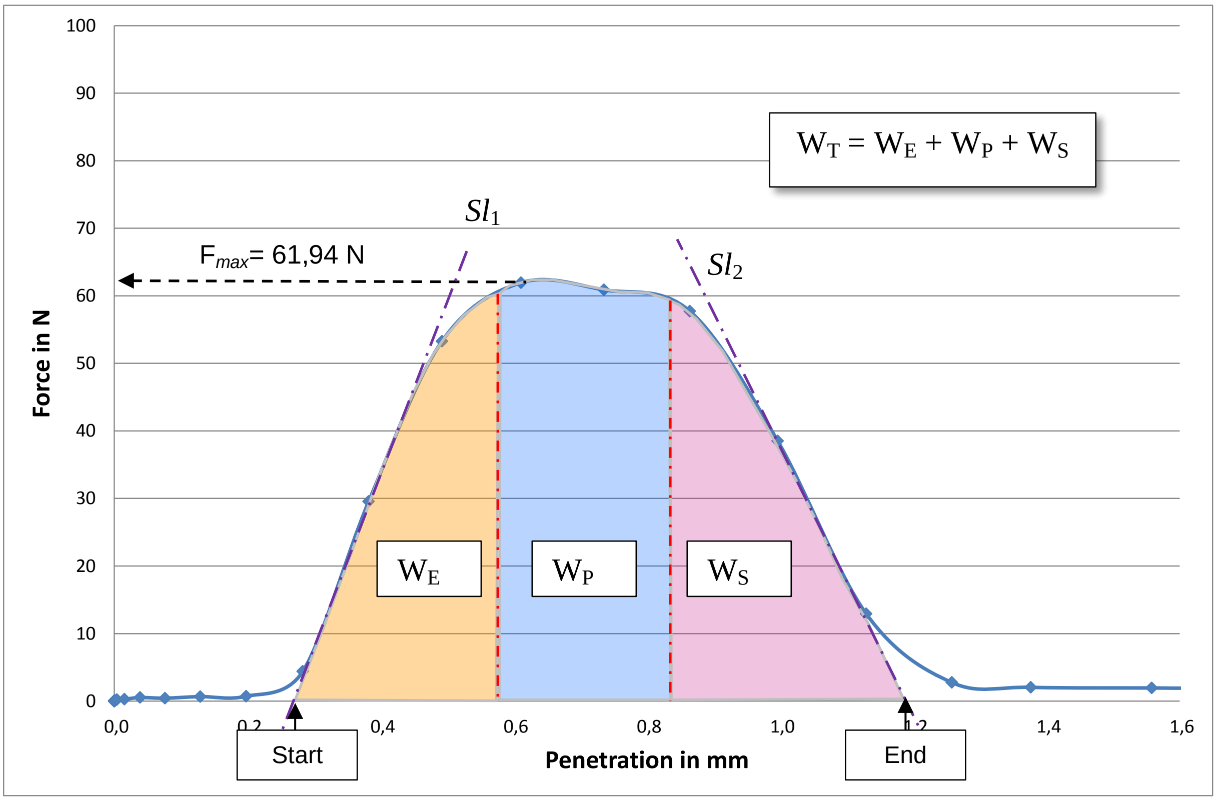


Figure 46: Interpretation of the cutting curve and information observed

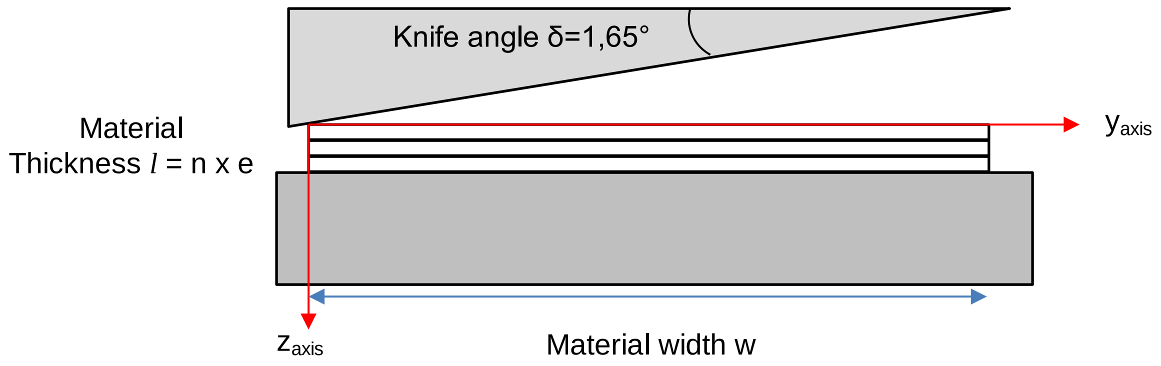
The reproducibility of the measurement was measured with a deviation up to 2,5% for the maximum force within the same series. This deviation is explained by the limited measurement points at F = F_{max}. Since this device is used to simulate a shear cutting process, the evolution/shape of the curve during the cutting process can be explained by applying the equation of the cutting forces. As mentioned in chapter 4, the cutting force depends on the shear stress, the cutting section (depending on the geometry and the material thickness) and the material characteristics.

Equation 7: Expression of the cutting force as a function of the shear strain, shear modulus and main shear plane

$$F = k.G.\frac{\sqrt{l^2 + c^2}}{l}.S_0.f\left(\frac{\Delta l}{l}\right)$$

When looking at the cutting curves, there are three main phases where the cutting force is not zero: 2, 3 and 4 (see **Figure 46**). The transversal cutting section develops during those phases and can be calculated.

The following system is considered:



With *l*, material thickness

n, number of sheets being cut simultaneously

e, thickness of one sheet

Figure 47: System used for transversal cutting sections and forces calculations

At any time t, the following equation is verified:

Equation 10: Blade's angle as a function of knife position

$$\tan\delta = \frac{z_t}{y_t}$$

With: δ the angle formed between the knife and the paper surface (cutting angle)

z_t, position of the tip of the knife at the instant t at y=0

y_t, position of the knife at the instant t at z=0

- <u>In the phase 2: $0 < z_t < n \,.\, e$</u>

In this phase, the transversal cutting section will increase continuously until the tip of the blade reaches the bottom knife ring at y = 0. In **Figure 48** below, two different positions of the blade during this phase are illustrated. In orange, the transversal cutting section is represented.

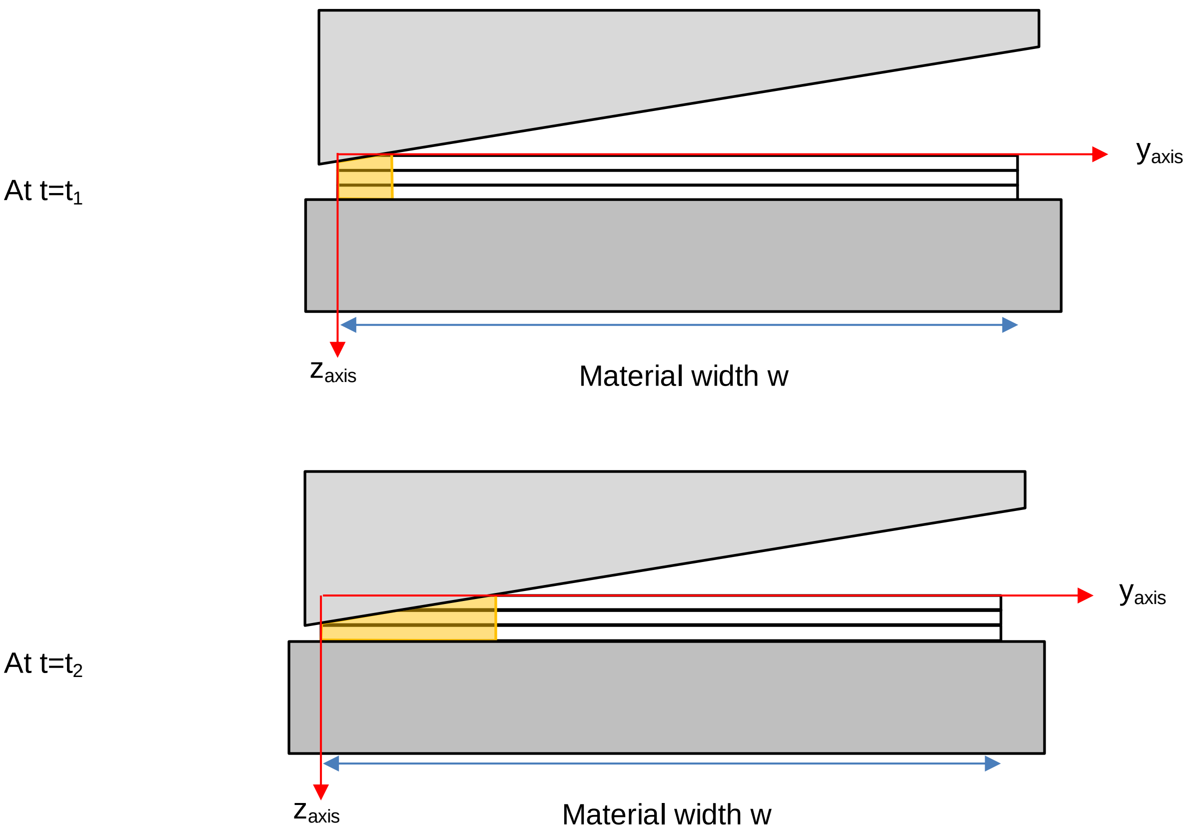


Figure 48: Representation of the transversal cutting section during the first cutting phase (phase 2) at two instants t_1 & t_2

The transversal cutting section (area below the knife) is calculated as the difference of two areas (total paper area below the upper shear blade touched by the blade – areas which have been already cut by the knife).

Equation 11: Transversal cutting section expression during phase 2

$$S_2 = n \,.\, e \,.\, y_t - \frac{z_t \,.\, y_t}{2} = \frac{z_t \,.\left(n \,.\, e - \frac{z_t}{2}\right)}{\tan \delta}$$

So the cutting force during this phase evolves like a parabolic curve:

Equation 12: Cutting force expression during phase 2

$$F_2 = k \, . \, \tau_0 \, . \, \frac{z_t \, . \left(n \, . \, e - \frac{z_t}{2} \right)}{\tan \delta}$$

- <u>In the phase 3: d < z_t < w.tan δ</u>

The transversal cutting section (area below the knife) in this section is constant (but being shifted along the y_{axis}).

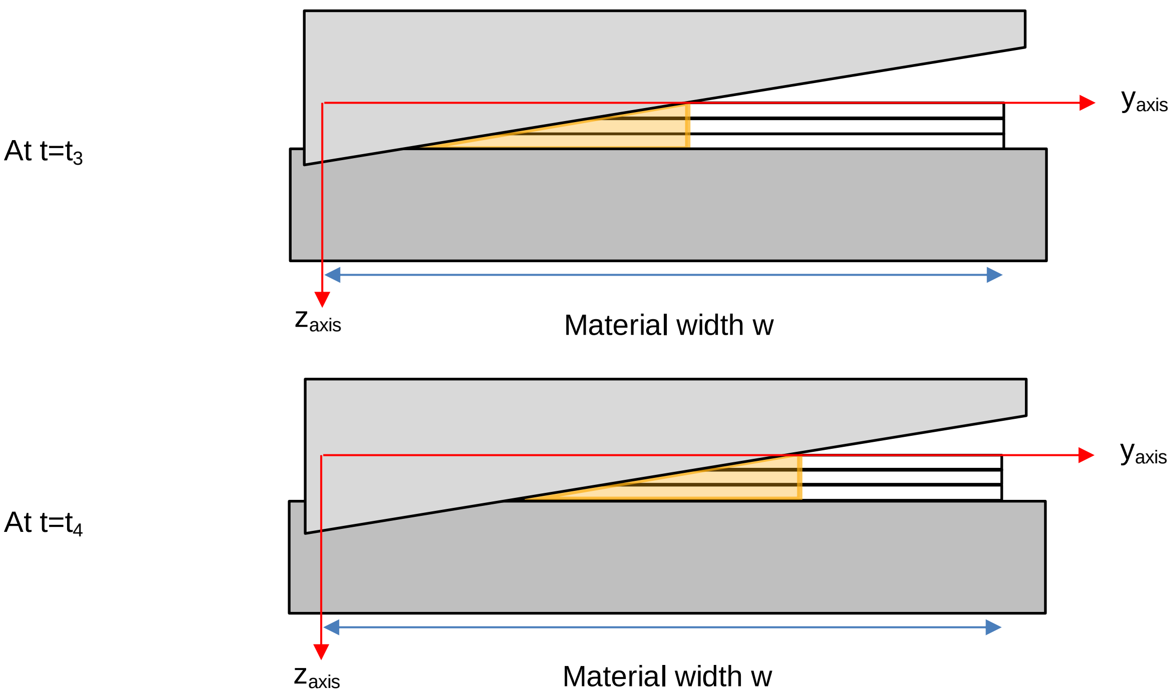


Figure 49: Representation of the transversal cutting section during the second cutting phase (phase 3) at two instants t_3 & t_4

The transversal cutting section here is simple to calculate; it is the half of the rectangle having a height of $n \, . \, e$ and a width of y_e and can be calculated as follow:

Equation 13: Transversal cutting section expression during phase 3

$$S_3 = \frac{n \, . \, e \, . \, y_e}{2} = \frac{n^2 \, . \, e^2}{2 \, . \, \tan \delta}$$

with y_e being the width of material under the blade for z = n . d

So the cutting forces will also be constant in this phase and independent of the sample width. The force reached in this phase corresponds to the maximal cutting force. It can be expressed as:

$$F_3 = F_{\max} = k \, . \, \tau_0 \, . \, \frac{n^2 \, . \, e^2}{2 \, . \, \tan \delta}$$

Equation 14: Expression of the maximal cutting force (cutting force phase 3)

$$\Rightarrow \quad F_{max} = k.G.\frac{\sqrt{n^2.e^2+c^2}}{n.e}.\frac{n^2.e^2}{(2.\tan\delta)}.f\left(\frac{\Delta l}{n.e}\right) = k.G.\frac{\sqrt{n^2.e^2+c^2}}{(2.\tan\delta)}.f(\Delta l)$$

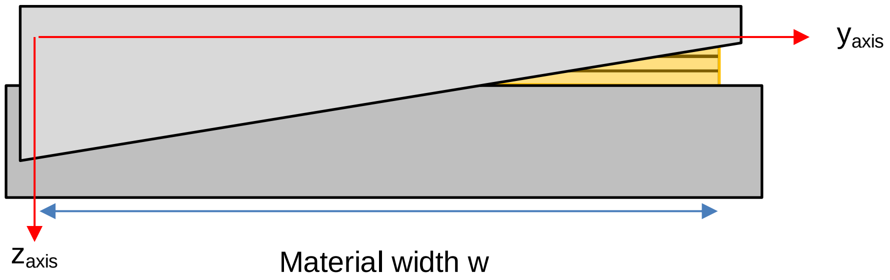
This equation clearly shows:

- The importance of having a cutting angle (δ) when cutting the paper webs: indeed, the function y=tan(x) has the following rules: tan(0) → 0 and tan(90) → +∞. It means that if the angle is close to 0, the cutting forces will clearly increase and tends towards +∞ while the higher the angle, the lower the cutting force will be.
- The negative impact of the clearance: the higher the clearance, the higher the cutting force.
- The negative impact of the number of sheets being cut simultaneously, any additional sheet cut simultaneously will increase the transversal cutting section by the power of two. It will also result in an increase of the cutting force.

- In the phase 4: w.tan δ < z_t < w.tan δ + n . e

The knife has now reached the end of the first layer top (y=w) and the surface below the knife will start to decrease. In this phase, the area below the knife is permanently a trapezoid shape.

At t=t_5



At t=t_6

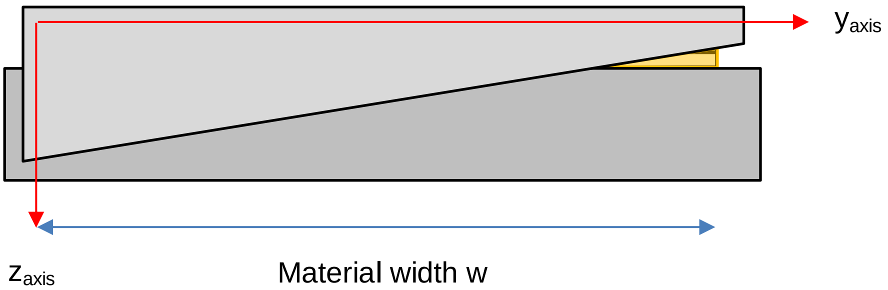


Figure 50: Representation of the transversal cutting section during the third cutting phase (phase 4) at two instants t_5 & t_6

In this phase, the surface can be calculated as follow:

Equation 15: Transversal cutting section expression during phase 4

$$S_4 = \frac{1}{2}.(w.\tan\delta + n.e - z_t).\frac{(w.\tan\delta + n.e - z_t)}{\tan\delta} = \frac{(w.\tan\delta + n.e - z_t)^2}{2.\tan\delta}$$

So the cutting force will be:

Equation 16: Cutting force expression during phase 4

$$F_4 = k.\tau_0.\frac{(w.\tan\delta + n.e - z_t)^2}{2.\tan\delta}$$

In order to give an idea of how the transversal cutting section is evolving during the test, this area has been plotted as a function of the knife displacement (z-axis) considering a standard thickness of e=100 µm and 3 sheets being cut simultaneously (see **Figure 51**). The development of the surface by the power of two with the number of sheets in phase 3 can be clearly observed.

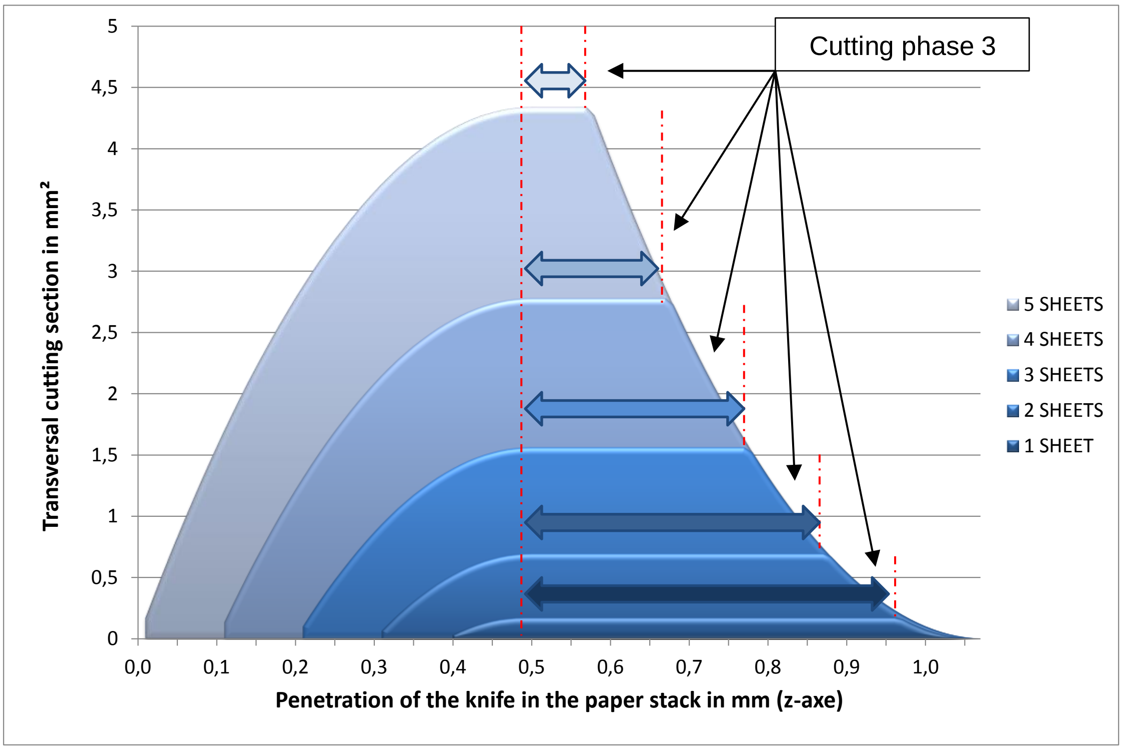


Figure 51: Evolution of the transversal cutting section as a function of the knife displacement (z-axis) for different numbers of sheets being cut simultaneously

When looking at what actually happens at the sheeter in practice, the cutting process is mostly taking place in phase 3 where the cutting force is maximal and constant. It is always the case at the slitter and 99,9% of the time at the rotary cross cutter. Therefore, only the information collected in this phase (F_{max}) will be used to explain the differences and to analyse the cutting parameters.

4.4.2. Industrial practical trials vs. laboratory tests

4.4.2.1. Paper web behaviour and stability during cutting

Before looking at the influences of the paper properties, it is important to understand the paper behaviour during the cutting process. Indeed, depending on the cutting edges, the paper webs do not behave the same. Several trials were made with a high speed camera (see **Figure 52**) to observe what is happening to the paper webs during the cutting process. These tests make it possible to view and understand the differences between a ”supported” (band side) and an “non supported” (blade side) edge. As mentioned by Meehan and Burns [38], the paper stability clearly affects the forces during the cutting process and most probably the cut quality. Pictures of the paper webs at different penetration times of the blade have been taken at our laboratory cutting device and are shown in **Figure 54**. In these pictures, it can clearly be observed that the webs on the band edges are very stable during the full process while the webs on the blade edges are free to deflect and undergo several movements. The reasons for this instability on the blade edges are the thickness of the blade going through the materials forcing it to move away and its response, influenced by its physical properties, to these external forces. On a microscopic scale, the paper webs are more or less compressed and folded depending on their position before being sheared. This was unfortunately not possible to be filmed precisely but, further on in this thesis, **Figure 120** gives a good representation of a material deformation before reaching the shearing process. Similar tests were performed on a commercial sheeter but unfortunately it was not possible to get a proper view to really differentiate the layers or to see whether the upper web is torn before the cut point or not. The main issues when performing these tests are:

- The high light flux required to take up to 8000 pictures per second and unfortunately, the blades are made of a very smooth metal which strongly reflects the light. As a consequence, everything turns out to be white around the blade tip (see **Figure 53**). A solution to avoid this problem could be to cover the blade with a matt coating layer or fit colour filters and polarizing filters to the camera lens assembly. Due to time limitation, it was not possible to test this solution.
- The area just upfront to the cut point is the area of interest but due to the blade diameter and diverse security protection placed around the blade, it was not possible to focus on this area with our standard sheeters.

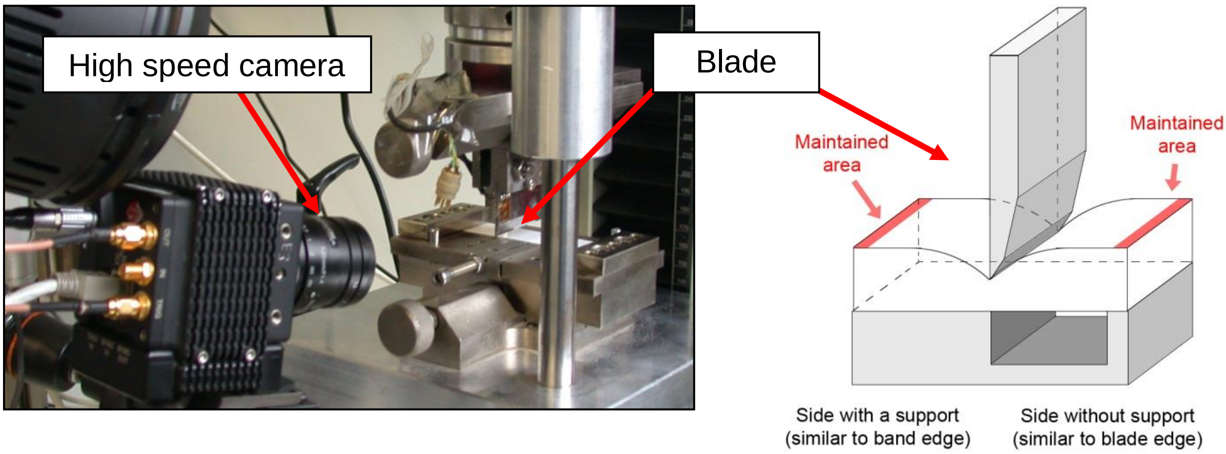


Figure 52: Installation of the high speed camera to observe the webs displacement during the cutting process and schematic representation of the blade adjustment (the blade is 5 cm wide)

Figure 53: Upper shear blade in rotation

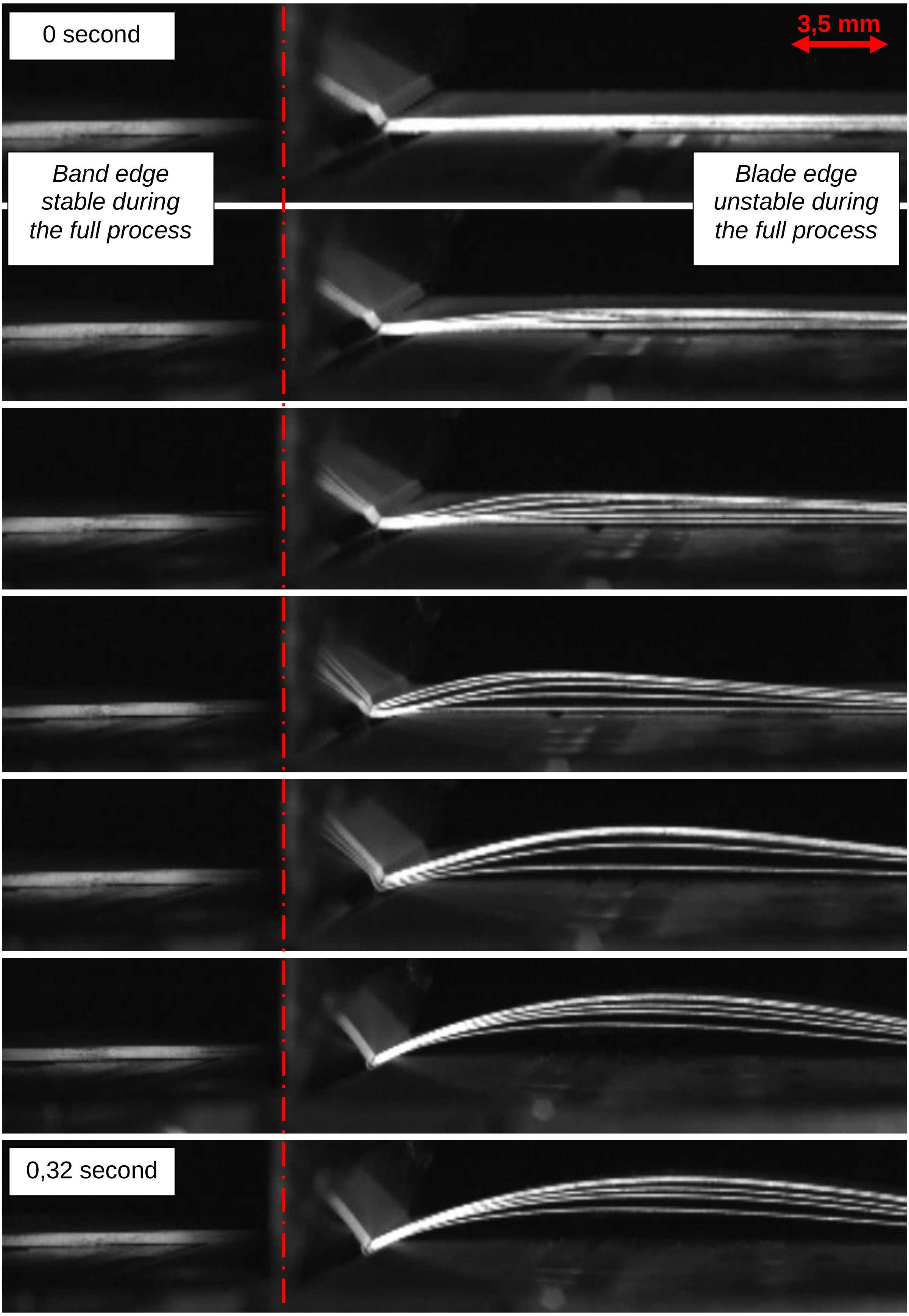


Figure 54: Paper webs behaviour on a macroscopic scale during cutting (simulation in the laboratory of 5 webs being cut simultaneously) – the red dotted line corresponds to the blade position

4.4.2.2. Quality of the cut

Even though attention has been made to produce and develop this laboratory cutting device, it is not a commercial sheeter. To check whether the cut quality obtained with both systems can be compared, the following test was performed [47]: 4 different paper grades (2 gloss and 2 matt grades) were collected at the sheeters and their cut quality was fully analysed in the laboratory. These samples were afterwards cut with the laboratory cutting device and their cut quality was compared to the samples obtained at the sheeter.

The following conclusions were made:

- The raggedness of the edges and the fibre pull obtained with the laboratory cutting device is better and cannot be compared with practice even though similar trends are being observed. For example, raggedness increases with the number of sheet being cut. As mentioned by Penaso [47], a possible explanation could be the stability of the process and the perfect knife quality and adjustment in the laboratory.
- As observed in practice, the presence of cracks is also detected on the samples cut with the laboratory cutting device. By comparing the samples cut on the commercial sheeters to those cut with the laboratory cutting device, it is possible to see a correlation ($0,7 < R^2 < 0,82$) only when focusing on the bottom side of the paper layers on the band edges (supported side). When focusing on those areas, several observations are common:
    - *Higher number of cracks present on the first sheet to be cut*
    - *Medium number of cracks observed on the sheets located in the middle of the paper stack*
    - *Almost no cracks observed on the last sheet being cut.*
    - *More cracks created when performing the cut parallel to the main fibre direction (LC).*

To conclude, it was not possible to establish a 100% correlation between the cut quality obtained in the laboratory and the samples cut at the commercial sheeter. This is not really surprising considering the complexity of the cutting process and the number of factors influencing the process. The reproducibility obtained with the laboratory device is at a good level. This allows us to use the laboratory device as a model system to compare different papers and study whether there is a relationship between cutting force and cut quality. Since similar trends are being observed between practice and laboratory experiments, it could be possible to predict to some extent what is happening in practice from parametric laboratory studies.

4.4.3. Paper effects

WFC paper, due to its composition and structure, presents some particular properties compared to other materials which are important to keep in mind. The main ones are:

- *Paper is an anisotropic material which means that its mechanical properties will depend on which direction the strain is applied. Particularly for cutting, different levels of forces will be required and different cut qualities will be obtained depending on the direction where the cut is performed.*
- *Paper is a visco-elastic material and to some extent, the paper materials will be able to absorb the deformations applied.*
- *Wood free coated papers are composed of different layers having completely different properties: base paper, pre-coated layer, middle coated layer and top coated layer.*

Besides being composed of completely different components, the base paper and coating layers mainly differ from each other with respect to their mechanical properties. Depending on its properties, the base paper will be able to elongate to some extent contrary to the coating layer. It is expected that during this phase, some cracks will appear within the coating layer which follows the base paper. This can be easily simulated by doing a tensile test. **Figure 55** shows the state of the coated paper surface after performing tensile tests in both directions (machine direction and cross direction).

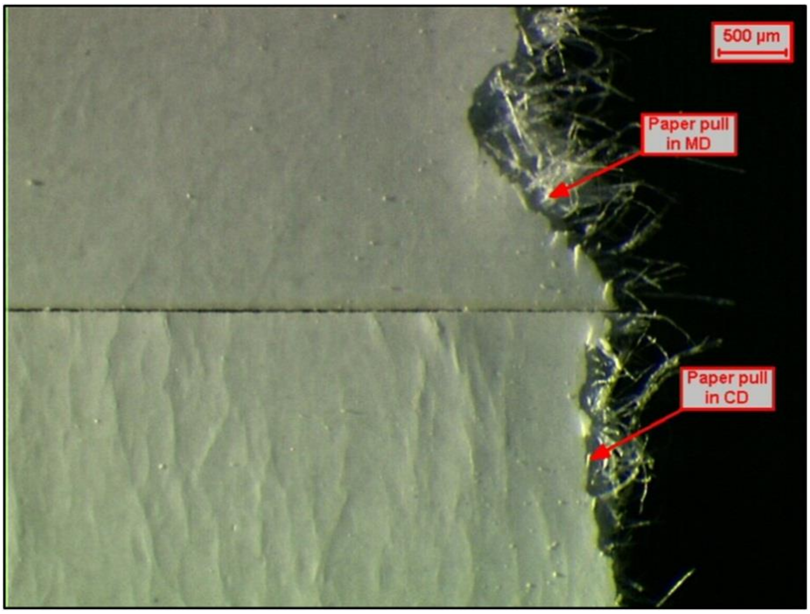


Figure 55: Differences observed at the surface of the coated paper after performing a tensile test in machine direction and in cross direction.

Observation of the paper surface with a microscope shows thousands of small cracks all over the paper surface perpendicular to the strain direction applied. A large difference can be noticed between a paper which has been elongated in the machine direction and a paper which has been elongated in the cross direction with more cracks generated for the test performed in cross direction. This is due to the higher potential for the base paper to elongate in this direction. Indeed, it is well known that the paper shows a higher stretch in cross direction than in long direction (up to 5% compared to 1-2% for WFC papers) before breaking. This effect is also observed when cutting the paper webs at the sheeter. Around the cut point, a tension is created in the paper webs. If the paper is cut in long direction (parallel to the fibre orientation), an elongation will occur in cross direction and vice versa, if it is cut in cross direction, an elongation in machine direction will take place. Therefore, more cracks are generated at the sheeter when cutting in the long direction (when cutting the same number of sheets at once). These differences are represented in **Figure 56**.

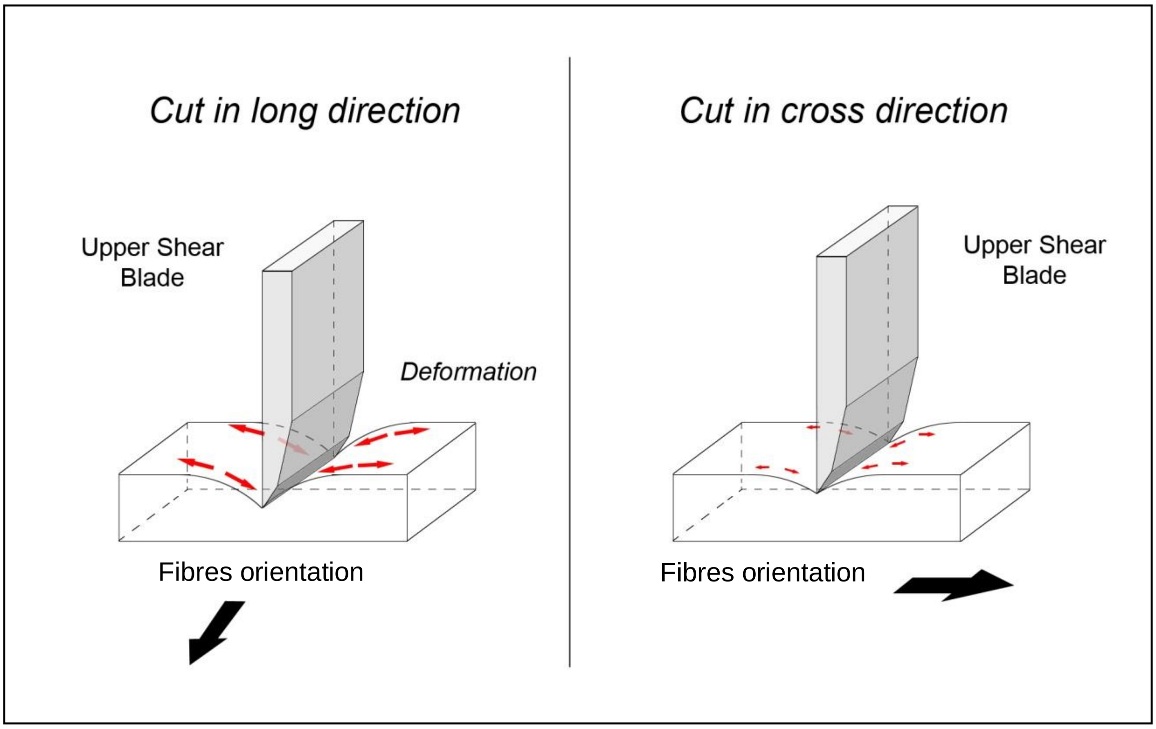


Figure 56: Schematic representation of the cutting process to explain the differences between long and cross cut concerning the paper deformations just before the knife is penetrating in the paper web

4.4.3.1. Fibre orientation

The fibre orientation is the key attribute that gives rise to paper anisotropy. Based on their mechanical and physical properties the fibres will more or less easily align with the running direction of the fibre suspension at the exit of the paper machine head box. The fibre orientation is also highly influenced by the jet/wire speeds ratio. As mentioned before, the cutting force is proportional to the amount of material being cut. Paper material is defined as a network of fibres oriented in the machine direction to an extent governed by the production process, and linked together by hydrogen bonds. Depending on the localisation of the cutting process, there may be a variation in fibre quantity due to inhomogeneity in paper thickness and orientation. This will result in variation in amount of fibre being cut and the cutting force applied. Penaso [47] performed an interesting experiment: Several samples of a same material were cut at different angles (see **Figure 57**) before being tested with the laboratory cutting device.

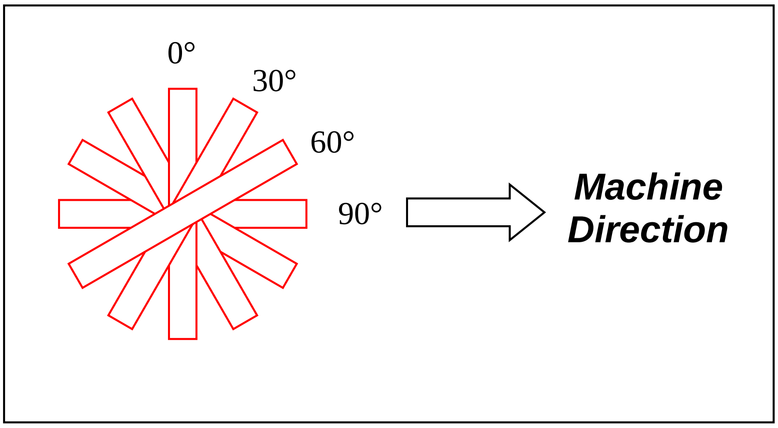


Figure 57: Schematic of samples cut at different angles to perform the cutting test to investigate the influence of fibre orientation.

The probability to cross fibres based on the fibres orientation of the paper can be calculated using the equivalent pore concept [49] [50]. The following polar system is considered (see **Figure 58**).

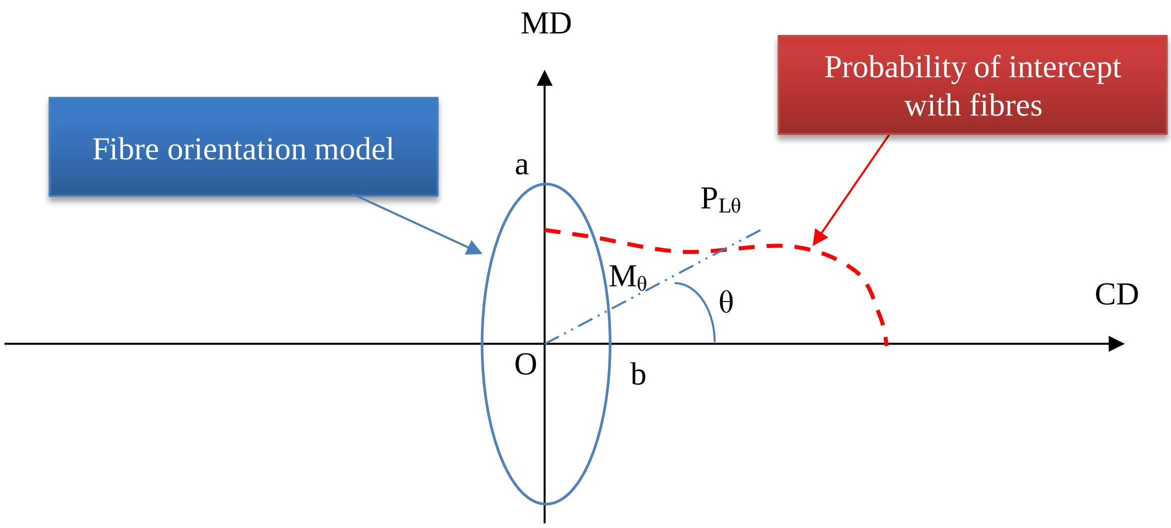


Figure 58: Schematic of fibre orientation and the probability of intercepts as a function of the angle θ (from the cross direction).

The ratio a/b can be approximated by measuring the $LR0_{MD}$ and $LR0_{CD}$ with the help of the zero span test devices [51]:

Equation 17: Orientation factor as a function of breaking force obtained with the zero span test

$$\frac{a}{b} \approx \left(\frac{LR0_{MD}}{LR0_{CD}}\right)^{0,5}$$

The equation of an ellipse having a semi major axis, “a”, and a semi minor axis, “b”, in a polar system is as follows:

Equation 18: Ellipse’s equation in polar coordinate with the origin at the centre of the ellipse and θ measured from the minor axis [52].

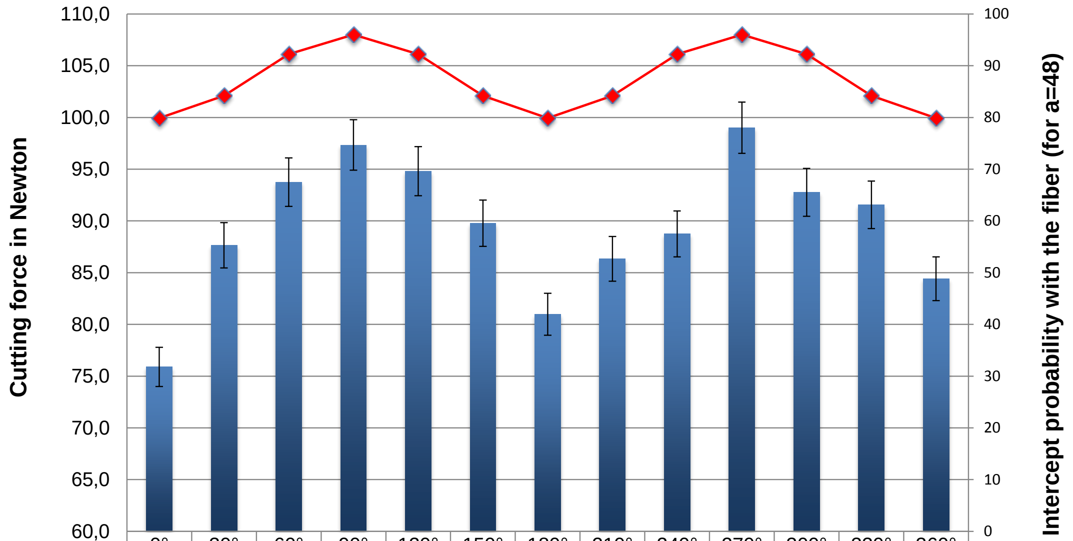
$$\rho(\theta) = OM_\theta = \frac{a}{\sqrt{1 - \frac{b^2 - a^2}{b^2}.\cos^2\theta}}$$

Considering the direction of [O$P_{L\theta}$], the thickness of the ellipse in O (perpendicular to the direction) represents the number of intercept in this direction. It can be found in literature [49] [52] than the probability of intercept as a function of the angle θ can be expressed as:

Equation 19: Probability of fibre intercept as a function of a, b and θ

$$P_{L\theta} = \frac{2.a.b}{OM_\theta} = 2.\sqrt{b^2.(\sin\theta)^2 + a^2.(\cos\theta)^2}$$

By fixing a value for a, b can be calculated knowing a/b owing to the zero span measurement. Having a and b, $P_{L\theta}$ can be easily calculated for the different values of θ. In **Figure 59**, the cutting forces measured with the different papers have been plotted (bars series), on the second y-axis, the probabilities of intercept with fibres have also been plotted.



	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	360°
Cutting Force	75,9	87,6	93,8	97,3	94,8	89,8	81,0	86,3	88,7	99,0	92,8	91,6	84,4
Intercept probability	80	84	92	96	92	84	80	84	92	96	92	84	80

Figure 59: Evolution of the cutting force as a function of the fibre orientation (source for cutting forces measurement: Penaso [47])

The correlation between the two parameters is clear (see **Figure 60**). During the cutting test and as expected, the highest forces are obtained when cutting the material perpendicular to the main fibre direction (90°: cross direction). A difference of 20% on average can be noticed between the two directions. This explains why higher forces are required at the cross cutter compared to the slitter.

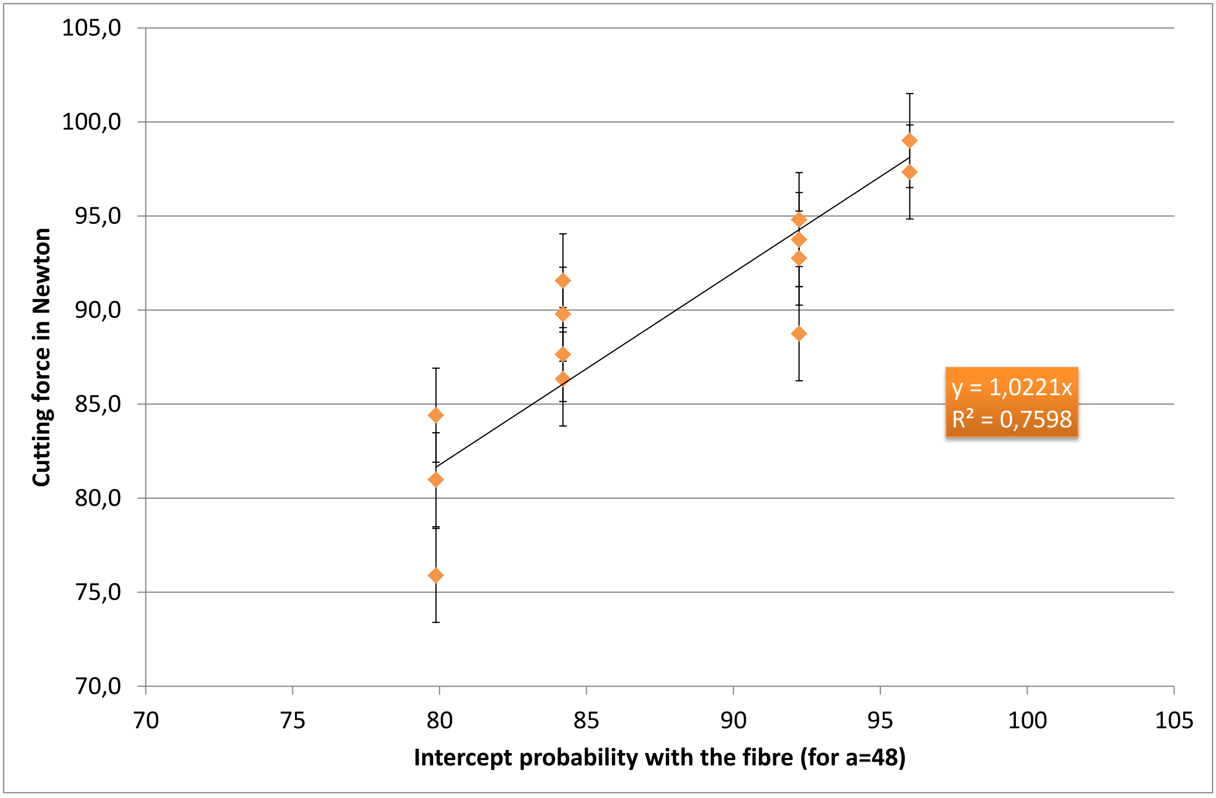


Figure 60: Cutting force as a function of the intercept probability with the fibres

4.4.3.2. Basis weight effect

To study the effect of the basis weight, production samples of the same paper quality at different basis weight were selected. Due to the fact that the ratio between coating and base paper is not fixed and also changing with the basis weight, it was decided to focus on base paper only. The base papers for the final coated products to give 90 g/m², 100 g/m² and 115 g/m² "end" basis weights were selected. Tests were performed perpendicular to the main fibre direction (CC) and parallel to the main fibre direction (LC). The three paper samples analysed had similar fibre orientation (a/b): 1,1. The results are plotted in **Figure 61**.

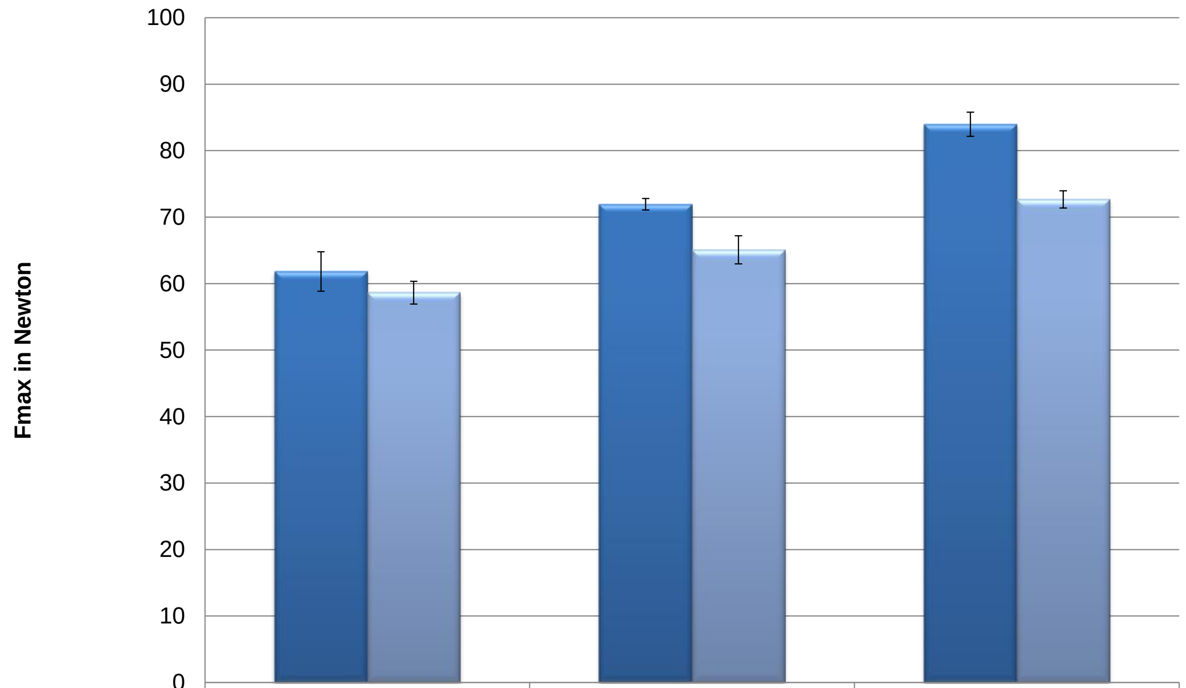
A linear correlation can be observed between the basis weight and the maximal cutting force (for LC & CC: $R^2 = 0,97$). In this case, we found out that for 3 sheets cut simultaneously[2]:

[2] Linear regressions have been calculated by considering that the $F_{max}=0$ with basis weight = 0

$$F_{max}(CC) = 0{,}30 \ . \ \text{Basis weight} \ (R^2 = 0{,}97)$$

$$F_{max}(LC) = 0{,}27 \ . \ \text{Basis weight} \ (R^2 = 0{,}97)$$

$$\Rightarrow F_{max}(CC) = 1{,}11 \ F_{max}(LC)$$



	69,9 g/m²	78,8 g/m²	90 g/m²
Base Paper CC	61,82	71,93	83,98
Base paper LC	58,63	65,08	72,67

Figure 61: Evolution of the cutting force with the basis weight (standard deviations are represented with the error bar: average $^+/-$ σ)

Looking closely at the correlation, the force in CC seems to be slightly more affected by the increase in basis weight (0,30 > 0, 27). Due to this, the difference between CC and LC is also more and more visible when the basis weight increases. This has been observed with several grades of paper and can be explained and attributed to the fibre orientation of the paper.

To demonstrate this explanation, the following hypotheses are made:

- The constant cutting phase is considered ($F=F_{max}$),
- The fibres are oriented either in CD or in MD,
- The fibre thickness is assumed to be 40 µm, the fibre length 2 mm and the fibre coarseness 0,25 mg/m,
- The paper is composed of 1 or several fibre network layers depending on its basis weight and has a fibre orientation of 1,1. Thus one fibre network is composed of X fibres oriented in CD and approx. $(1{,}1)^3$ X fibres oriented in MD [49].

We consider three different papers: a) 90 g/m², b) 180 g/m² and c) 270 g/m² respectively composed by one, two or three fibre network layers (see **Figure 62**).

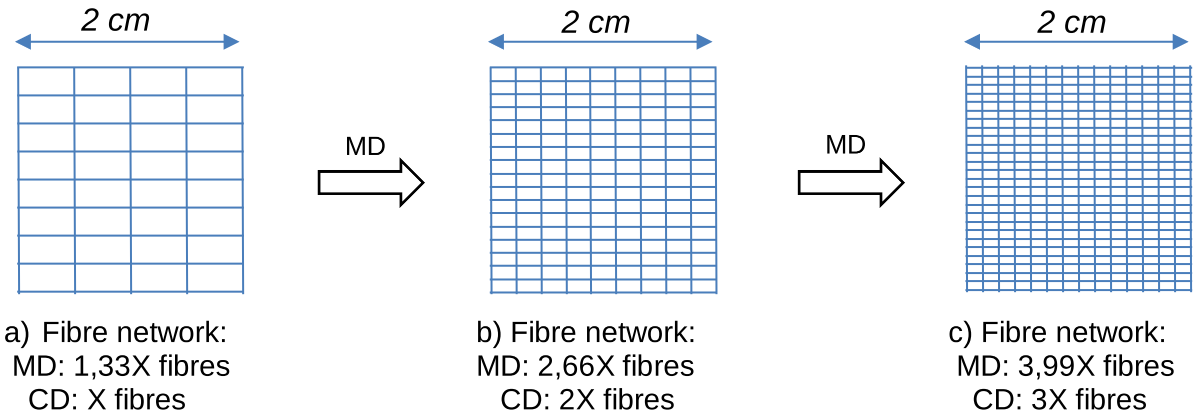


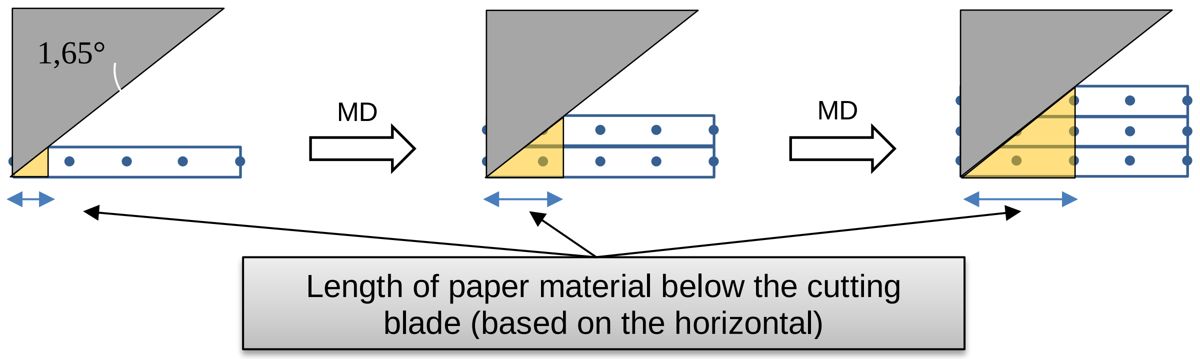
Figure 62: Schematic representation from above of the fibre network for papers of 4 cm² and different basis weights (a=90 g/m², b=180 g/m² and c=270 g/m²)

For the paper a), we can calculate that there are 72000 fibres in four square centimetres by using the supposition made about the coarseness, fibre length and basis weight.

Equation 20: Expression of the number of fibres contained in a defined surface as a function of fibre coarseness, length and weight of the surface considered.

$$Number\ of\ fibers = \frac{Weight\ of\ the\ surface\ considered\ (mg)}{coarseness\ \left(\frac{mg}{m}\right).fiber\ lenght\ (m)} = \frac{90000\ .\ 4.10^{-4}}{0{,}25.2.10^{-3}}$$

Due to the fibre orientation, it gives around 30901 fibres oriented in CD and 41099 fibres oriented in MD in a 4 cm² paper sample. With this information, we can calculate the number of intercepts under the cutting blade for each paper and each direction. Attention is still needed to consider the influence of the angle of the blade (1,65°), the paper thickness and the fact that there are around 10 fibres per 2 cm length. The magnitude of the length of paper under the blade can be calculated by considering that the thickness of 1 fibre network in the 100 µm scale (see **Figure 63** and **Table 4**).



a) Fibre network: CD: X fibres

b) Fibre network: CD: 2X fibres

c) Fibre network: CD: 3X fibres

Figure 63: Schematic representation from CD point of view (through the fibre network) for papers with different basis weights (a=90 g/m², b=180 g/m² and c=270 g/m²)

Example of the calculation for the paper a):

$$\textit{Number of intercepts when cutting in LC} = \frac{\textit{thickness in cm} \,.\, \textit{number of fibres oriented in CD}}{\textit{lenght of the sample in cm}.\tan(1{,}65)\,.\textit{number of fibres in 2 cm}} = 268$$

Finally, we know that the maximal cutting force is a function of the transversal cutting section divided by the total thickness of the paper stack being cut (as demonstrated previously). Therefore, we need to normalize the number of intercepts with the number of layers (or make the assumption that the total thickness does not change).

	Paper a	***Paper b***	***Paper c***
Length of paper material below the knife in cm at an instant t	0,347	0,694	1,041
Number of intercepts when cutting in LC below the knife at an instant t	268	1073	2414
Number of intercepts when cutting in CC below the knife at an instant t	357	1427	3210
Number of intercepts when cutting in LC (normalized with the total thickness)	805	1609	2414
Number of intercepts when cutting in CC (normalized with the total thickness)	1070	2140	3210
Difference between the normalized number of intercept ⇨ CC – LC	**266**	**531**	**797**

Table 4: Evolution of number of intercepts between the blades for the different papers being cut

The following example shows that the higher the basis weight, the higher will be the difference between the numbers of intercepts to be cut when comparing LC and CC. So the difficulty to cut a paper will therefore increase faster with the basis weight in cross direction compared to the long direction. This explains the differences observed in the slope of the curve when considering the evolution of the cutting force as a function of the basis weight. If we consider that the force required to cut the Paper c (270 g/m²) is similar to the force we found in our practical experiment (when cutting 3 x 90 g/m²) then we get the following correlations:

$$F_{max}(CC) = 0,33 \,.\, \text{Basis weight } (R^2 = 1)$$

$$F_{max}(LC) = 0,25 \,.\, \text{Basis weight } (R^2 = 1)$$

$$\Rightarrow F_{max}(CC) = 1,32 \,.\, F_{max}(LC)$$

The development is similar to what we found during our experiment. The difference can be explained by the error measurements.

This information is very important for the operators at the sheeter because it means that when increasing production by increasing the number of sheets cut simultaneously, more difficulty can be expected on the cross cut. It also means that with higher basis weights, the difference between cross cut and long cut quality will also be higher.

4.4.3.3. Number of sheets cut simultaneously

The amount of paper cut simultaneously is a very important parameter for the paper maker. Indeed, any extra layer being cut simultaneously will bring significant improvement in terms of productivity and therefore will reduce the costs of production. Nowadays, it is becoming common to cut up to 6 or 7 sheets simultaneously and modern machines are being promoted with capability of cutting up to 1000 g/m² simultaneously [20]. To check the evolution of the cutting force with the number of sheets being cut simultaneously, a simple test with different number of sheets was performed using the laboratory cutting device. The paper samples for testing were cut in long and cross directions. The paper selected was a glossy paper of 90 g/m². Up to six sheets were cut simultaneously (540 g/m²). The graphs obtained with the device (Force as a function of the displacements) have been sum up in **Figure 64**.

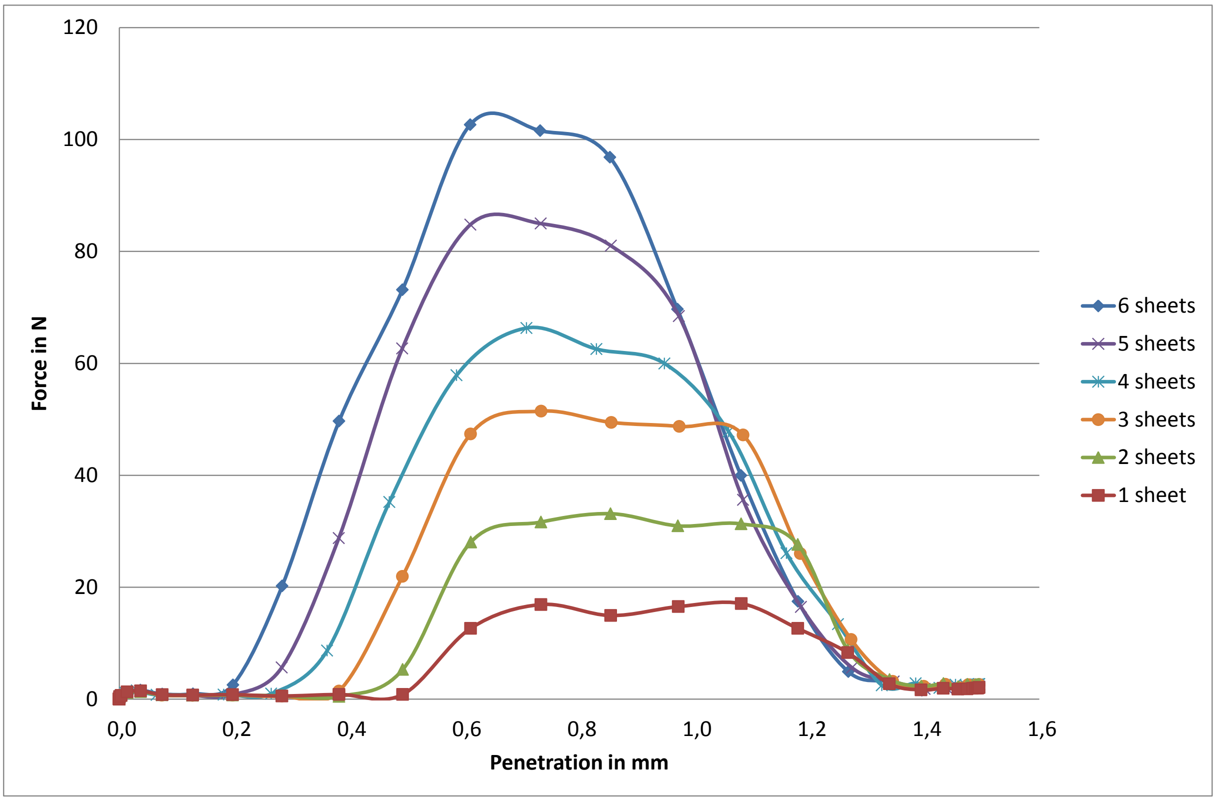


Figure 64: Evolution of the cutting force with the number of sheets cut at once for the cross cut.

From **Figure 64**, it can be seen that the greater the number of sheets, the earlier the cutting process starts. This is due to the thickness of the paper stack. Due to the same reason, the plateau will also become smaller when increasing the number of sheets. It was observed that the maximal force (F_{max}) required is proportional to the number of sheets being cut (see **Figure 65**).

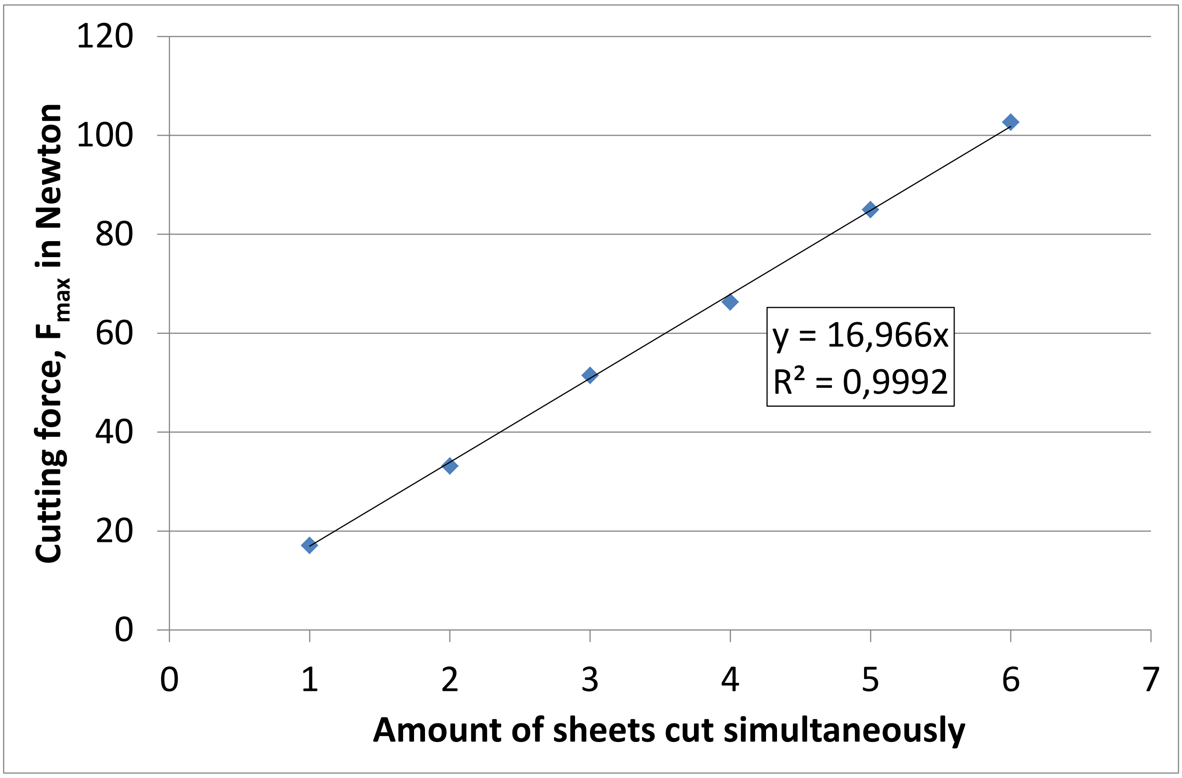


Figure 65: Maximal cutting force (F_{max}) as a function of the number of sheet cut simultaneously for the cross cut.

The same test was performed with different basis weights, paper qualities and in both directions. The relationship described in Equation 21 was found to hold in any case:

Equation 21: Maximal cutting force as a function of the number of sheets being cut simultaneously

$$F_{max}\text{ (n sheets)} = F_{max}\text{ (1 sheet)} . n$$

This observation confirms the formula developed previously for the maximal cutting force. In our case, the clearance is very small and can be neglected, and we clearly have F_{max} which evolved in a linear way with respect to the number of sheets being cut simultaneously

$$F_{max} = k.G.\frac{\sqrt{n^2.e^2 + c^2}}{(2.\tan\delta)}.f(\Delta l) \sim k.G.\frac{n.e}{(2.\tan\delta)}.f(\Delta l)$$

From a production point of view and considering that the cut quality becomes worse when the cutting force increases [38]*: this means that the higher the number of sheets cut, the lower will be the influence of adding an extra layer on the cut quality.*

4.4.3.4. Bulk, thickness and roughness: calendering effect

The thickness is an interesting parameter to study. In practice, a non-negligible part of the paper produced will undergo calendering operations. During this step, the paper web is going through a series of nips with defined pressure and temperature. As mentioned in chapter 2, the main aim of this phase is to reach a desired level of gloss. In this step, the bulk of the paper, its rigidity and its roughness will be affected. By definition the bulk can be defined as the volume occupied by 1 gram of material. It is expressed in cubic centimetres per gram and is obtained with the following calculation:

Equation 22: Bulk as a function of the thickness and basis weight

$$Bulk\ \left(cm^3/g\right) = \frac{Thickness\ \ (\mu m)}{Basis\ weight\ \ (g/m^2)}$$

The PPS roughness [53] gives an indication of the state of the paper surface: either it is rough or smooth. It is important to underline what are the differences between a bulky and non-bulky material. From a simple point of view, at similar basis weight, a more bulky paper will just be thicker. The amount of material to be cut will be the same; more air will be contained in the material within the fibre matrix. A bulky paper is often stiffer than a calendered paper (since the stiffness depends on the thickness cubic). At first sight, it can be questioned why such a parameter needs to be studied due to the assumption that its influence on cutting will be limited. Indeed cutting “air” does not require energy. But as explained previously, the cutting force depends on the transversal cutting section and this one will decrease during calendering. In order to study the impact of the calendering, several experiments were carried out on the laboratory calender. For each test, paper samples were run twice through the nip. A satin paper grade of 150 g/m² with an initial bulk of 0,79 cm^3/g was calendered under different conditions in order to reduce the bulk of the paper to 0,71 cm^3/g. **Table 5** summarizes the conditions used to prepare the samples.

	Pressure (kN/m)	Temperature (°C)	150 g/m² papers		
			Thickness (µm)	Bulk (cm^3/g)	Roughness (µm)
Sample 1 (ref)	-	-	118,8	0,79	1,1
Sample 2	26	-	114,5	0,76	0,9
Sample 3	53	-	111,6	0,74	0,8
Sample 4	132	-	106,5	0,71	0,6

Table 5: Calendering conditions of different samples and the resulting paper thickness, bulk and PPS roughness

After calendering, the paper samples were cut with the laboratory cutting device under standard condition in both cutting directions (LC and CC). Results of the cutting force are plotted as a function of the bulk in **Figure 66**.

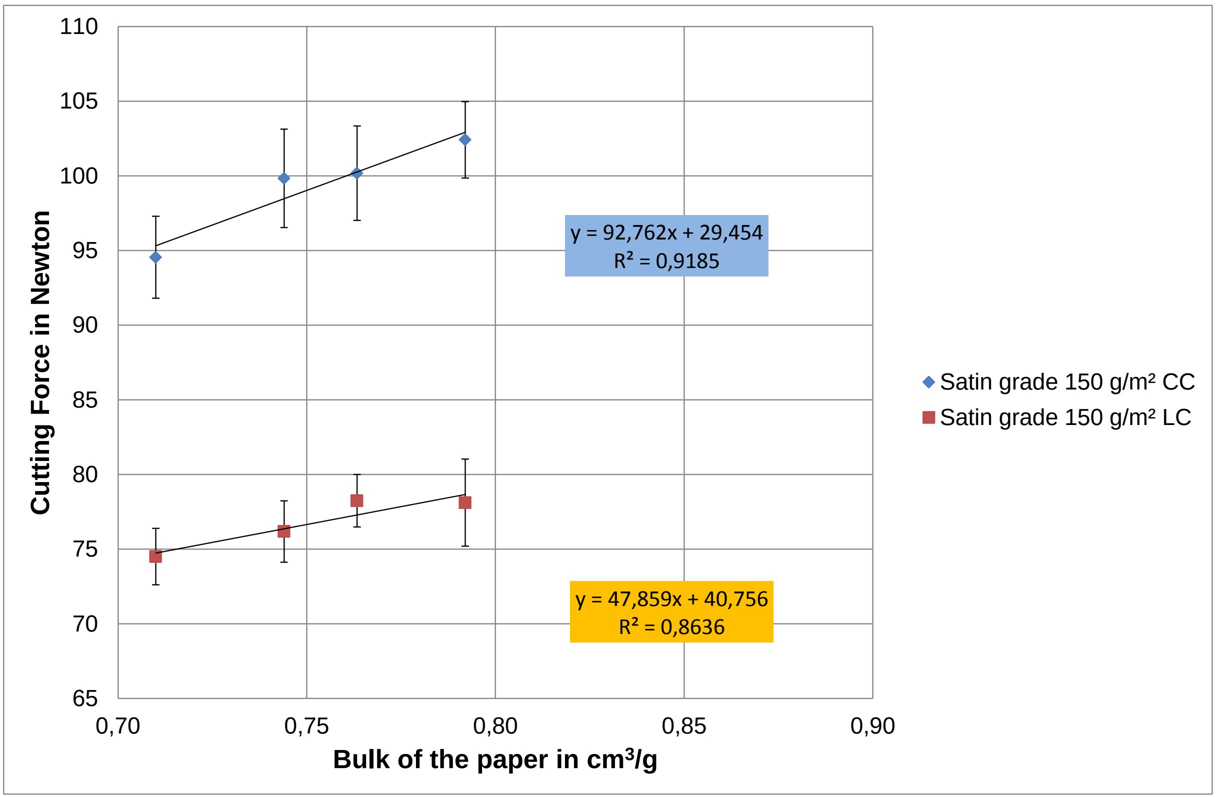


Figure 66: Evolution of cutting force with bulk of the paper (standard deviations are represented with the error bars: average $^{+}/-\ \sigma$)

Looking at the trends obtained with the measurements, it seems that the bulkier the paper, the higher the cutting force. This observation was made in both cutting directions (long cut and cross cut). The cutting force is increasing in a quite linear way with the bulk of the paper (R^2 = 0, 91 in cross cut and R^2 = 0,86 in long cut). Similar correlations were obtained when plotting the cutting force as a function of the roughness.

Due to the limited variations of bulk, the cutting forces (which are quite close to each other between the different samples: 8% difference in CC between min and max and 5% difference in LC between min and max) and finally the standard deviation of the measurement, it was not possible to draw a clear conclusion from these initial results.

Therefore, similar tests were carried out with bulkier papers at a different basis weights (90 g/m² and 115 g/m²). Those papers have an initial bulk of approximately 1,15 cm^3/g and were calendered several times until a bulk of 0,95 cm^3/g was obtained. The conditions for the samples preparation are summarized in the **Table 6** and **Table 7**.

	Pressure (kN/m)	Temperature (°C)	90 g/m² papers		
			Thickness (µm)	Bulk (cm^3/g)	Roughness (µm)
Sample 1 (ref)	-	-	105,3	1,17	4,7
Sample 2	13	-	96,7	1,07	-
Sample 3	39	-	89,9	1	2,8
Sample 4	79	-	87,5	0,97	2,5
Sample 5	118	-	86	0,96	2,2

Table 6: Calendering conditions for the 90 g/m² papers and the resulting paper thickness, bulk and roughness.

	Pressure (kN/m)	Temperature (°C)	115 g/m² papers		
			Thickness (µm)	Bulk (cm^3/g)	Roughnes s (µm)
Sample 1 (ref)	-	-	130,1	1,13	4,6
Sample 2	26	-	114,7	1,0	2,9
Sample 3	79	-	108,9	0,95	2,4

Table 7: Calendering conditions for the 115 g/m² papers and the resulting paper thickness, bulk and roughness.

All the paper samples were cut in both directions (LC and CC) with the laboratory cutting device using the same procedures as in previous tests (**Figure 66** and **Figure 67**). The variations of the cutting forces between the different samples were slightly higher (11% in CC between max and min; 6% in LC between max and min). Similar trends as in the previous trial were observed with these papers: the bulkier the paper, the higher the force required to perform the cutting action. Again a similar correlation was observed when plotting the cutting force as a function of the roughness. However, I believe that the bulk is the real reason for the observation made with the cutting force. When comparing **Figure 66** and **Figure 68**, it is interesting to see that a similar force is required to cut a paper of 115 g/m² and a paper of 150 g/m² even though the paper of 150 g/m² has obviously 30% more material to cut. It is important to mention that paper composition do differ with papers of 115 g/m² having a higher fibre ratio compared to its total basis weight.

Two reasons are given to explain the influence of the bulk on the cutting force:

- First of all and as shown previously, the cutting force is directly related to the transversal cutting section below the blade. With bulky material this area is definitely bigger.
- Finally, the deformation of the paper increases the area of contact between the blade and the material prior to cutting. A direct consequence of this is the dissipation of energy within the paper material. So to reach the shear strength of the material (leading to rupture of the substrate), more force is required. This deformation results in a much lower cut quality of the end product seen mainly in terms of raggedness.

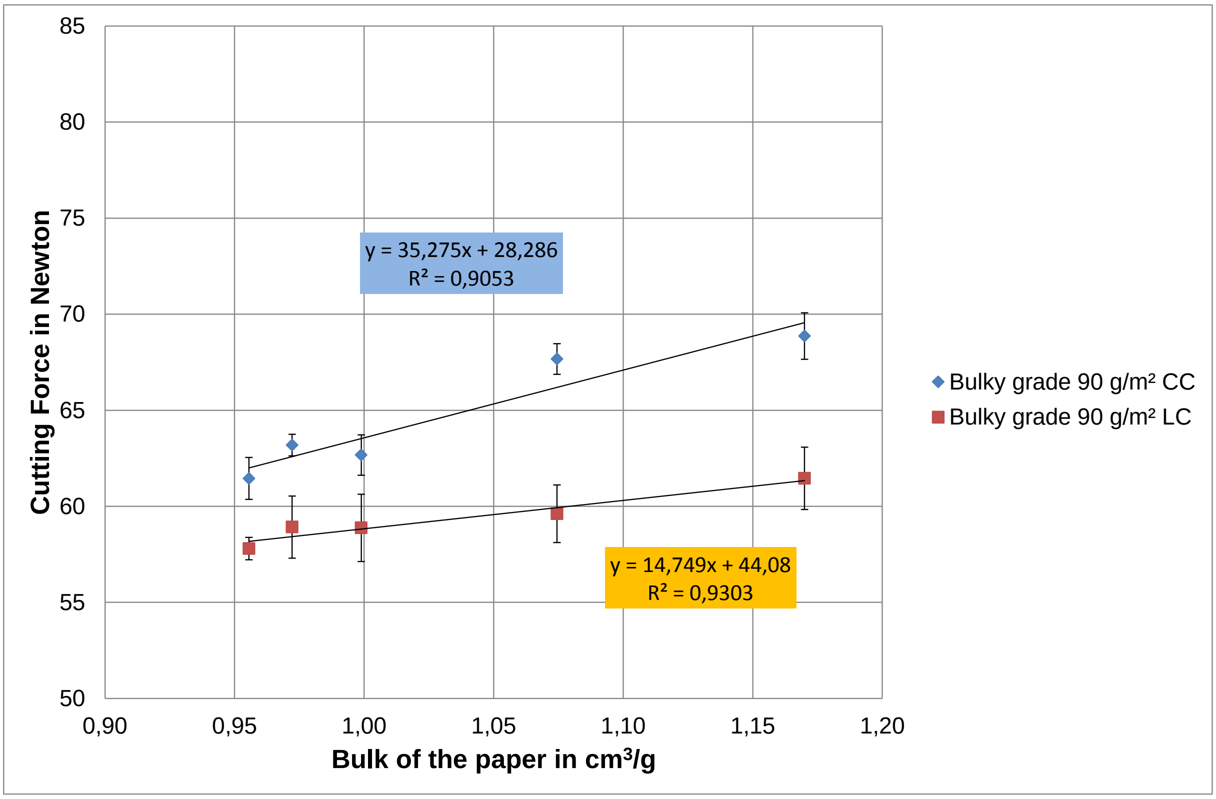


Figure 67: Influence of bulk of the paper on cutting force (standard deviation represented with the error bars)

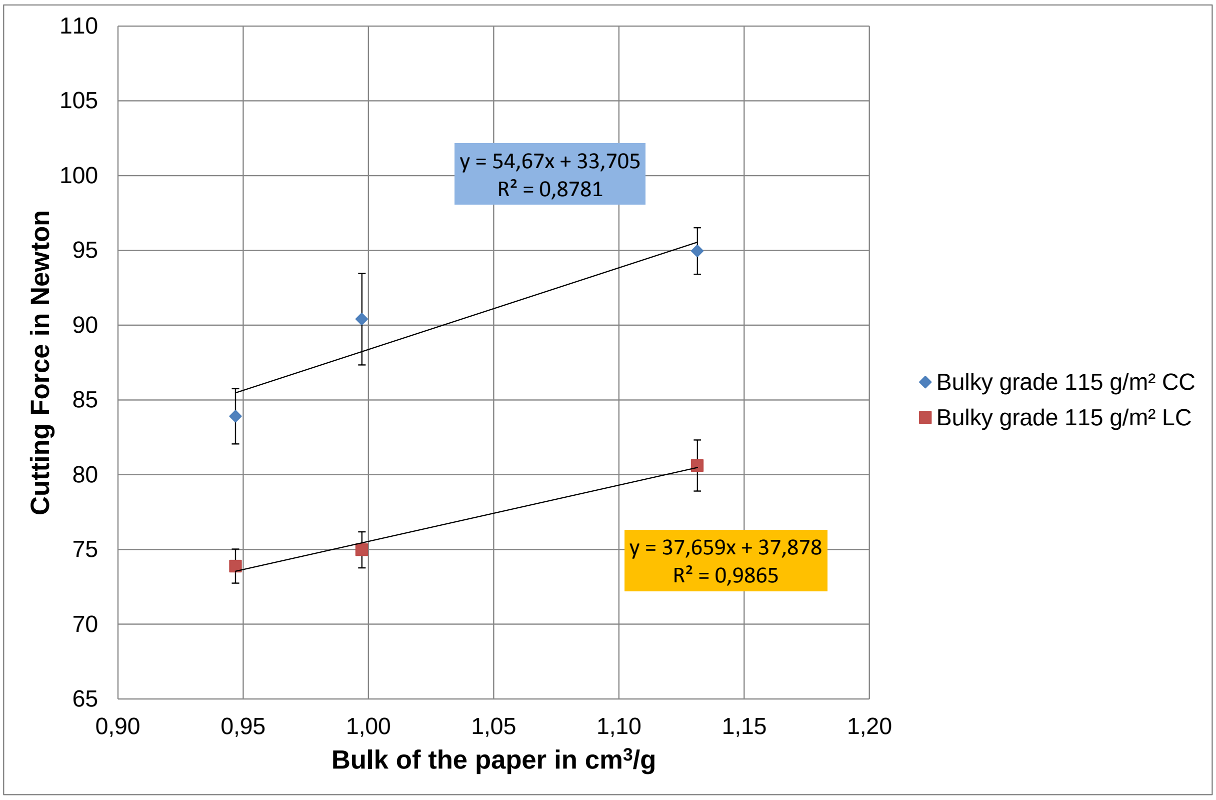


Figure 68: Influence of bulk of the paper on cutting force (standard deviation represented with the error bars)

For the basis weight and for the bulk, we can conclude that, for a 90 g/m² paper, the increase in the number of sheets cut simultaneously (thereby increasing the basis weight) has 5 times more impact on the maximum cutting force than similar increase made with the bulk feature of the paper in LC and approximately 2 times more impact in CC:

- An increase of 10% of the bulk results in:
  - ⇨ An increase of 2,5% for the F_{max} in LC
  - ⇨ An increase of 5,5% for the F_{max} in CC
- An increase of 10% of the basis weight results in:
  - ⇨ An increase of 10% for the F_{max} in LC
  - ⇨ An increase of 10% for the F_{max} in CC

From a production point of view, it means that at similar basis weights, calendered papers results to better cutting quality than bulky papers. Indeed in practice at the sheeter, even though the runnability with bulky papers is better (due to a higher rigidity), it is often required to reduce the total load (number of sheets cut simultaneously) to obtain similar visual cut quality (raggedness) as attained with glossy papers.

4.4.3.5. Paper structure

As mentioned earlier, WFC papers have the particular property of being coated and sometimes calendered. During the production process, the base paper is produced and then the coating layers are applied on both paper surfaces (increasing the basis weight). Finally, the paper is calendered to impart the desired gloss value for the paper grade (reducing the roughness and trying to keep the bulk as high as possible). To study the impact of these different steps on the cutting force, paper samples from the same mother reel were collected at the different steps of the process for three end basis weight (90, 100 and 115 g/m²):

- At the end of the paper machine: Base paper
- At the end of the coating machine: Coated paper
- At the end of the calender machine: Silk coated paper

The main basic paper properties of these three papers are summarized in **Table 8** and evolutions of the basis weight and bulk are expressed in % based on the values from the previous production step:

		1^{st} step: Base paper	2^{nd} step: Coated paper	3^{rd} step: Calendered paper
Paper A	Basis weight in g/m²	69,9	90 (**+28%**)	90 (-)
	Thickness in µm	105,4	107,4	104,9
	Bulk in cm3/g	1,51	1,19 (**-22%**)	1,17 (**-1,7%**)
	PPS Roughness in µm	8,1	5,2 (**-36%**)	4,4 (**-15%**)
Paper B	Basis weight in g/m²	78,8	100 (**+27%**)	100 (-)
	Thickness in µm	117,7	118,1	112,6
	Bulk in cm^3/g	1,49	1,18 (**-21%**)	1,13 (**-4,3%**)
	PPS Roughness in µm	8,2	5,0 (**-39%**)	4,2 (**-17%**)
Paper C	Basis weight in g/m²	90	115 (**+28%**)	115 (-)
	Thickness in µm	129	131,4	129,5
	Bulk in cm^3/g	1,43	1,14 (**-20%**)	1,13 (**-0,9%**)
	PPS Roughness in µm	8,4	5,2 (**-38%**)	4,5 (**-15%**)

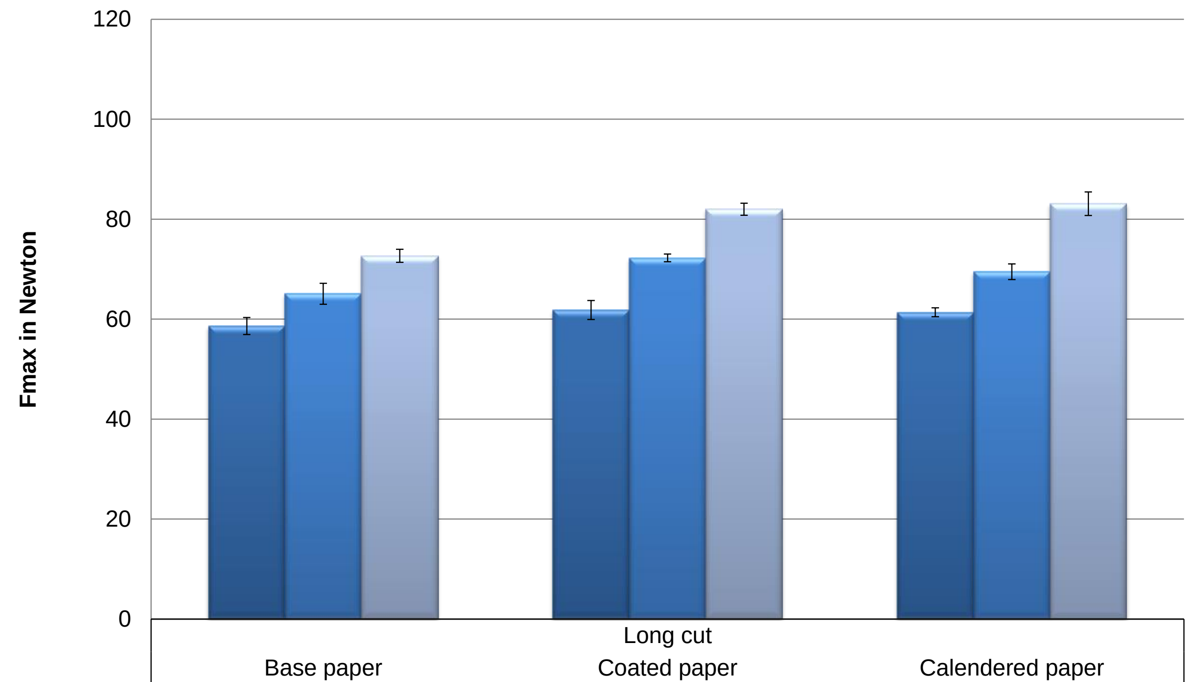
Table 8: Evolution of the main paper properties during the process for the different papers analysed (in bracket is represented the evolution vs. the previous steps in %)

It can be noticed that it is mainly after the application of the coating layer that the paper properties are varying. The calendering has only limited effect on the bulk in this case due to the fact that the paper grades were designed and planned in the production cycle to be bulky papers and therefore only underwent one soft nip calendering. However, this process step will be interesting to analyse since it gives us the opportunity to study the effect of the roughness itself.

The application of the coating layer has two opposing consequences: it increases the basis weight on one hand (which should result in an increase of the cutting force) and reduces the bulk of the paper on the other hand (which should reduce the cutting force). Both parameters develop in quite similar proportions: -21% for the bulk and +28% for the basis weight. If cutting the coating layer requires similar force as cutting fibres, then based on our previous experiments, we can expect an increase of the cutting force during the coating step due to the higher influence of the basis weight. Secondly during the calendering steps, effects can be different:

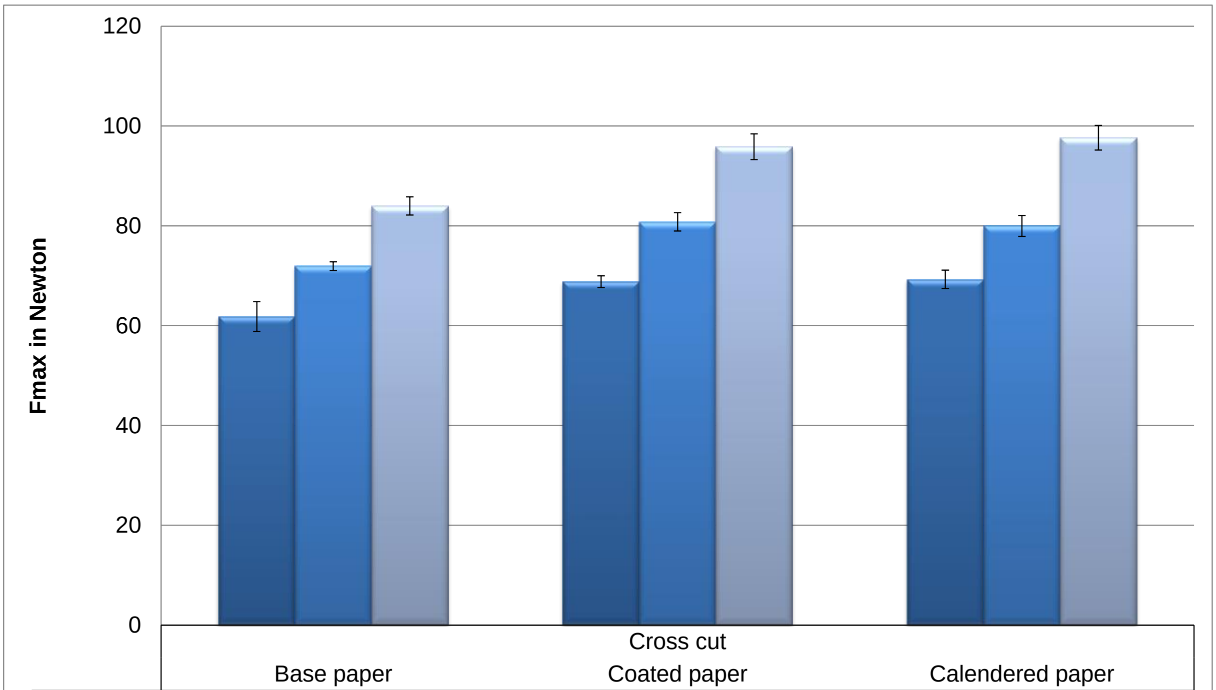
- Either the cutting force will stay stable if the bulk is the predominant factor (compared to the roughness
- Or the cutting force will decrease if the roughness is the predominant factor (compared to the bulk).

The results are plotted in the **Figure 69** and **Figure 70**.



	Base paper	Coated paper	Calendered paper
PAPER A	58,63	61,83	61,38
PAPER B	65,08	72,26	69,48
PAPER C	72,67	82	83,09

Figure 69: Evolution of the cutting force in long cut during the paper making process



	Cross cut Base paper	Cross cut Coated paper	Cross cut Calendered paper
PAPER A	61,82	68,8	69,29
PAPER B	71,93	80,81	80
PAPER C	83,98	95,85	97,67

Figure 70: Evolution of the cutting force in cross cut during the paper making process

For all three papers considered, an increase of the cutting force after the coating process occurs. As in all cases the increase is more noticeable for CC. No real conclusions can be drawn here regarding the cutting force required to shear the coating layers itself due to the fact that several parameters are playing a role simultaneously: bulk & basis weight. However, the coating layer might have similar effects than the base paper on the cutting force: If no force or a very small one was required to shear the coating layer then a decrease of the general cutting force should be noticed due to the lower bulk. Concerning the second step, the calendering of the paper, no significant development of the cutting force with the three different papers is observed. Knowing that the basis weight stays constant and that the bulk decreases only slightly (max 4%) during this step, we should just notice a decrease of around 1 to 2% of the cutting force which is definitely within the measurement error. This confirms the assumption that the roughness is not the reason for the change in the cutting force.

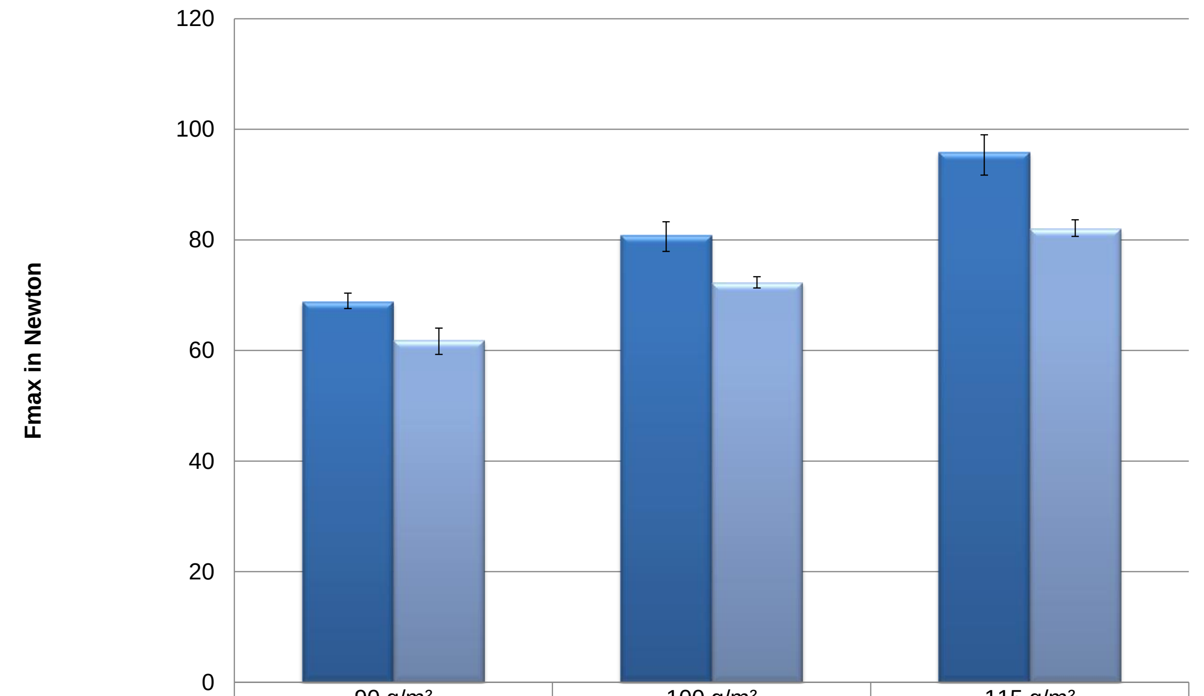
Comparing the papers (change of basis weight only), and taking out the effects of the paper production steps, the same conclusions as observed in the previous parts of this chapter can be made.

$$F_{max}(CC) = 0{,}27 \ . \ Total\ Basis\ weight\ (R^2 = 0{,}93)$$

$$F_{max}(LC) = 0{,}24 \ . \ Total\ Basis\ weight\ (R^2 = 0{,}97)$$

$$F_{max}(CC) = 1{,}14 \ . \ F_{max}(LC)$$

The results are plotted in the following graph, **Figure 71**:



	90 g/m²	100 g/m²	115 g/m²
Coated paper CC	68,8	80,81	95,85
Coated paper LC	61,83	72,26	82

Figure 71: Evolution of the cutting force with the basis weight for single coated papers

4.4.3.6. Fibre composition effect

To reduce costs and to improve paper properties, paper makers are trying to optimize the type of wood fibres used. Therefore, over the last decades, Kraft eucalyptus pulp has been increasingly used especially in WFC papers. This is attributed to several reasons including:

- *Fast growing period (7 years vs. to 15-20 years for standard softwood),*
- *Good optical properties and good formation,*
- *Relatively good strength properties.*

However to maintain some other properties of the produced paper, such as the breaking length, at the required level, a mixture between the different wood species is often used. In order to see the influence of the fibre raw material on cutting, a test was made in the laboratory. Papers with different fibre mixtures were produced on a dynamic sheet former to keep the influence of the fibre orientation and cut with the laboratory cutting device. The papers were produced with the same basis weight and same bulk in order to focus only on the influence of the fibre types. The following mixtures were used:

a. 100% Short fibre (Eucalyptus) Kraft (sulphate) process
b. 100% Long fibre Sulphite process
c. 100% Long fibre Kraft (sulphate) process

d. 50% Short fibre (Eucalyptus) Kraft process – 50% Long fibre Kraft process

The results of the maximum cutting force obtained in LC and CC are shown in **Figure 72**:

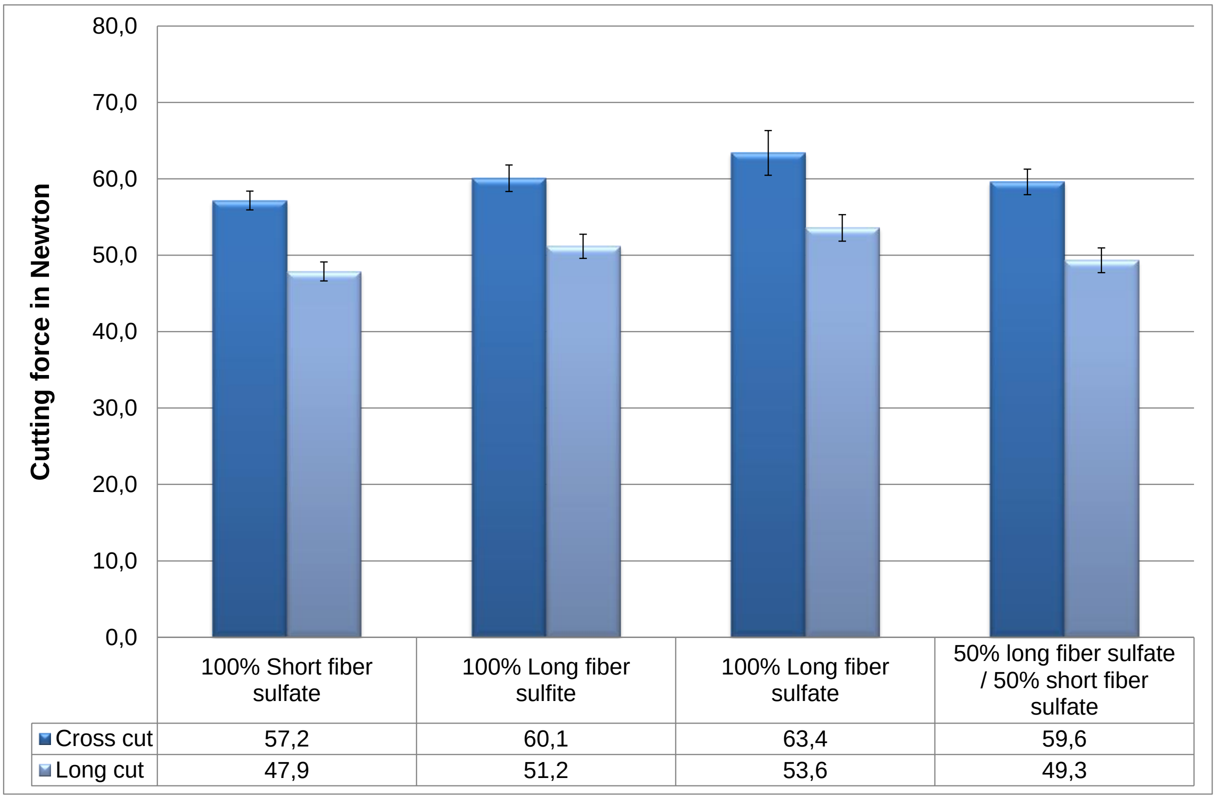


Figure 72: Influence of fibre composition on cutting forces (standard deviations are represented with the error bars)

Figure 72 shows that the results are similar and a conclusion cannot be drawn based on these results. The indication is that long fibres require more force to be cut than short fibres. It seems that the effect of the fibre can be averaged. Mixing long and short fibres lead to an average force to cut the samples. From a production point of view, the usage of short fibres does not seem to bring any negative impact on cutting operations. Considering the lower coarseness and length of Eucalyptus fibre, more intercept are expected when cutting papers made with 100% eucalyptus fibres than paper made with 100% long sulphate fibre. Therefore, it is important to consider the number of intercept and the strength required to cut one intercept.

4.4.3.7. Filler content effects

In order to study the effect of the filler content, three series of sheets were produced on the Dynamic Sheet Former (DSF) with the same fibre composition and with two different levels of filler: 16% and 21%. Fibre orientation measured with the tensile test for the three papers was kept around 2,3. The first series with 16% filler was used as a reference, and for the other series the level of filler was increased to 21%. In the second series, the level of filler was increased without keeping the basis weight constant giving the possibility to see how the filler increase impacts the cutting force. In the third series, the level of filler was increased keeping the basis weight constant by reducing the fibres content. Afterwards, all papers were coated in the laboratory with the same coating recipe to reach a similar end basis weight of 200 g/m². Unfortunately rather high variations in end basis weight compared to the targeted values were observed (up to 2,5%). Main properties of the papers produced are summarized in **Table 9**:

Paper	Properties	Units	1. Series	2. Series	3. Series
Base paper	Basis weight	g/m²	150	159	150
	Filler content	%	16	21	21
Coated paper	Basis weight	g/m²	202	205	199
	Ash content	%	33,9	35,2	39,3

Table 9: Properties of the sheets produced to study the filler content effect on cutting force

Only the coated papers were tested with the cutting device. Cutting force measurements are shown in **Figure 73**.

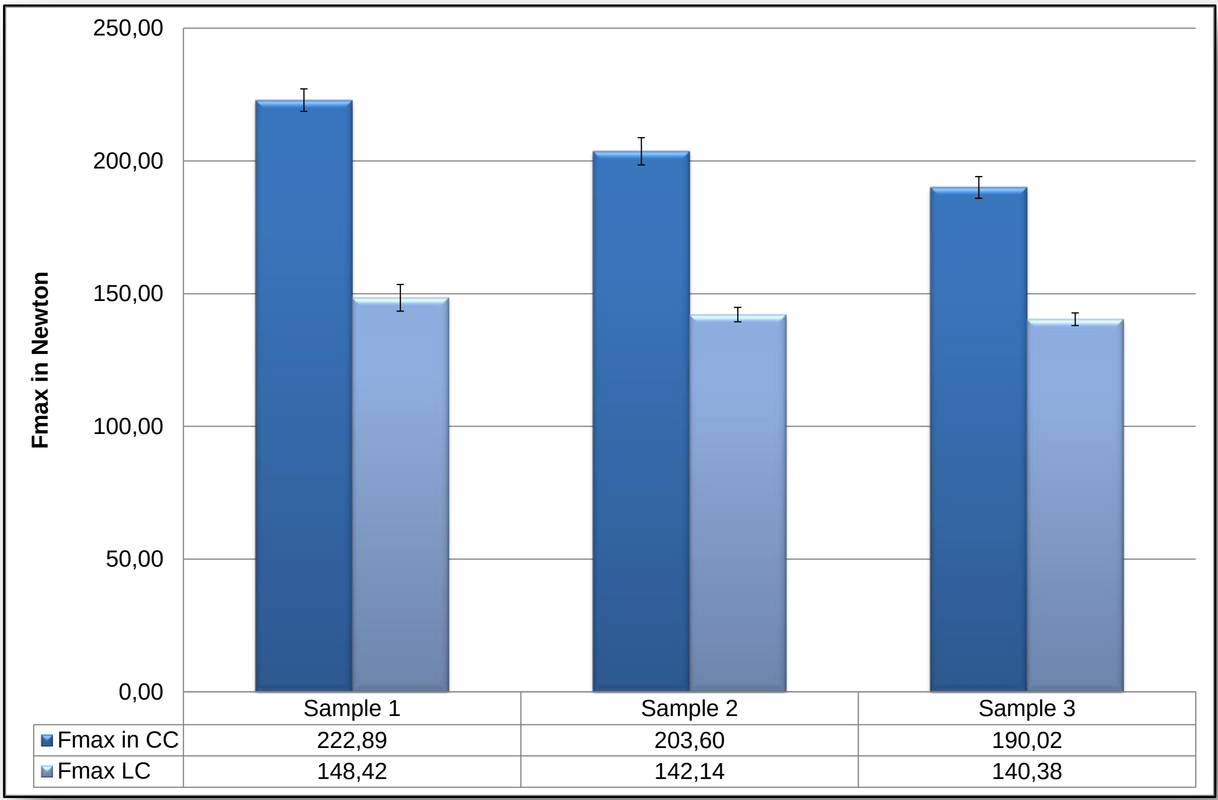


Figure 73: Evolution of cutting force for papers with different filler amounts

As noticed before, greater differences are observed in cross direction. Differences between the first and second series are quite important even though the amount of fibres was kept constant: It seems that the dispersion of the filler within the fibre networks has to some extent weakened the fibre network which consequently requires a lower force to be sheared. More tests would be required to confirm this hypothesis. The difference between the first and third sample is not surprising considering the difference noticed between the first and second series and due to the fact that by keeping the total basis weight constant, the amount of fibre contributing to the total basis weight has been reduced.

4.4.3.8. Starch effects in the coating layer

The application of starch in the coating recipes has increased over the last decade although this appears to be tailing off and stabilizing in the latter years. This increased use of starch in the coating formulation is attributed to several reasons including:

- ***Cost***: Starch has been cheaper than the synthetic binders for a long time due to the strong coupling of synthetic binders to the price of crude oil. However, this difference has been decreasing over the last months.
- ***Eco-friendly image***: Starch is made out of renewable materials such as potatoes and corn and it is therefore considered as a sustainable and biodegradable material.

Starch products also have certain disadvantages:

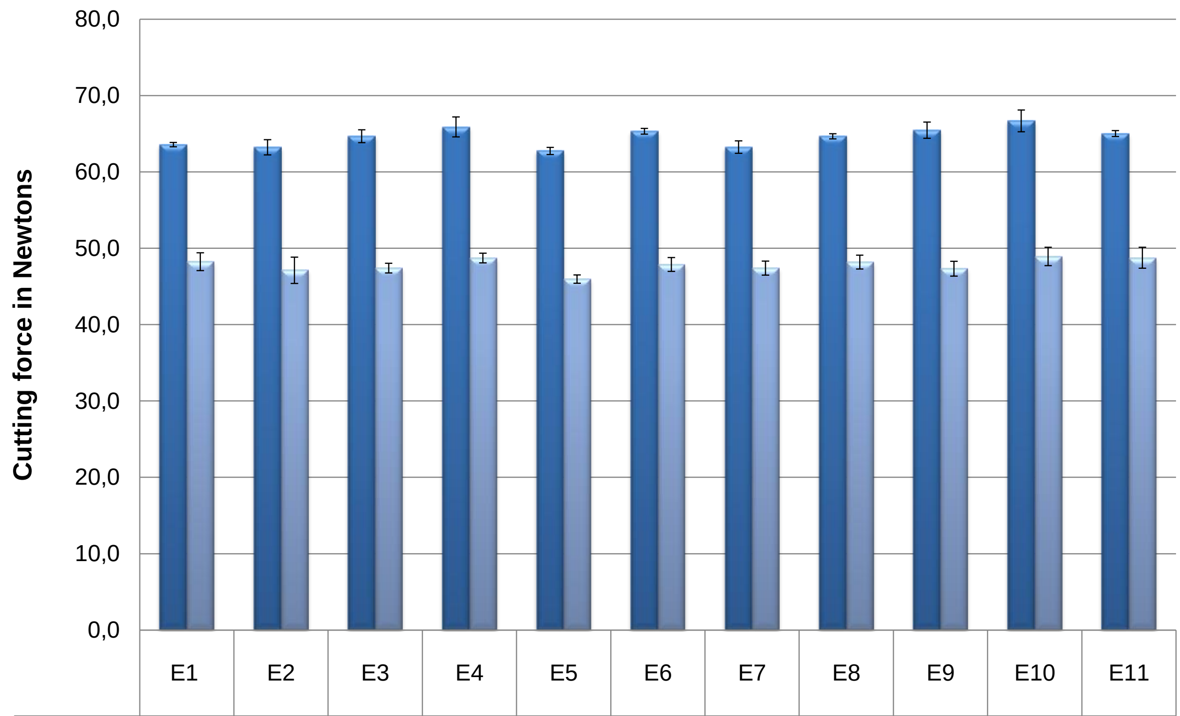
- Starch is ***water soluble*** and therefore if used in the top coat, it can be deteriorated during the printing process, under the action of the fountain solution resulting in some coating particles being released leading to a phenomenon called “coating piling”.
- Starch films are ***brittle*** contrary to the synthetic binder films which are more elastic. The resulting brittleness of the coating layer results in several cracks during the cutting process which lead to the weakening of the coating layer or/and dust generation. Besides that, it is also known to negatively impact the cracking at the fold behaviour of the WFC papers [54].
- Starch is produced from ***natural resources*** which could also be used to feed people. Today using food resources to produce material is perceived negatively due to the millions of people suffering from undernourishment.

A pilot trial was performed where only the type of starch and its amount in the coating formulation were studied. Base paper reels produced on a commercial paper machine were coated at a pilot coater with different coating recipes (see **Table 10**). Sample E1 is the reference and does not contain any starch in the coating formulation. For samples E2 to E7, 2 parts of latex were replaced by 2 parts of starch. Six different kinds of starch were tested. For samples E8 to E10, the amount of starch type 6 was increased respectively by 2, 4 and 6 parts while simultaneously reducing the latex to 4,3, 2,3 and 0 parts and increasing the amount of PVA from 0,5 to 1 part. Sample E11 can be directly compared to sample E3 with one more part of latex replaced by one part of starch.

	E1 Ref.	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
HC90 (pigment)	100	100	100	100	100	100	100	100	100	100	100
Latex	7	5	5	5	5	5	5	4,3	2,3		4
PVA	0,5	0,5	0,5	0,5	0,5	0,5	0,5	1	1	1	0,5
Starch 1		2									
Starch 2			2								3
Starch 3				2							
Starch 4					2						
Starch 5							2				
Starch 6								2	4	6	
Starch 7						2					

Table 10: General overview of the changes made in the coating recipes of the paper samples (in parts)

All these papers were cut in both directions with the laboratory cutting device. No noticeable differences were recorded in the maximal cutting forces either in CC or in LC (see **Figure 74**).



	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11
Fmax CC	63,6	63,2	64,7	65,9	62,7	65,3	63,3	64,7	65,5	66,7	65,0
Fmax LC	48,2	47,1	47,4	48,7	46,0	47,9	47,4	48,2	47,3	48,9	48,8

Figure 74: Cutting force (F_{max}) for papers with different coating recipes

Regardless of the ratio between starch, latex and PVA, it was not possible to measure any difference. The shape of the curve was also not modified. These results point out the limit for the developed cutting device. When such details in the recipes need to be studied, the amount of measurement points during the laboratory cutting process would have to be significantly increased to improve the precision of the measurement. But even then it is questionable whether differences become observable.

As mentioned in paragraph 4.4.2.2, the number of cracks on the bottom band side edges generated in the laboratory cutting device correlates to some extent with the number of cracks observed on the sheeter. Using the test method to analyse the cut quality of the papers produced at the sheeters (see chapter 2), the number of cracks present on the laboratory cutting samples were counted (cracks per 2 cm). Only bottom band sides were considered as advised by Penaso [47]. As always observed in the experiments carried out during this thesis, more cracks are developed when cutting in MD (LC). For both directions, the reference paper shows the lowest number of cracks which is explained by the absence of starch which is known to make the coating more brittle. However, no clear link is established between the amount of starch and the presence of cracks. The number of cracks from sample E8 to E10 should increase because of increased starch content in the coating. The results for the LC show this trend, but the CC results follow an opposite trend.

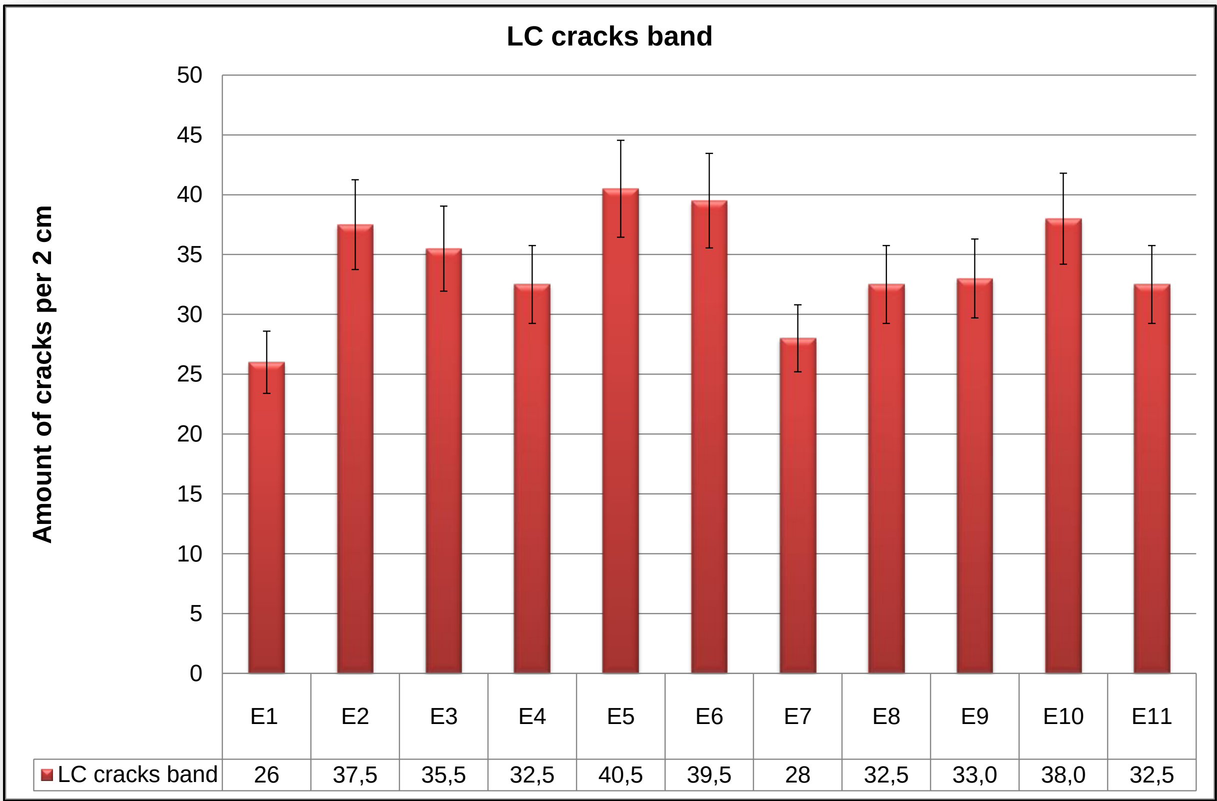


Figure 75: Evolution of the number of cracks in paper coated with different coating recipes (long cut)

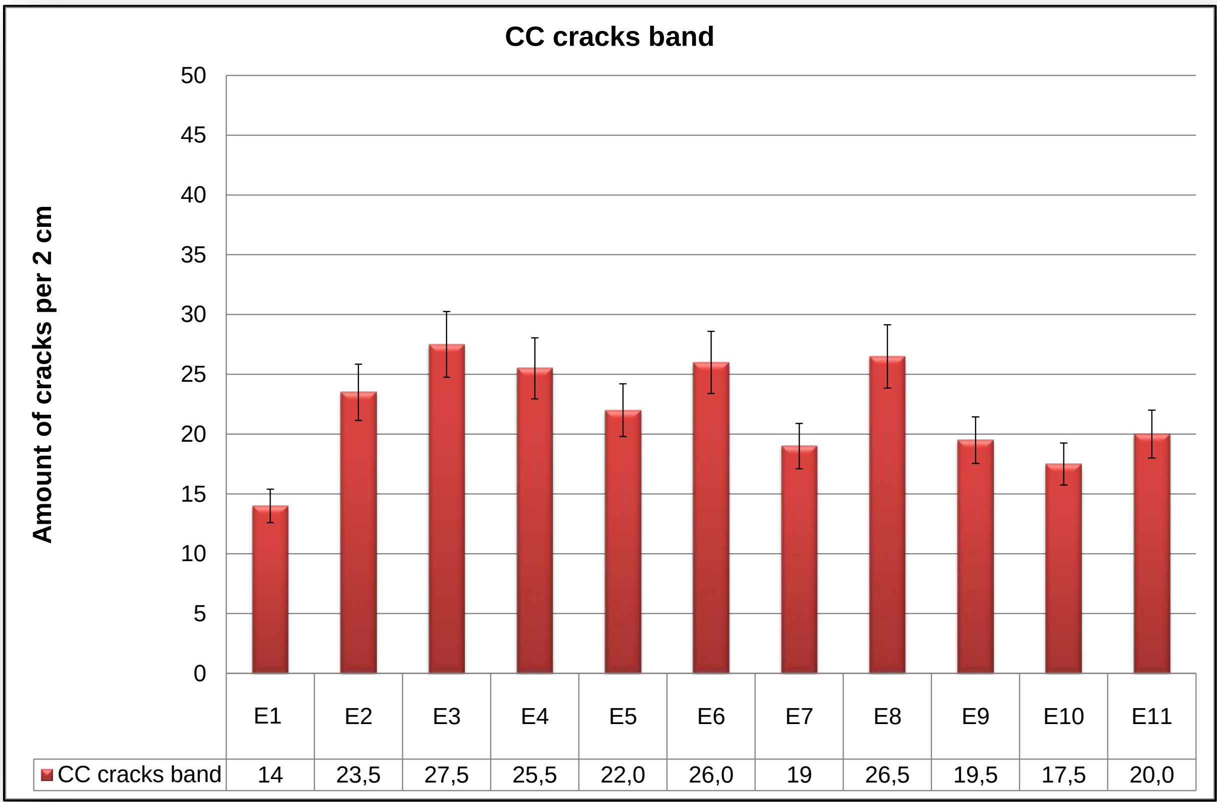


Figure 76: Evolution of the number of cracks in papers coated with different coating recipes (cross cut)

These results make it obvious that the laboratory cutting device is at its limit in terms of sensitivity. In case of minor changes in the coating or base paper composition, significant differences between the various papers cannot be detected. A significantly increased number of tests would be required to reduce the measurement error, but even then it is unlikely that a differentiation in case of small changes in recipes will be noticeable. Based on these findings a decision was taken to focus on the commercial sheeters for further experiments.

In summary, the detailed study of the cutting process and the construction of a laboratory cutting device enabled the identification of the main factor influencing the shear cutting force which is the transversal cutting section. The transversal cutting section depends on the number of sheets cut simultaneously, the basis weight, the bulk and the clearance. The experiments carried out with the different furnish mixtures (fibre types and filler content) proved the influence of the material being cut.

4.5. Practical trials: Influence of sheeter configuration and settings

In this chapter, the planning of the tests and the calculation made to explain the different processes and the study of their effects has been developed from the works of Schable: *"Slitter Performance, Problems and Solutions"* [55] and "*A Guide to Slitting*" [19]. This has been a great source of motivation and inspiration towards idea generation during this thesis.

4.5.1. Impact of sheeter types and paper web configuration

In this subsection, the absolute values of the parameters describing cut quality (number of cracks, raggedness…) are less interesting and therefore focus is placed on the differences observed between the different sheets cut simultaneously. Due to a number of reasons (high number of webs being cut simultaneously, distribution of the stresses during the cutting process, displacement of the webs…) huge differences in cut quality are noticed from one sheet to the other within the same paper stack. With the experience acquired during this thesis, it becomes clear that all results based on a single cutting test are questioned for reasons given below even when all possible precautions are taken to avoid external influences:

- Analysed areas are always too small.
- Cutting is a dynamic process and the paper webs can "move" to some extent under the blade. So depending on the location and time of sampling, different cut qualities are likely to be observed.
- Cutting blades might be damaged exactly at the very position which was unfortunately involved in cutting the area analysed later.
- Paper samples might be damaged during sampling at the sheeter or during transport to the laboratory.
- Paper is a highly inhomogeneous material regarding e.g. basis weight, thickness and moisture, so some variations due to this inhomogeneity between two trial points have to be expected.

In consideration of these facts, this thesis is based on 3 years of measurement of over 500 paper samples from 11 different sheeters. All tests were prepared and carried out based on the observations made on a daily basis. Whenever possible and where appropriate, an average over several tests was used to demonstrate the influence of the various parameters on cut quality. This average is based on the following standard conditions in the sheeting department: Shear cutting of six webs (two times 3 webs simultaneously on a twin slitter for the LC and six webs simultaneously on a rotary cross cutter for the CC). All tests made during this PhD thesis and corresponding to those criteria were selected. An average per sheet, per position and per characteristics (raggedness and number of cracks) was calculated. In total the evaluated samples comprise:

- ✓ *108 different paper stacks presenting 143 band edges, 50 blade edges and 216 leading and trailing edges.*
- ✓ *38% Silk papers and 62% Gloss papers*
- ✓ *51% 135 g/m², 23% 115 g/m², 11% 130 g/m², 10% 90 g/m², 4% 100 g/m² and 1% 160 g/m²*

Where it was not possible to use average values (e.g. to study the effect of the blade age), special tests plans were set up and the specific results were used. In these cases, the accuracy of the raggedness measurement is expected to be +/- 3 µm and for the number of cracks: +/- 5. In the next paragraph, the general observations with respect to quality parameters are summarized.

4.5.1.1. Raggedness of the cut

4.5.1.1.1. Band vs. Blade edges

The operators of the sheeter often speak about the existence of a “good” and a “bad” cutting edge at the slitter. The good cutting edge is the band edge and the bad one the blade edge. Looking at the sheeter construction, most of the blade holders are placed to ensure that most of the edges will be band edges (The blade edges pointing towards the trim). The specific of each edge will lead to differences in paper behaviour and in cut quality. The main differences between both edges are summarized in **Figure 77**.

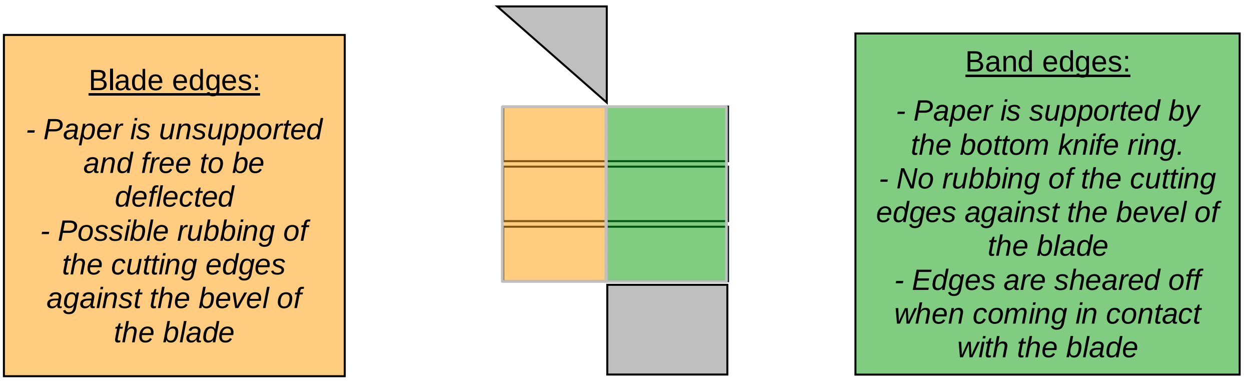


Figure 77: Main differences between blade and band edges (In this figure, only the top unit of a twin slitter is represented)

As mentioned earlier, paper is a deformable material. Due to its compressibility and the fact that the paper is supported by the bottom knife ring, there is a folding of the first layer on the band edge and a compression of the last layer during the cutting process. On the blade edge, there is a folding of the last layer and a rubbing of the first layer against the bevel of the blade. So both edges are not submitted to the same forces due to the sheeter configuration and the geometries of the knives. In addition to the specific characteristics of both edges, the position of the paper web within the stack appears to be crucial and strongly impacts cut quality. The average results of 108 analysed paper stacks are shown in **Figure 78** and the variation coefficients in **Figure 79**.

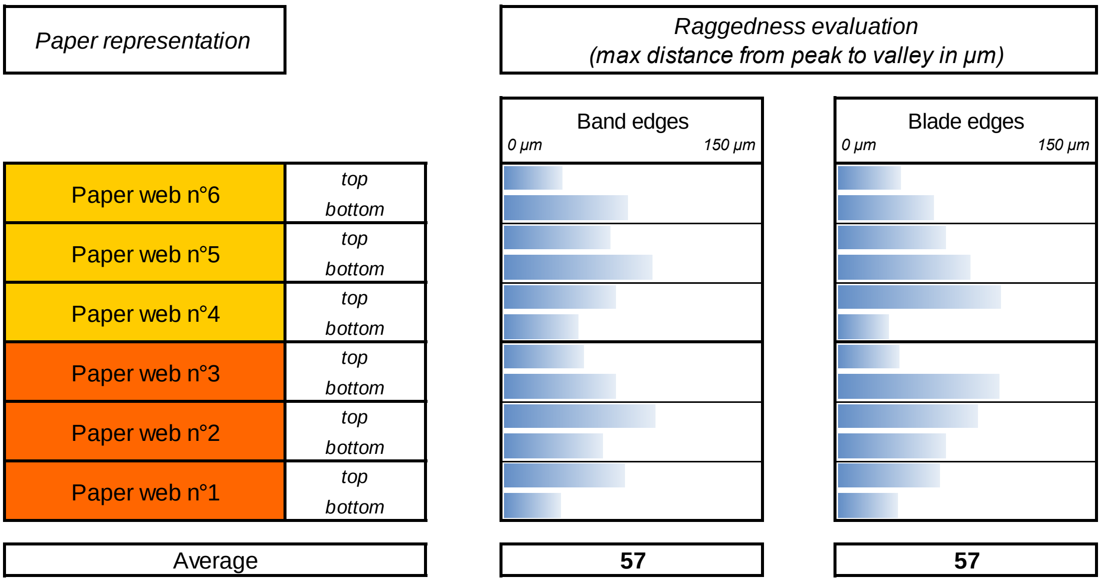


Figure 78: Average raggedness within the paper stack when cutting 6 sheets simultaneously on a twin slitter (106 paper stacks analysed)

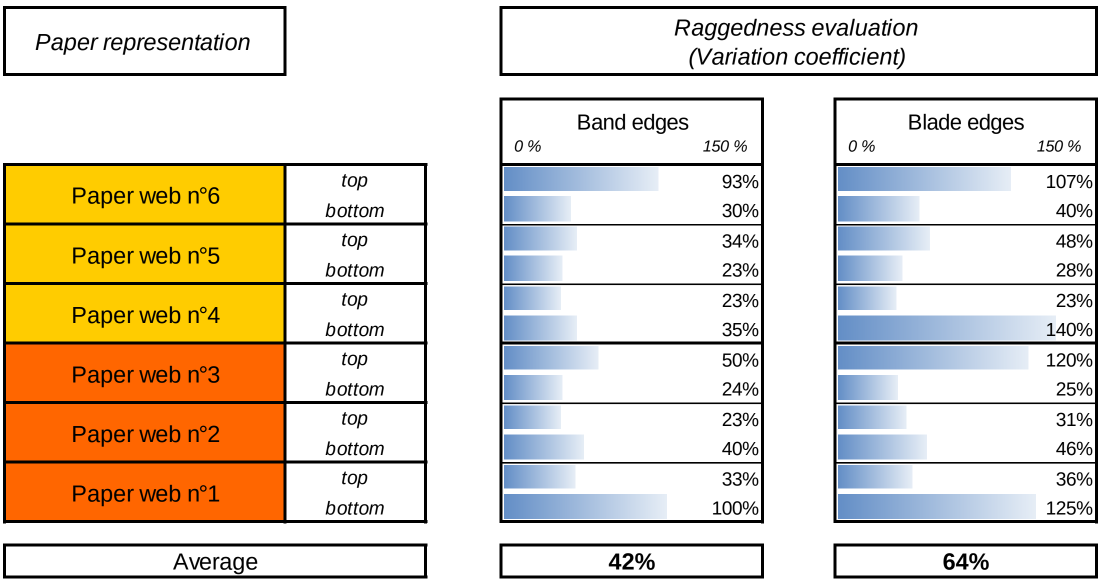


Figure 79: Variation coefficients for the raggedness at the long cut for each layer (106 paper stacks analysed)

The measurements show that on the band edges (stable paper stack), the raggedness of the layers located in the middle of the stack (2nd and 5th layers) are always higher. So the further away the paper is located from the blades, the worse will be the raggedness. When looking at the shape created by the raggedness, it is obvious that this shape presents strong similarities with the stress concentration developed when pressing two cutting knives on a material (see chapter 4.2.3, **Figure 35**). In the middle of the paper stack, the paper is not only cut by the knives but torn to some extent before the knives are coming in contact with it. Looking at the variation coefficient of the measurements, the first side in contact with the upper shear blade shows the highest variation. Looking in detail at the single measurements, this variation is due to the state of the upper shear blade during the measurement. A perfect sharp blade creates a perfect cut (raggedness closed to 0) and an old dull blade destroys the paper surface resulting in a high raggedness. Furthermore, small absolute variations in these edges result in high variation coefficients due to the low average value on those sides.

On the blade edges, where the paper stack is unsupported, the situation is different. The raggedness of the edges increases until the layer in contact with the bottom knife ring is reached. On this specific layer, the side in contact with the bottom knife ring presents most of the time a “perfect” raggedness (closed to 0 µm) while the other side always has the worse raggedness. When the bottom knife ring becomes dull the raggedness is high on both sides. It is likely that the paper layer is pushed by the pressure of the upper shear blade against the bottom knife ring (resulting in a proper shear cut at the bottom side) and at the same time, the upper side will not be cut but torn because the paper is free to be deflected (see **Figure 80**).

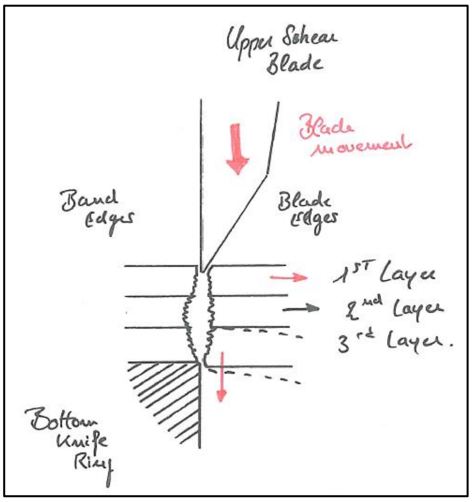


Figure 80: Behaviour of the layers during the cutting process on the slitter

The comment by several operators regarding the better quality obtained on the band edges was not confirmed by our measured average values (57 µm for both edges on average). Schable also mentioned a somewhat better quality on the band edges [18]. His explanation is that the paper can be torn before the cutting point due to the stresses created in front of the blade. This tearing of the paper before the cut point could be related to a too low strength of the paper or due to a bad blade positioning. After this tear point, the band edges are sheared off by the rotating blade, while the blade edges are just rubbed against the bevel angle of the blade: they can move in Z-direction contrary to the band edges which are supported by the bottom knife ring. So, the blade edges keep a high raggedness while the raggedness of the band edges is “corrected” by being sheared off. In my opinion, this theory is valid and a tearing of the paper before the cut point can take place. It is however likely to happen only under special circumstances such as in presence of a thick blade or some low paper strength. As mentioned previously, average measurements were made with different kinds of paper and the states of the blades (old or new) were also varied. The shape obtained over the number of cut sheets is generally similar from one paper to the other; only the absolute values of the edges vary. However, the age of a blade particularly influences the cut quality of some specific layers. Most of the time, it concerns the layer in contact with the blade. The variation coefficients per position clearly point out those changes. On average the coefficient of variation was 30-40%. On some layers however, variation coefficients of up to 140% were reached. These high variations are due to the state of the knives which, in addition to the paper properties, are affecting particularly the layers directly in contact with the knives (see **Figure 79**). To summarize, average results show that the raggedness is similar on blade and band edges. However, slightly higher variation coefficients are noticed on the blade edges. This could be due to the fact that the blade edges are more affected by the condition of the blade than the band edges. This agrees with observations made by the operators. Further test will be needed to confirm this hypothesis.

4.5.1.1.2. Leading vs. Trailing edges

As mentioned for the long cut, it is important to keep in mind the blade position during the cutting process in order to understand the differences between the edges (see **Figure 81**).

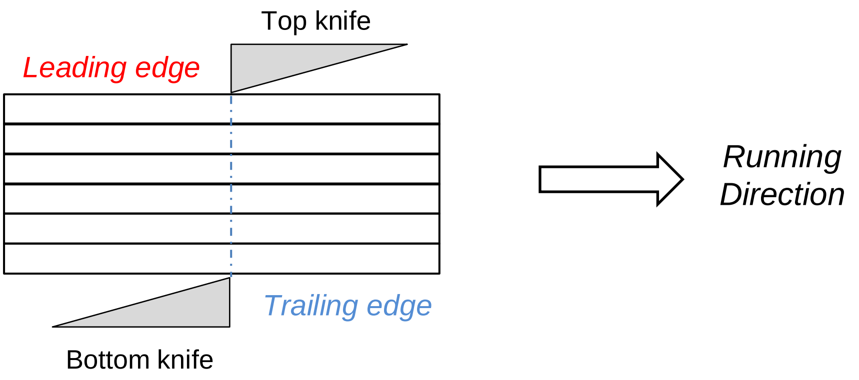


Figure 81: Configuration of the knives at the cross cutter

Again an average of all measurements performed during this thesis was calculated and the raggedness of the edges of the six sheets within the paper stack is represented in **Figure 82** with the variation coefficients of each edge in **Figure 83**. Observations made regarding leading and trailing edges are quite similar to the ones for the band edges. The sheets presenting the worst raggedness are located in the middle of the paper stack. This is not surprising because looking at both edges, supported sides are present.

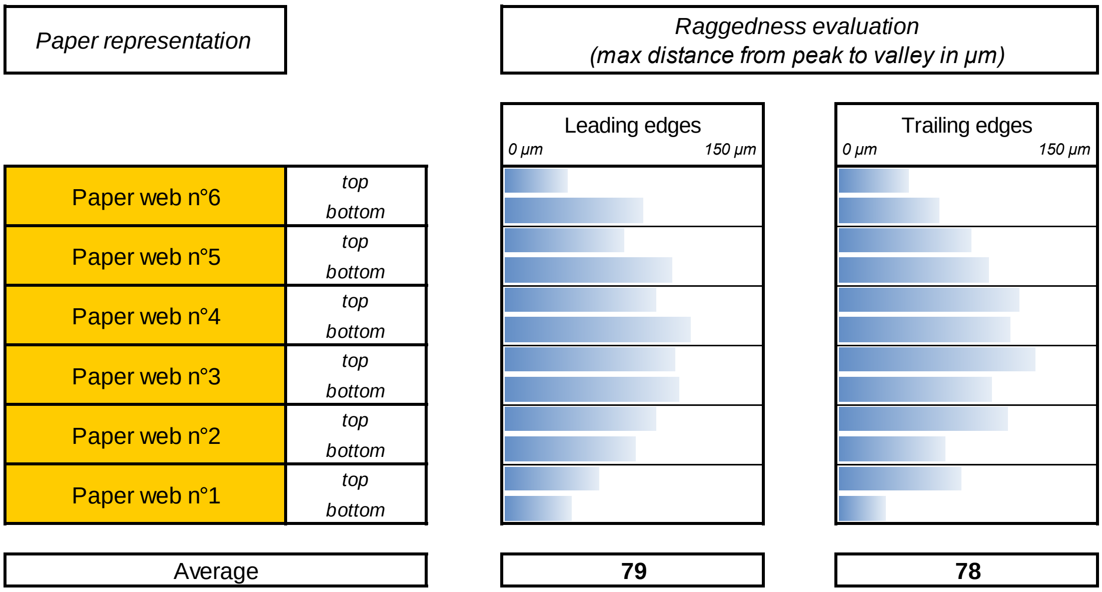


Figure 82: Average raggedness within the paper stack when cutting 6 sheets simultaneously on a double rotary cross cutter (108 paper stacks analysed).

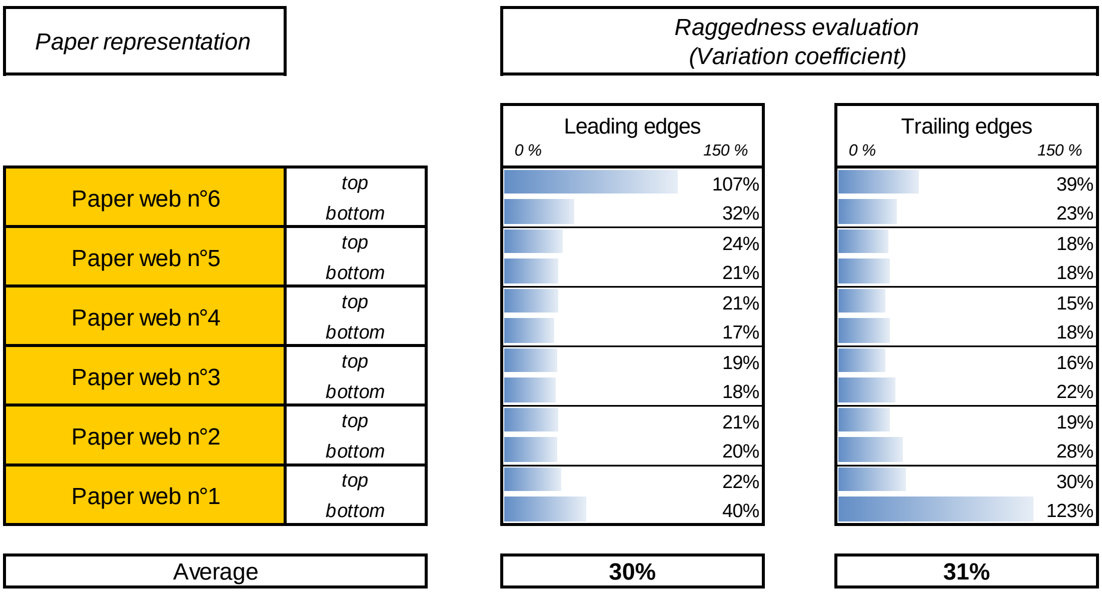


Figure 83: Variation coefficients for raggedness at the cross cut for each layer (108 paper stacks analysed)

On average, the raggedness of the edges obtained from the cross cut is worse than the raggedness obtained for the long cut (57 µm for the long cut vs. 78 µm for the cross cut). This is due to the fact that two times more paper webs are cut simultaneously at the rotary cross cutter (six sheets simultaneously vs. two times three sheets simultaneously). Leading and trailing edges are quite similar (78 µm for the trailing edges and 79 µm for the leading edges) except that the first layer of the trailing edge is not comparable to the first layer of the leading edge but with the last one. This is due to the symmetry between both edges at the cross cutter. The knife in contact with the first layer (paper web n°6) is located on the trailing edge while the knife in contact with the last layer is located on the leading edge (see **Figure 81**). Contrary to the old system (single rotary cross cutter), it is nowadays very difficult to differentiate both edges except by knowing the top of the paper stack. The variation coefficients show values of 20-30% but were on average similar at both edges (30%). Only some layers were found to have strong variations again related to the layers in contact with the blades. The variations are mainly due to the state of the blades during the paper collection. Brand new blades create edges with a very low raggedness while old blades result in high raggedness. It is exactly the same situation as observed in the long cut for the layers 3 and 4.

4.5.1.2. Location and number of cracks

The location of the cracks and their quantities are interesting. The in-depth analyses of several papers carried out during this thesis have pointed out several aspects. As mentioned previously, the generation of cracks is normally due to a deformation of the coating layer and this deformation can have several origins such as:

- *An elongation of the coating layer,*
- *A compression of the coating layer,*
- *An external strain applied to the coated layer.*

Their amount and location are strongly linked with:

- *The age of the blade and its characteristics,*
- *The type of paper being cut,*
- *The number of paper webs being cut simultaneously,*
- *The direction of the cutting action (longitudinal or cross).*

Cracks are a good indicator to understand the cutting process in more details and in particular the folding behaviour of the layer during the process. Indeed, when folding a paper web, the stresses created inside the fold are much higher than outside the fold. This leads to a higher number of cracks on the inner fold compared to the outer fold. Folding phenomena can be detected via the asymmetry, between top and bottom side of a sheet, of the number *of cracks. These differences between the forces in the inner and outer fold and the resulting number of cracks being generated has been studied by Wildberger during his PhD on cracking at the fold* [54].

4.5.1.2.1. Band vs. Blade edges

As observed with the raggedness, the average number of cracks on both edges is exactly the same: 21 for both edges. The results are shown in **Figure 84** and **Figure 85**.

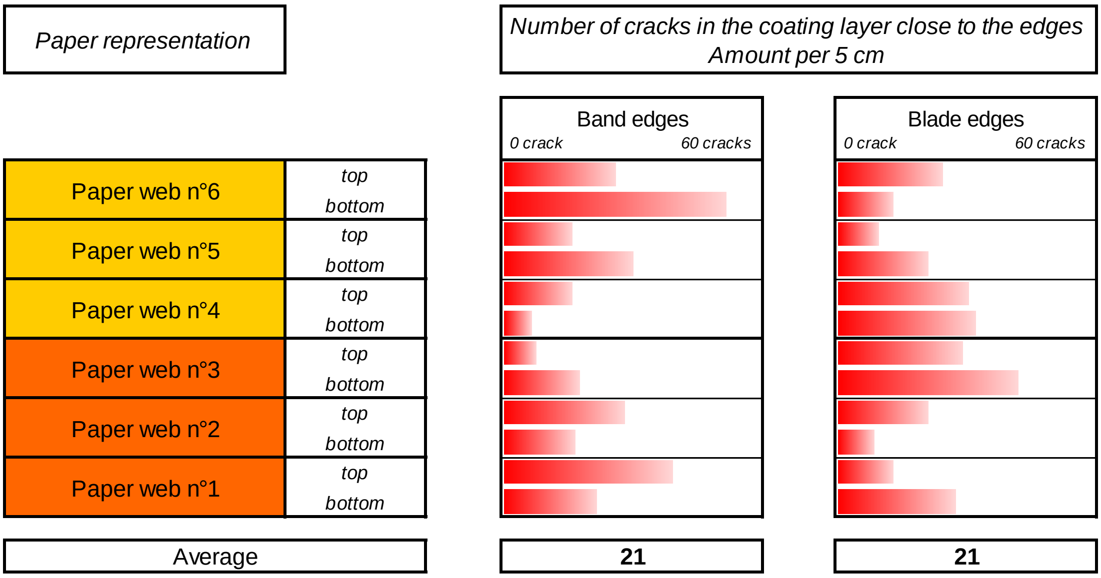


Figure 84: Repartition of the average number of cracks within a paper stack when cutting 6 sheets simultaneously on a twin slitter (108 paper stacks analysed).

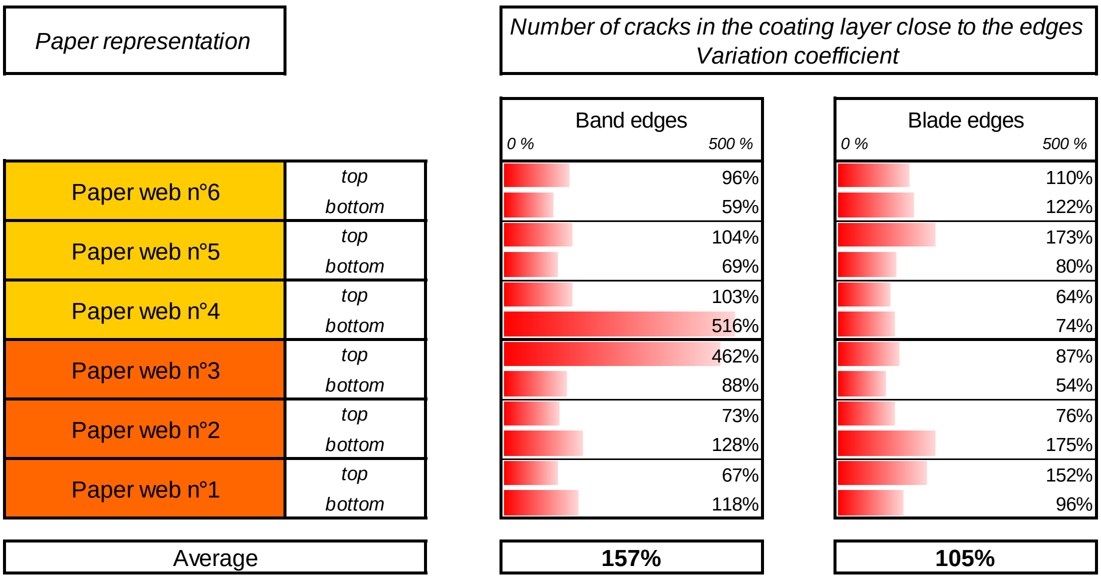


Figure 85: Variation coefficients for the number of cracks at the long cut for each layer (106 paper stacks analysed)

Even though the average numbers of cracks are the same, their distributions within the paper stack are completely different at the two edges. On top of that, their occurrence is influenced to a large degree by the “age” of the blades and therefore the variation coefficients are much higher than observed for raggedness: 30-40% for the raggedness vs. more than 100% for the cracks. As explained with raggedness, the presence of the cracks depends on the edges and the slitter and knives’ geometries.

- On the band edge, the first layer in contact with the blade is generally more folded than the previous one due to the fact that the paper stack can in a first step be compressed. More folding gives more deformation leading to the occurrence of more cracks. This results in a decreasing number of cracks going layer (paper webs) 6 to 4. This stronger folding in layer 6 can also be confirmed by the fact that the difference in the number of cracks between the top and bottom sides is higher than in layer 5. As a reminder, there is always more cracks in the inner fold (see **Figure 84**: for example on the upper slitter unit, the paper webs n°6 and 5 present on average more cracks on the bottom sides). The layer 4, which is in contact with the bottom knife ring, was found to have more cracks on the top side. This is not surprising and explained by the fact that the bottom side cannot undergo any deformation. It is supported by the bottom knife ring and maintained compressed by the upper layers. So, the cracks on the bottom side of the layer 4 can only come from a worn bottom knife ring. Most of the time, if such a situation occurs, the number of cracks is very high, and the resulting cut quality unacceptable which leads to the replacement of the blade. Due to this reason the bottom side of the paper layer is showing the strongest variation coefficient (up to 500%) because there are either no cracks or a high number of cracks.
- On the blade edges, the top side of the first layer in contact with the upper shear blade (layer 6 and 1) show a noticeable number of cracks due to the rubbing action of the blade against the coated paper surface. This number of cracks is influenced by the paper properties and finishing quality of the blade (grinding). For a defined paper quality, the number of cracks is also strongly linked to the state of the blade. The layers in contact with the bottom knife ring (4 and 3) also causes a high number of cracks mainly due to the stress created within the material during the cutting process (this edge is free to deflect and the last layer being cut will therefore undergo the strongest deformations).

To conclude from the results of the print trial performed to validate our test method, it is important to know that both edges present a similar number of cracks on average. It means that whatever kinds of edges are delivered to the customer, a similar print quality is expected during printing if a dust extractor is used. On the other hand, the differences observed within the measurement panel clearly point to strong variations in terms of quality. Further tests are required to better understand and identify the parameters at the origins of crack formation and thus helping us to take appropriate corrective actions.

4.5.1.2.2. Leading vs. Trailing edges

Leading and trailing edges present a similar distribution of the cracks. Results are shown in **Figure 86** and **Figure 87**.

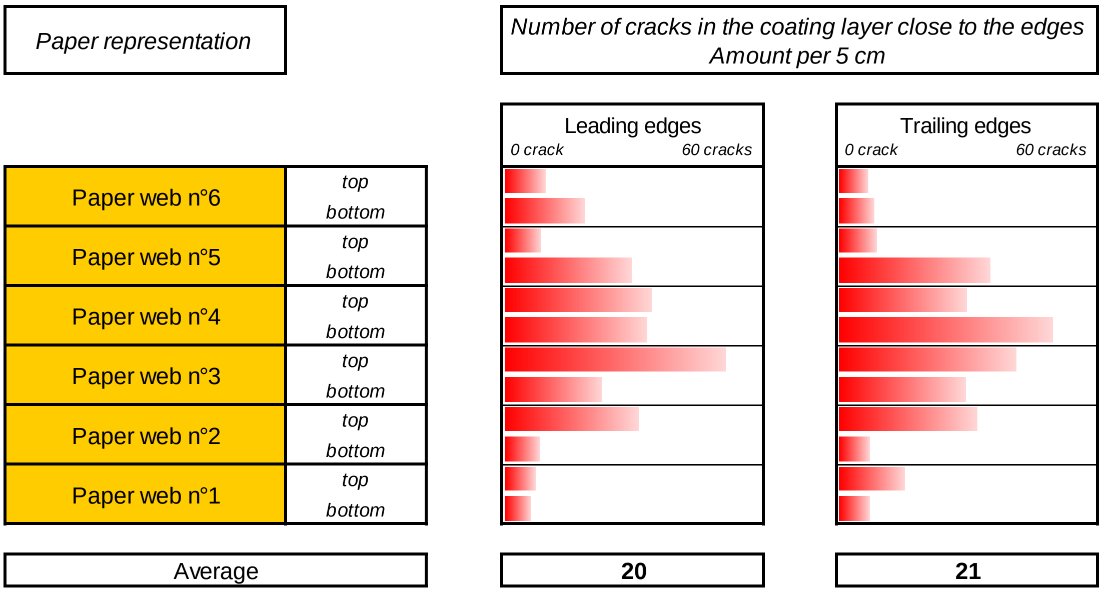


Figure 86: Repartition of average number of cracks within the paper stack when cutting 6 sheets simultaneously on a double rotary cross cutter (108 paper stacks analysed).

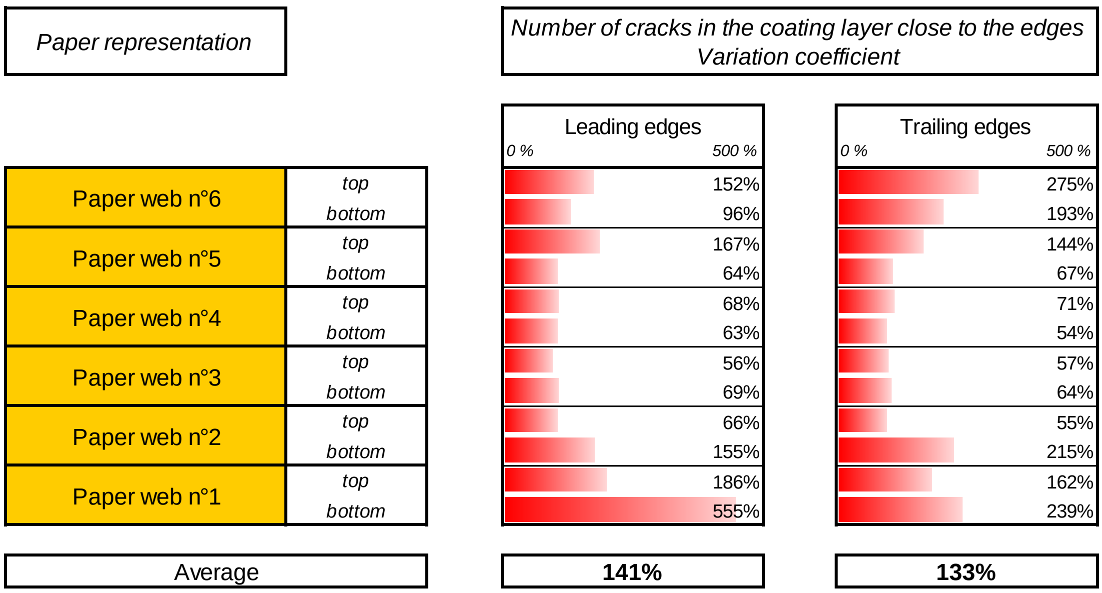


Figure 87: Variation coefficients for the number of cracks at the cross cut for each layer (108 paper stacks analysed)

As observed with the raggedness, even when both edges are similar, by knowing the position of the sheets during cutting, it is possible to differentiate leading and trailing edge due to small differences between them. The first layer of the leading edge (1) presents more cracks on the bottom side and the last layer of the trailing edge (6) presents more cracks on the top side. This difference may be due to the web being folded during the cutting process. As explained later, it may also be due to the presence of a burr on this layer.

Looking at the variation coefficients, these are very high on the external layers which is mainly due to the very low number of cracks in these layers. Therefore the simple augmentation of one or two cracks increases the variation coefficient dramatically (example: for the last layer on the leading edge, the average number of cracks is 0,11 and the standard deviation on 0,64).

The numbers of cracks for long and cross cut are similar (~ 21 in both cases). It should not be forgotten that twice the amount of paper is cut on the cross cut. This means that if the same number of sheets are cut in both directions, much less cracks would be generated on the cross cut. This confirms our theory proposed at the beginning of this chapter that the paper tends to be more deformable during the long cut than during the cross cut. For the cross cut, most of cracks are concentrated in the middle of the paper stack. As mentioned before, it is also in this area that most of the stress is concentrated.

4.5.1.3. Presence and location of the burr

Burr is a phenomenon which can be observed on both cuts (long and cross cuts). **Figures 88**, **89** and **90** show the distribution of the burr with the different cutting systems. The presence and location of the burr is found at the cut point and may be pointing upwards or downwards (depending which side of the sheet is affected). Several publications on cutting were published but only a few of them focus on burr generation associated with shear cutting. Lu & al. investigated the burr height in shear slitting of aluminium webs [56]. They studied the effects of several parameters such as the “can’t angle” (angular relationship between the lower knife ring and the upper shear blade, see **Figure 95**), the blade overlap, the clearance, the web thickness on a laboratory slitting machine. They found out that the clearance must be lower than a certain critical value and that the blade overlap has to be within a certain range otherwise both of them can result in high burr production. The “can’t angle” was mainly affecting the blade service life. Even though the process conditions are quite different (cutting of multiple webs) to those tested by Lu & al., all our measurements tend to confirm part of their findings: the burrs observed on the cross cut and at the top slitter (with a clearance) are worse than on the twin slitter (no clearance). Moreover, reducing the clearance leads to an improvement of the quality.

4.5.1.3.1. Twin slitter

At the twin slitter, the clearance is kept at zero because the contact between the blades is required in order to ensure the rotation of the upper shear blade. Indeed, only the bottom knife ring is driven. Even if the burr is minimal most of the time, it still is noticed at high loading (high number of webs being cut simultaneously). The main reasons to explain why burrs are not often observed on twin slitters is the absence of clearance and the fact that most of the time, a maximum of 3 webs (in some cases 4 webs) are cut simultaneously. The webs possibly affected by the burr are:

- On the band edges: bottom side web of n°6 and 5 and top side web of n°1 and 2
- On the blade edges: top side web of n°4 and 5 and bottom side web of n°3 and 2

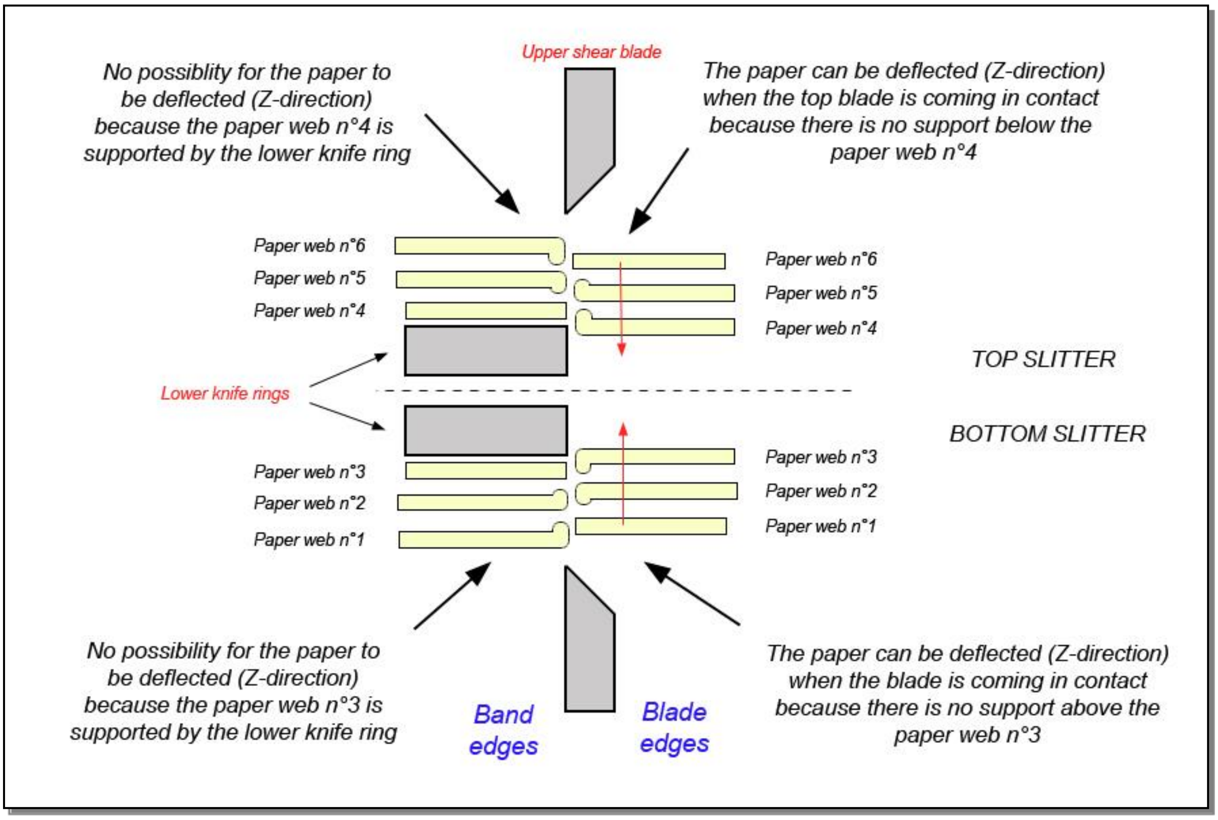


Figure 88: Occurrence of the burr on a twin slitter

4.5.1.3.2. Top slitter

For the top slitter, the clearance is minimal. After a blade change, both blades are brought in contact and then they are separated by a clearance of few µm. The burr observed on paper webs cut on those sheeters is normally higher than on a twin slitter. Two reasons are likely to be responsible for this: the clearance and the fact that much higher loads are run on those machines giving a higher compression of the sheets. The webs affected by the burr are:

- On the band edges: bottom side of web n°6, 5, 4 and 3
- On the blade edges: top side of web n°1, 2, 3 and 4

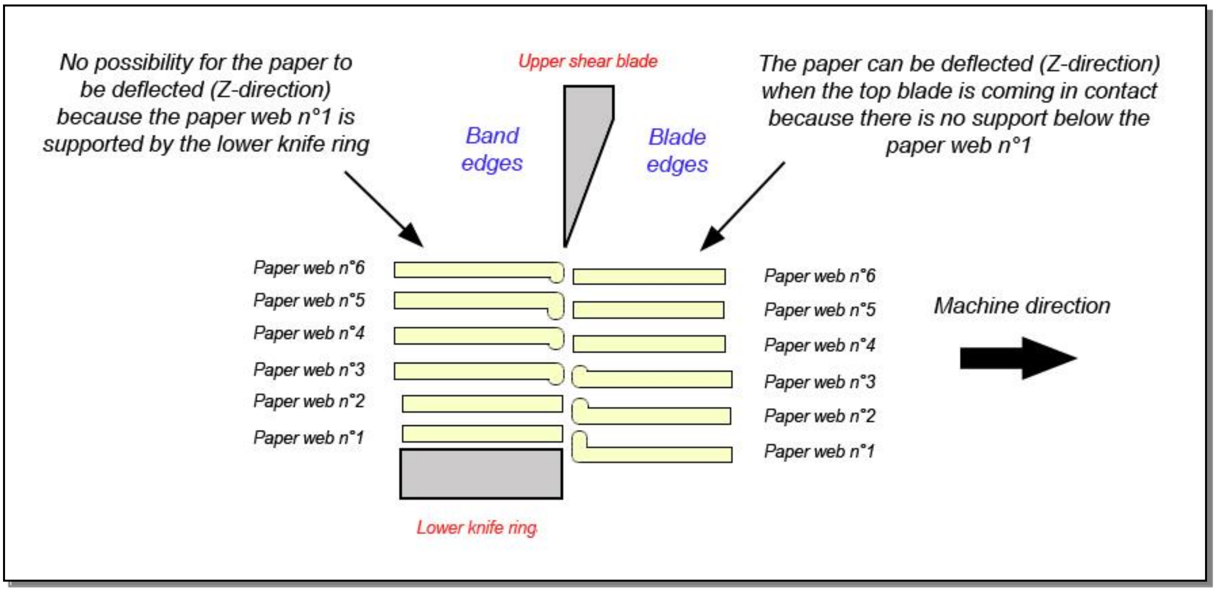


Figure 89: Repartition of the burr on a top slitter

4.5.1.3.3. Double rotary cross cutter

On the cross cutter, the situation is different. With this type of cutter, the clearance is kept as small as possible. This clearance cannot be adjusted to zero due to the high risk of damaging both cutting knives (in case they overlap each other) during the rotation of the drums.

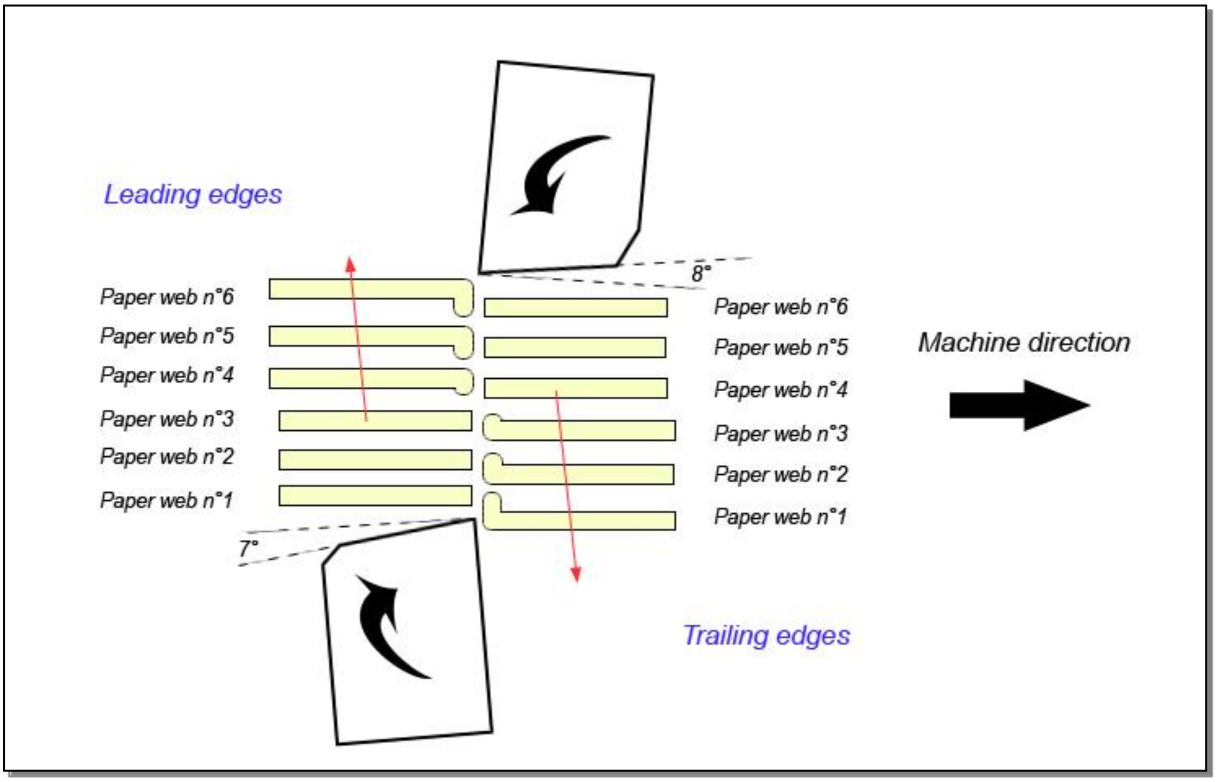


Figure 90: Repartition of the burr on a rotary cross cutter

The rotary cross cutter has a higher clearance compared to the top slitter and it is also at the rotary cross cutter that the higher burrs are observed. The webs affected by the burr are:

- On the leading edges: bottom side of web n°6, 5 and 4
- On the trailing edges: top side of web n°1, 2 and 3

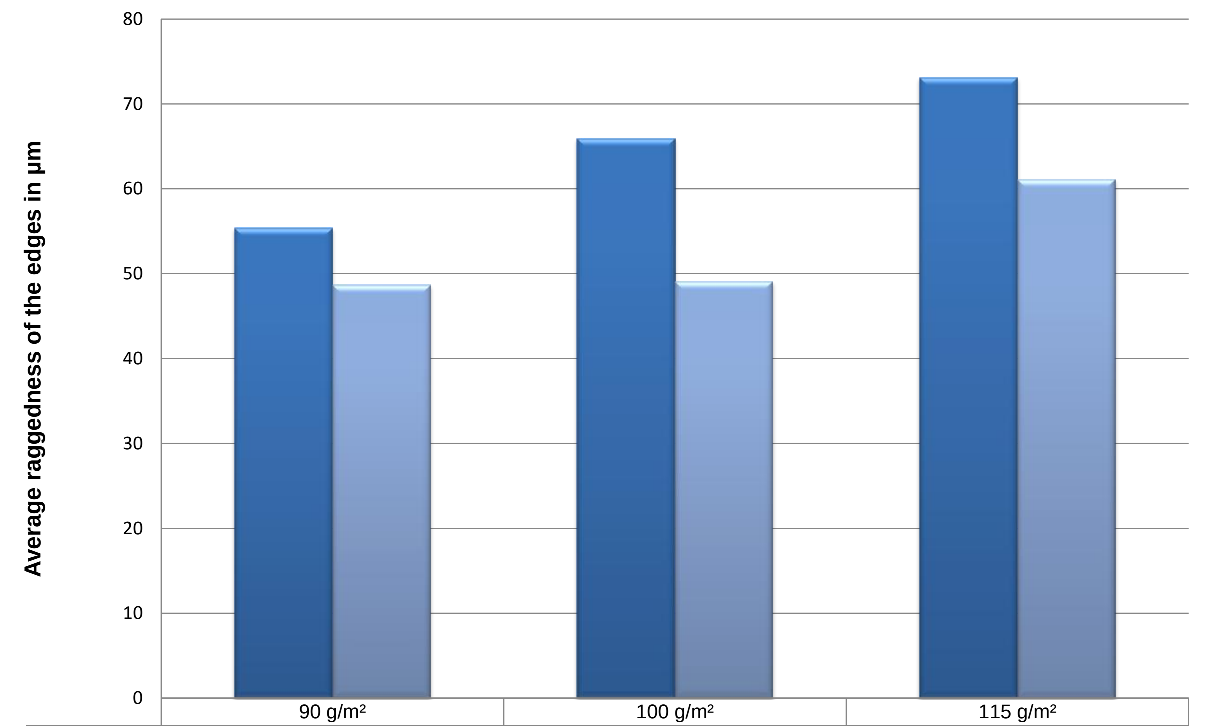
In addition to the sheeter configuration affecting the occurrence of the burr, we found out that the paper properties, the number of webs being cut simultaneously and the state of the blades are also playing an important role regarding burr.

4.5.1.4. Number of webs (or total load) cut simultaneously

Due to the competitive market situation, paper producers are constantly trying to increase productivity. There are two ways to achieve higher productivity in a finishing department: either by increasing the speed of the cutting machines or by increasing the tonnage of paper cut simultaneously. This last point can be performed by:

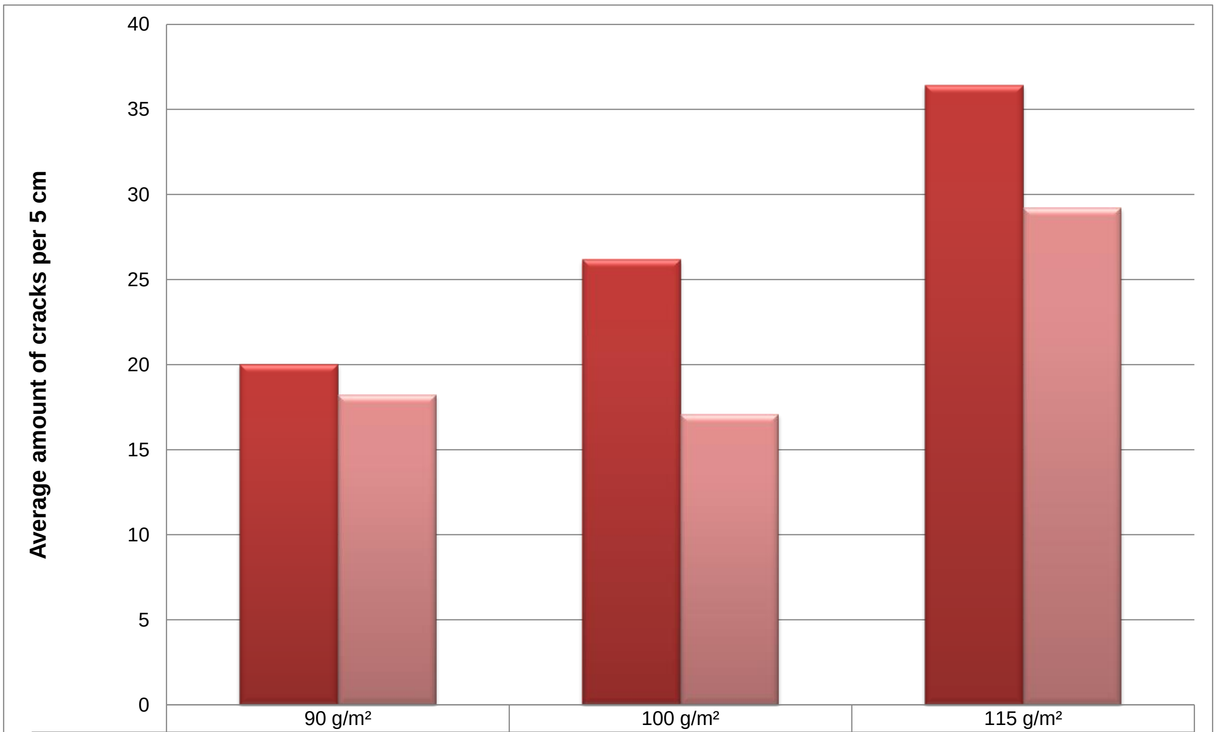
- Increasing the width of the sheeter,
- Increasing the number of paper webs cut simultaneously,
- Increasing the total load reachable at the sheeter.

Only the last two solutions can be implemented without the high investment costs for a new sheeter and therefore these are often implemented. Often these solutions are linked to each other: as the number of webs cut simultaneously is based on the total basis weight of the paper being cut. In general, the addition of a paper web on the sheeter decreases the cut quality significantly. Of course, depending on the paper properties, this decrease in quality can vary. For example, cutting seven webs simultaneously instead of six at acceptable cut quality might be possible with a given paper grade while it will be impossible with another. As studied before in the laboratory, one of the reasons for an increase in the force required to cut the material is the total thickness of the paper stack (transversal cutting section). The higher amount of material being cut also results in a higher folding of the external sheets of the stack and a higher deformation of the sheet inside the paper stack. To illustrate this effect, two trials were set up on a commercial sheeter, the first trial based on an increase in basis weight and the second based on the variation of the number of paper webs being cut simultaneously. During the first trial, seven webs of the same paper quality at three different basis weights were cut simultaneously. Selected basis weights were 90 g/m², 100 g/m² and 115 g/m² (gloss papers). Results of the evaluation of cut quality are shown in the **Figure 91** and **Figure 92**.



	90 g/m²	100 g/m²	115 g/m²
Band edges	55	66	73
Blade edges	49	49	61

Figure 91: Raggedness as a function of basis weight (seven webs being cut simultaneously on a twin slitter configuration at a speed of 160 m/min)



	90 g/m²	100 g/m²	115 g/m²
Band edges	20	26	36
Blade edges	18	17	29

Figure 92: Number of cracks as a function of basis weight (seven webs being cut simultaneously on a twin slitter configuration at a speed of 160 m/min)

The following observations resulted from this trial:

Raggedness:

- The level of raggedness of the cut edges is clearly dependent on the basis weight of the paper being cut: *the higher the basis weight, the higher the raggedness will be. The increase in basis weight from 90 g/m² to 115 g/m² results in an increase in raggedness of 20-30%*

Number the cracks:

- The number of cracks near the cut edges is clearly dependent of the basis weight of the paper being cut: *the higher the basis weight, the higher the number of cracks.*

The observations at the sheeters thus resulted in a clear negative correlation of cut quality depending on basis weight. This correlation is not so clearly noticed at the blade edges because there, the paper is free to deflect (no support from the bottom knife ring) and depending on its stability during the cutting process more or less variation will be created.

When considering the influence of the number of webs, it is not very common to cut fewer paper webs simultaneously than needed. For the second trial, a glossy 200 g/m² paper was cut on a commercial sheeter keeping all sheeter parameters constant while varying the number of webs cut simultaneously from three to five. It is important to mention that a twin slitter was used for the LC, so the blade loading just increased by one sheet and not two. The results regarding raggedness and coating cracks are depicted in **Figure 93** and **Figure 94**. Two separate graphs were prepared per cutting properties. In the left side graph, separate results for all four edges are presented and in the right side graph, an average for the long cut respectively the cross cut is shown. As frequently observed in previous trials the results in cut quality for the two edges created during one cut vary depending on how the paper web is supported during the cutting process.

The following observations resulted from the second trial:

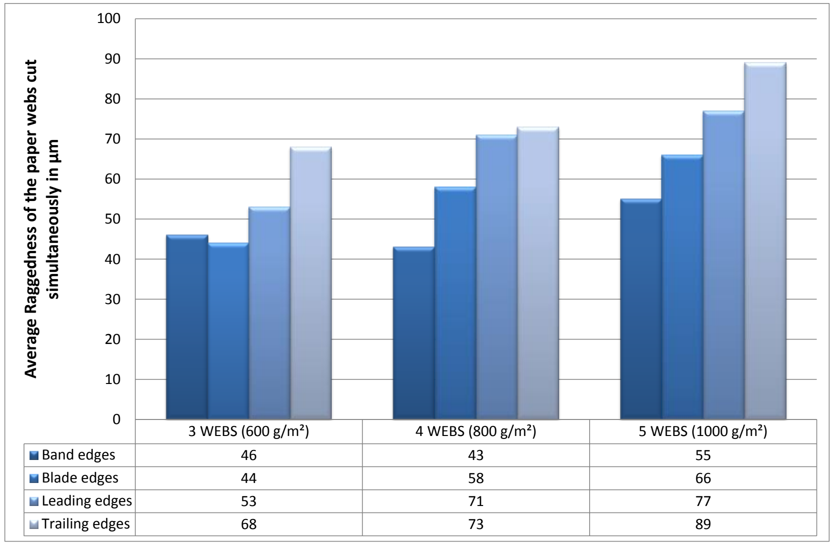
Raggedness (see **Figure 93**):

- Raggedness of the cut edges is clearly dependent on the number of webs being cut: *the higher the number of webs being cut, the higher the raggedness will be.*
- Main differences for raggedness are observed for the blade edges and for both cross cut edges. Increasing the number of webs cut simultaneously from 3 to 5 results in an increase of raggedness of 30 to 50% for those edges.
- For the band edges, the increase of raggedness with a higher number of webs cut simultaneously is lower compared to the other cut edges (around 20%). This is due to the fact that *those edges are being sheared off when passing through the knife*.

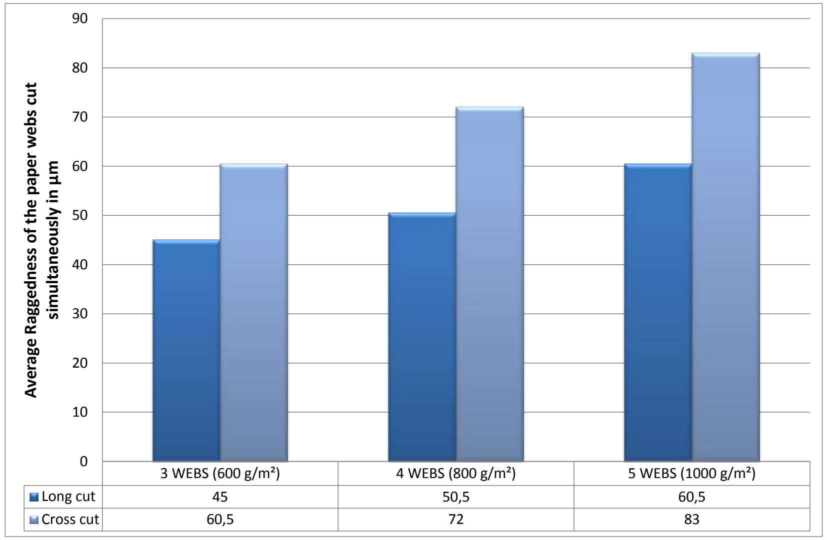
Number of cracks (see **Figure 94**):

- As expected, the number of cracks is significantly higher on the long cut as explained before (see section 4.4.2.2): 75% more cracks for long cut on average.

The results show a clear increase of the number of cracks for the cross cut (over 120% more cracks) and a small one for the long cut (25% more cracks). This increase is mainly due to the absolute number of cracks on the cross cut (e.g. 4 extra cracks lead to a 50% increase…). In any case, cutting 5 webs in cross cut still results in less cracks than cutting 3 webs in long cut.

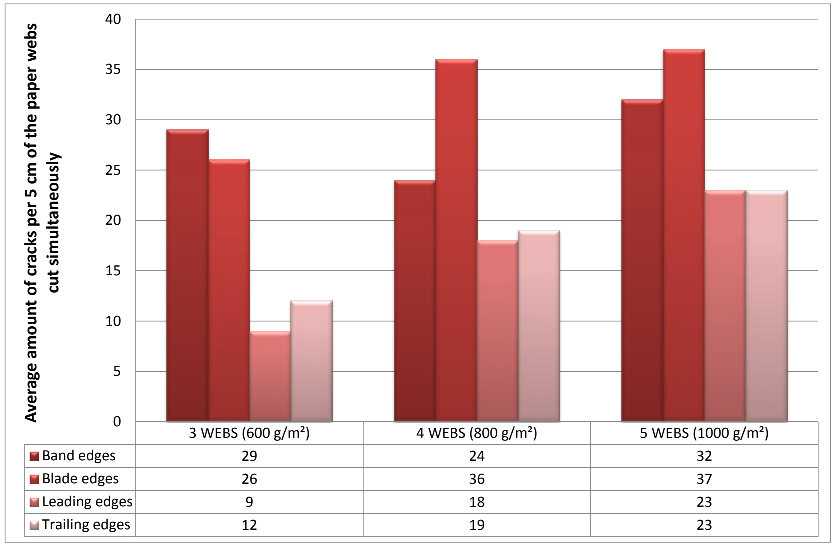


	3 WEBS (600 g/m²)	4 WEBS (800 g/m²)	5 WEBS (1000 g/m²)
Band edges	46	43	55
Blade edges	44	58	66
Leading edges	53	71	77
Trailing edges	68	73	89

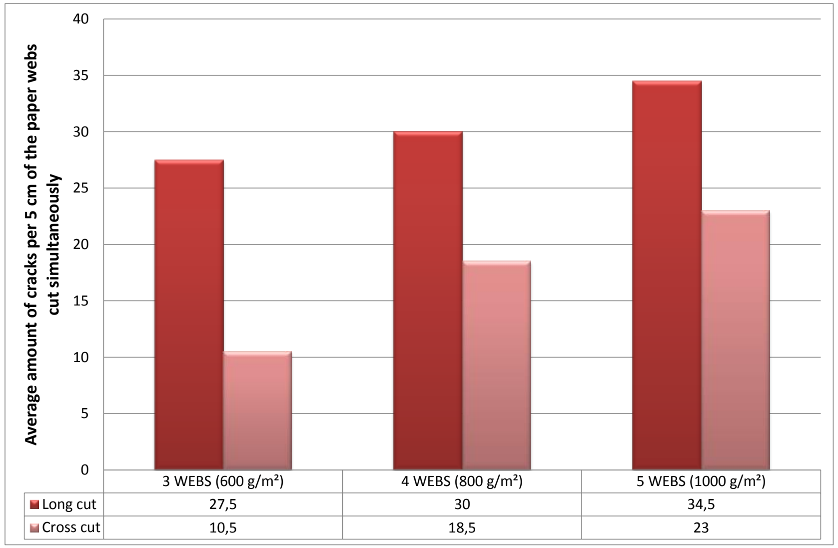


	3 WEBS (600 g/m²)	4 WEBS (800 g/m²)	5 WEBS (1000 g/m²)
Long cut	45	50,5	60,5
Cross cut	60,5	72	83

Figure 93: Raggedness as a function of the number of webs cut simultaneously (tests made with a 200 g/m² gloss paper)



	3 WEBS (600 g/m²)	4 WEBS (800 g/m²)	5 WEBS (1000 g/m²)
Band edges	29	24	32
Blade edges	26	36	37
Leading edges	9	18	23
Trailing edges	12	19	23



	3 WEBS (600 g/m²)	4 WEBS (800 g/m²)	5 WEBS (1000 g/m²)
Long cut	27,5	30	34,5
Cross cut	10,5	18,5	23

Figure 94: Number of cracks per edges as a function of the number of webs cut simultaneously (test made with a 200 g/m² gloss paper)

4.5.2. Influence of Slitter settings

Twin and top slitters are used to cut the material in the longitudinal direction. This system consists of two knives in contact with each other turning in the same direction as the paper web. The paper web undergoes shear between the two knives. With standard slitters, only the bottom knife ring is driven. The upper shear blade is just turning due to the friction forces exerted by the bottom ring on the upper blade. Depending how the material is fed to the cut point, the cutting process will be qualified as tangent or wrap slitting. Focus will be on the tangent slitting in this thesis because it is the most commonly used system. **Figure 95** shows the difference between tangent and wrap slitting and is intended to define the terms used in this section. The main influential parameters on cut quality are: the toe angle, the rake angle, the knives geometry, the over speed, the penetration and the material properties.

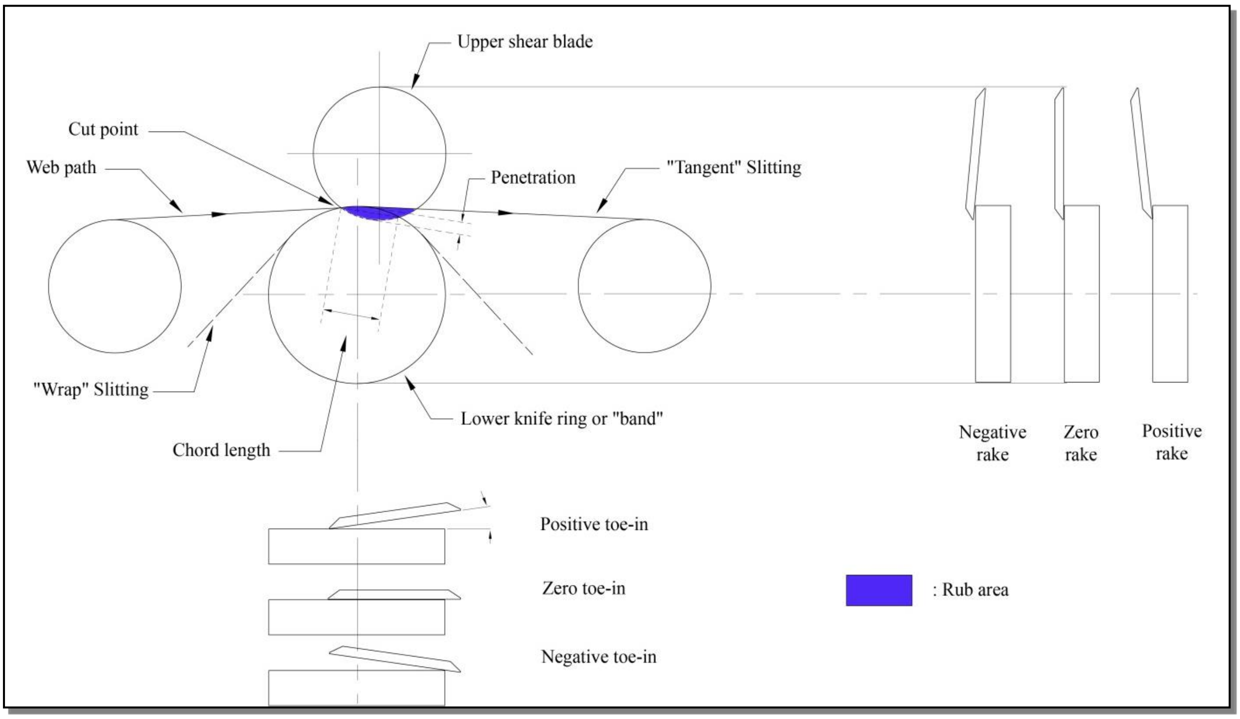


Figure 95: The basics of slitting, main terminology.

4.5.2.1. Toe angle and Rake angle

These parameters are very difficult to adjust and moreover on most of the machinery, they are a consequence of the construction. For the rake angle, it is directly built up in the blade during the grinding process. For the toe angle, it is included in the machine geometry (blade holder construction). Due to the difficulty to change these parameters, their impacts on cut quality have not been studied during this thesis.

4.5.2.2. Penetration / Overlap

4.5.2.2.1. Introduction

The position of the blade is one of the most important factors in shear slitting. It does not only influence the position of the cut point but also the overlap of the blades which affects their life time and the speed of the upper shear blade in the case of a standard slitter where the upper shear blade is driven by the bottom knife ring. All these parameters show interdependence (see **Figure 96**).

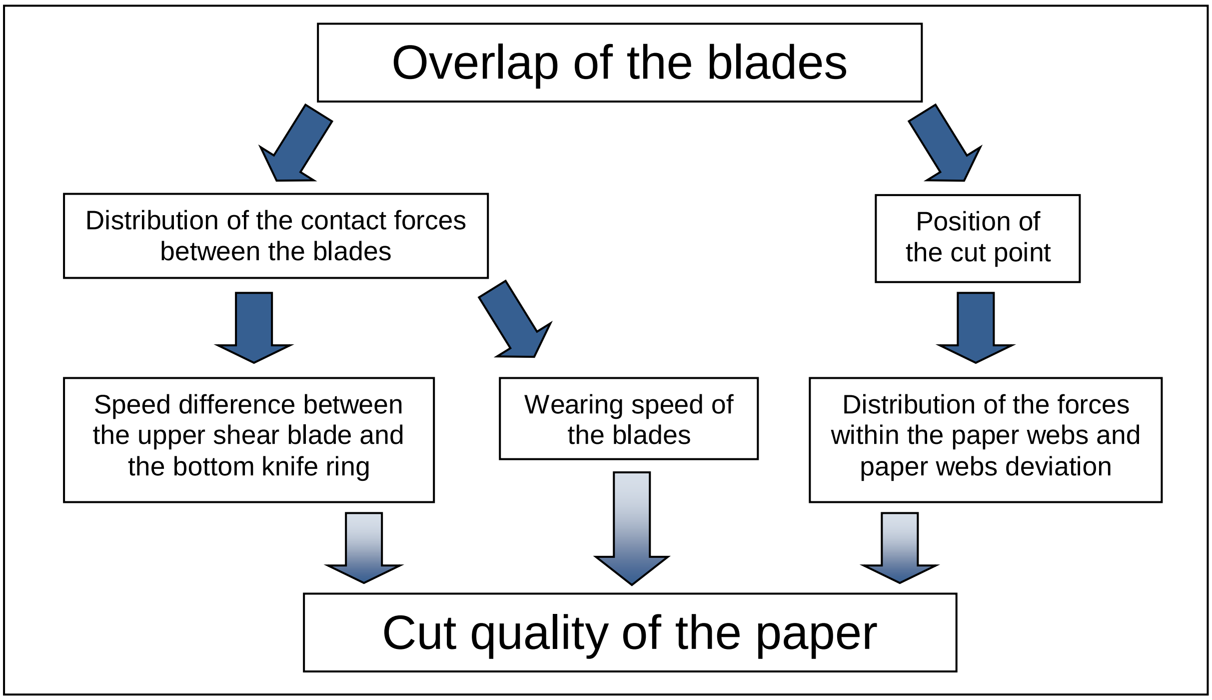


Figure 96: Influences of overlap on cut quality of paper.

4.5.2.2.2. Position of the cut point

The overlap between the top and bottom blades is normally set around 1-2 mm and can hardly be measured visually. Therefore the operators at the sheeter normally measure the so called "chord length" (see **Figure 95** and **Figure 97**) which is higher (around 15 mm) and therefore less sensible to error measurement. However, in practice, this chord length is known to be difficult to adjust and subjective to the operators taking care of this adjustment and their operational habit. The variations observed in the measurement are often due to the difficulty for the operators to properly access the surrounding area of the knives (because of the safety protections). Consequently, large differences can be noticed (+/- 5 mm). This variation can appear to be small but such variation has a strong impact on the cut quality and on the life time of the blades.

Optimum positioning of the blade results in a minimum overlap and a cut point located at the entrance point of the paper webs to be cut. Under the assumption that the paper web is fed horizontally at the top of the bottom knife ring, the optimal chord length can be calculated. A calculation running via a macro in Microsoft Excel was written to estimate the optimal chord length adjustment (see **Figure 97**) based on the machine configuration. The calculations are for a tangent slitting system. To facilitate the calculation, it was assumed that the paper webs are delivered horizontally between the knives. The origin “O” of the (x,y) coordinate system was taken as being on the apex of the bottom knife ring. For a tangent slitting system and in a perfect situation, the top knife should come in contact with the first paper web at x=0 (see **Figure 97**) in order to ensure that the cutting process start only once the paper webs are supported by the bottom knife ring.

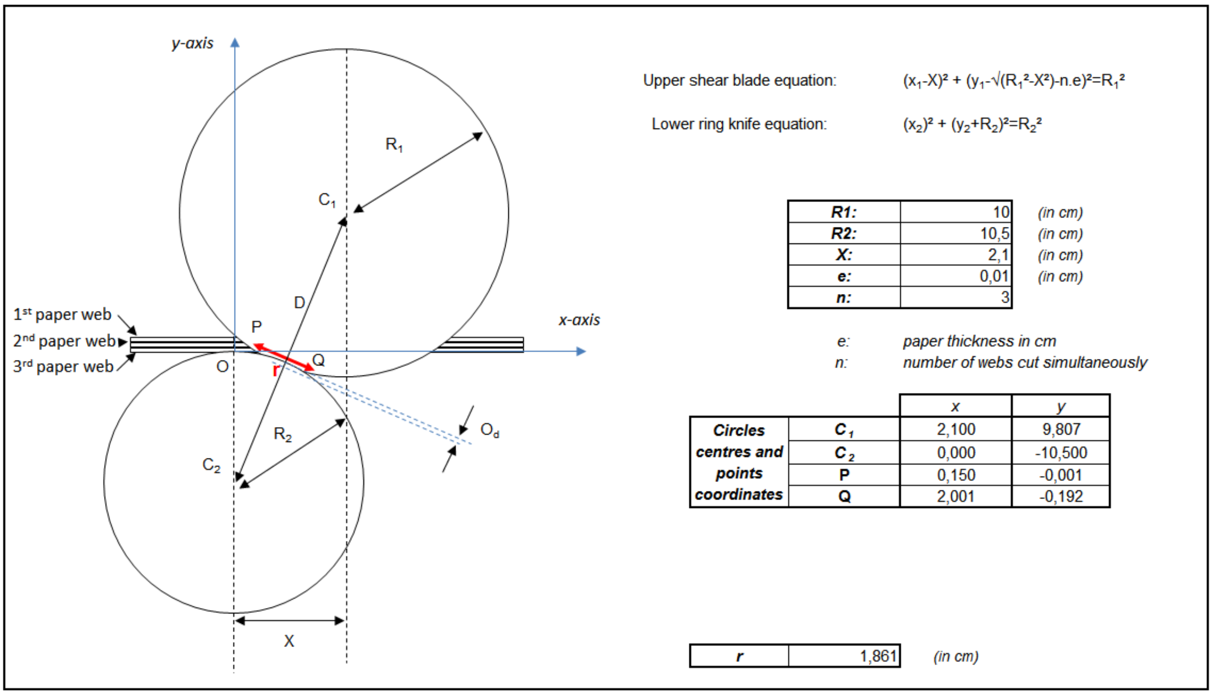


Figure 97: Calculi of the chord length depending on the slitter characteristics (macro running under Excel®)

Normally for every sheeter, the horizontal distance X between the centres of both knives is fixed. The centre of the bottom knife ring and its diameter is also generally fixed: C_2 (0;-R_2). Therefore the vertical position of the upper shear blade will depend on its diameter (2.R_1), on the amount of paper being cut (n sheets) and on its nominal thickness (e). It is important to mention that the diameter of the upper shear blade varies depending on the age of the blade. Indeed every blade undergoes regrinding to maintain suitability for use until it reaches a minimum critical diameter.

Equation 23: Equation of the circle C_1 (upper shear blade)

$$(x_1 - X)^2 + \left(y_1 - \sqrt{\left(R_1^{\,2} - X^2\right)} - n.e\right)^2 = R_1^{\,2}$$

With:

(x_1,y_1), coordinates of the circle C_1,

R_1: radius of C_1,

n: number of sheets cut simultaneously,

e: thickness of 1 paper web,

X: horizontal distance between the centre points of the two circles.

Equation 24: Equation of the circle C_2 (bottom knife ring)

$$(x_2)^2 + (y_2 - R_2)^2 = R_2^{\ 2}$$

With:

(x_2,y_2) coordinates of the circle C_2,

R_2: radius of C_2.

By using equations 23 and 24, the coordinates of the point P and Q (representing the two points of intersection of the circles C_1 and C_2) can easily be found (intersection of the 2 circles).

The distance A can be calculated as follow:

Equation 25: Chord length r as a function of blades position

$$r = \sqrt{\left(\left(y_q - y_p\right)^2 + \left(x_q - x_p\right)^2\right)}$$

Knowing the position of both blades, it is also possible to calculate the distance D between the two blades centres:

Equation 26: Distance between the two blades centres

$$D = \sqrt{\left(X_{C_2} - X_{C_1}\right)^2 + \left(Y_{C_2} - Y_{C_1}\right)^2}$$

Knowing the distance between the centres of the two blades, the overlap distance O_d can be calculated as follows:

Equation 27: Overlap distance between two blades

$$O_d = R_1 + R_2 - D$$

In order to evaluate the effect of the chord length on the cut quality, three tests were performed at a production sheeter. To avoid any possible influence of the blade diameter, brand new blades presenting the same diameter were used for each test. The following chord lengths were tested: 10, 15 and 20 mm. From each test, papers were collected and the cut quality was analysed, as described in chapter 3.2. **Table 11** below presents the results for blade and band edges. The percentages between brackets represent the change in the values compared to the best cut quality achieved with a chord length of 10mm:

	Raggedness in µm		Number of cracks per 5 cm		Fibre pull	
Chord length	*Band edges*	*Blade edges*	*Band edges*	*Blade edges*	*Band edges*	*Blade edges*
10 mm	38	25	17	11	3.3	3.1
15 mm	41 (+8%)	38 (+52%)	21 (+24%)	15 (+36%)	3.3 (~)	3.4 (+10%)
20 mm	50 (+32%)	51 (+104%)	33 (+94%)	23 (+109%)	3.3 (~)	3.9 (+26%)

Table 11: Cut quality as a function of the chord length (average from five sheets cut simultaneously using new blades)

The following conclusions were drawn:

- Even though the visual evaluation of the cut quality is acceptable with all three settings, a significant change in cut quality depending on chord length is noticed,
- The smaller the blade overlap, the better the cut quality,
- Both cutting edges are affected with the blade edges showing a higher variation,
- All the cut quality aspects are affected by the changes:
  - *The raggedness of the edges increases by more than 100% on the blade edges,*
  - *The number of cracks increases by more than 100%,*
  - *The fibre pull increases by more than 25% on the blade edges.*
- The life time of the blade is strongly affected by the blade positioning:
  - *Too small, an overlap presents a high risk for the blade to jump on the bottom knife ring,*
  - *Too high, an overlap results in high friction forces leading to faster wear of the blade. This point will be detailed further in this thesis.*

To visualize the changes in cut quality as a function of chord length, images of the blade edges viewed from the top and bottom sides are depicted in **Figure 98**.

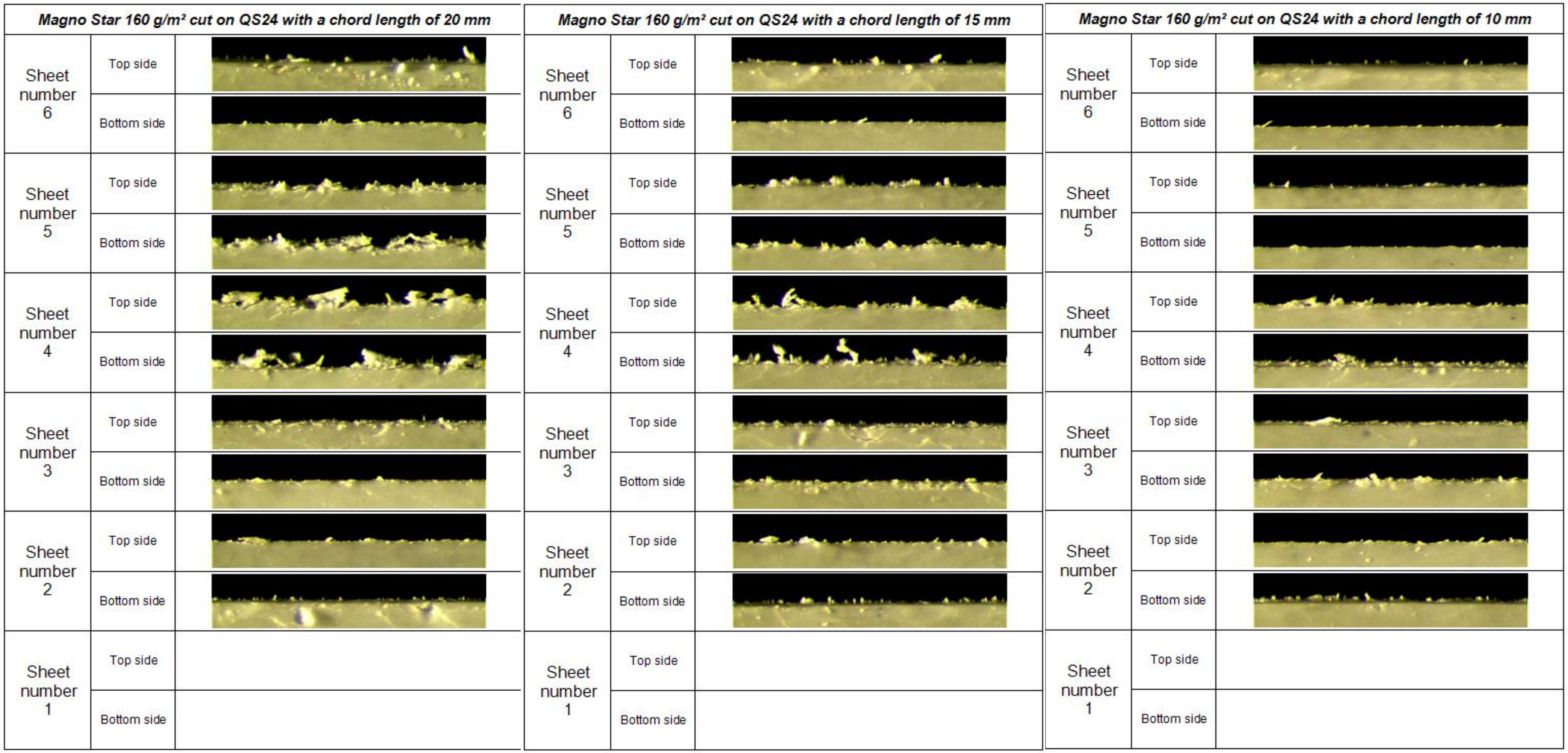
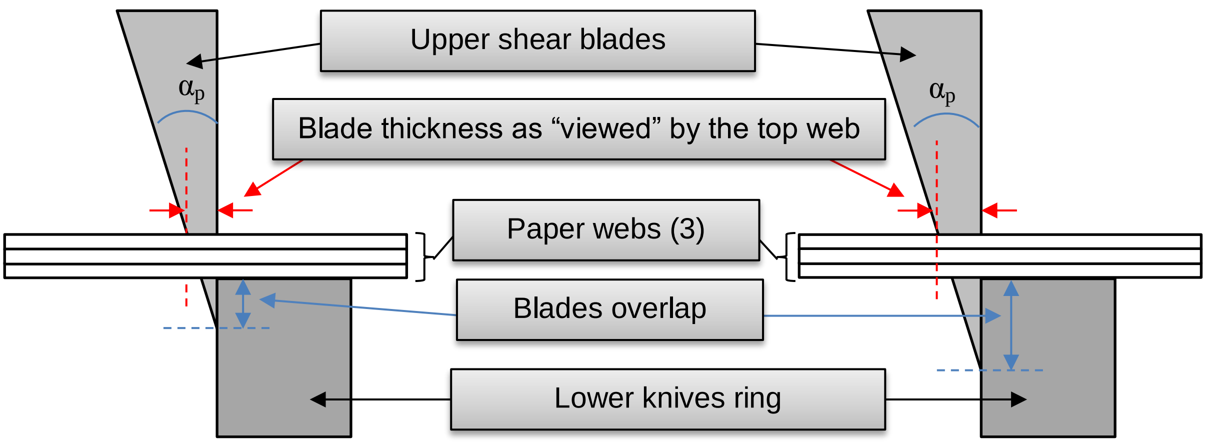


Figure 98: Cut quality on the blade edges through the paper stack as a function of chord length (five sheets cut simultaneously on a twin slitter)

One hypothesis to explain the observed differences regarding raggedness and fibre pull on both edges (band vs. blade edges) is that the band edges are sheared off when coming in contact with the knife contrary to the blade edges. Therefore only limited changes are noticed on the band edges. On the other hand, increasing the chord length increases definitely the raggedness and the amount of fibre pull on the blade edges because the cut point is located more and more upfront the tip of the blade leading to the fact that the paper is more torn than cut.

Concerning the number of cracks, both edges are impacted in similar proportion. This is explained by the position of the blade: the higher the chord length, the higher the blades overlap and the higher the stress created ahead of the cut point (see **Figure 99**). This stress ahead of the cut point will also be strongly impacted by the state of the blade, a worn blade creating a higher stress.

Front view:



Perspective view:

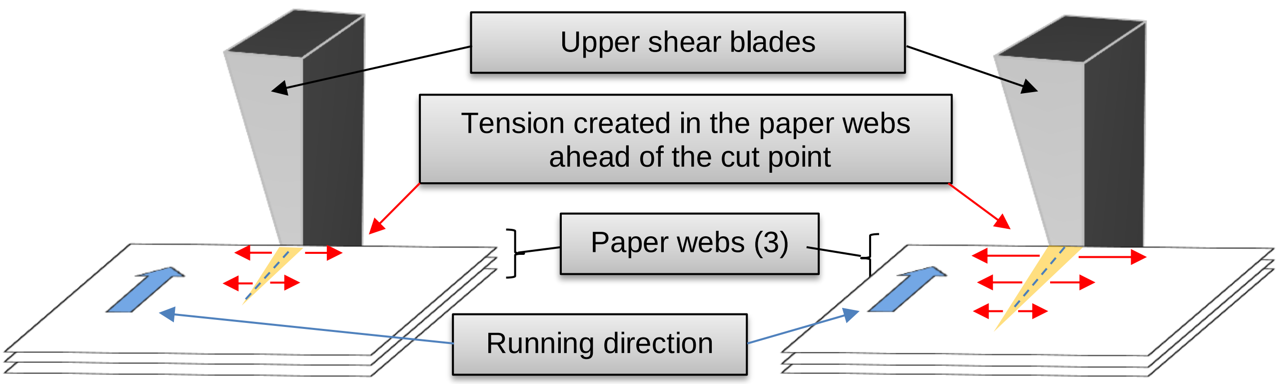


Figure 99: Effects of low (left) and high (right) blades overlaps in front of the cut point at the slitter (front view and perspective view)

With decreasing paper strength, e.g. due to the replacement of fibres by inorganic fillers, the influence of the chord length is likely to be even higher due to the paper being more sensitive to the stress created in front of the blades. This means that the positioning of the blades might become for the operators more and more important.

To check that the results seem to be dependent on the age of the knives, a similar test was performed with worn blades. The results are summarized in the **Table 12**:

	Raggedness in µm		Number of cracks per 5 cm		Fibre pull	
Chord length	*Band edges*	*Blade edges*	*Band edges*	*Blade edges*	*Band edges*	*Blade edges*
10 mm	63	61	34	27	3.3	3.1
15 mm	62 (~)	73 (+20%)	32 (~)	39 (+44%)	3.5 (~)	4.1 (+32%)
20 mm	58 (~)	81 (+33%)	28 (~)	33 (+22%)	3.2 (~)	3.7 (+19%)

Table 12: Cut quality as a function of chord length (average taken from six sheets cut simultaneously using worn blades)

As expected, the initial cut quality at a chord length of 10 mm was worse than with the new blades. The blade edges were the most affected by the decrease in cut quality at longer chord length. As observed with brand new knives, the evolution of the raggedness with chord length at the blade edges is approximately linear. However, this was not found to be the case for the number of cracks and is likely due to a very poor initial cut quality. Indeed, when the cut quality reaches a very bad level, even though the raggedness is increasing the number of cracks starts to decrease or stays at a constant level since the particles will just be released from the edges. In this situation, a lot of dust is created but the number of cracks stays constant or starts to decrease. The cut quality on band edges was staying poor for each cut quality parameter.

4.5.2.2.3. Distribution of forces

As mentioned before, two kinds of slitting systems exist: the top slitter with two driven knives and the standard slitter with only one driven rotating knife. Due to mechanical considerations, optimal operation conditions are achieved when the knives are running at the same speed as the material being cut. This is also occurring when cutting a piece of material with a pair of scissors. However, it is sometimes possible to cut without closing the blades of the scissors by just pushing them through the piece of material. This last solution works only with some specific materials: the “non velocity dependent” materials. Some materials are difficult even impossible to cut with such an approach as it is the case, for example, for soft plastic. In this case, the material is considered as “velocity dependent”. In such a case of velocity dependence, a too slow speed will result in poor cut quality: the material will wrinkle in front of the blade. Therefore, it is fundamental to ensure that the blades are running at least as fast, if not faster, than the material being cut.

In the case of a conventional slitter, the top knife is driven by contact with the bottom knife ring. Due to the friction between both blades and their position, a loss of energy occurs, resulting in a loss of speed. Therefore, the bottom knife is normally always running faster than the material being cut. Depending on the type of sheeter, the over speed of the bottom knife may be fixed. In this case, an over speed of approximately 5 to 6% is advised. The speed of the upper shear blade does not only depend on the bottom knife ring speed but also on the upper shear blade adjustment. The higher the penetration, the higher the friction forces resulting in a lower speed of the upper shear blade. With a shorter chord length, the speed difference between the bottom and top knives is lower since most of the force transferred from the bottom knife is used to make the top knife turn (tangential forces). With a longer chord length, a high amount of friction is created and therefore, this part of the force is not used to drive the top knife. This effect is quite easy to understand when looking at the slitter configuration (see **Figure 100**).

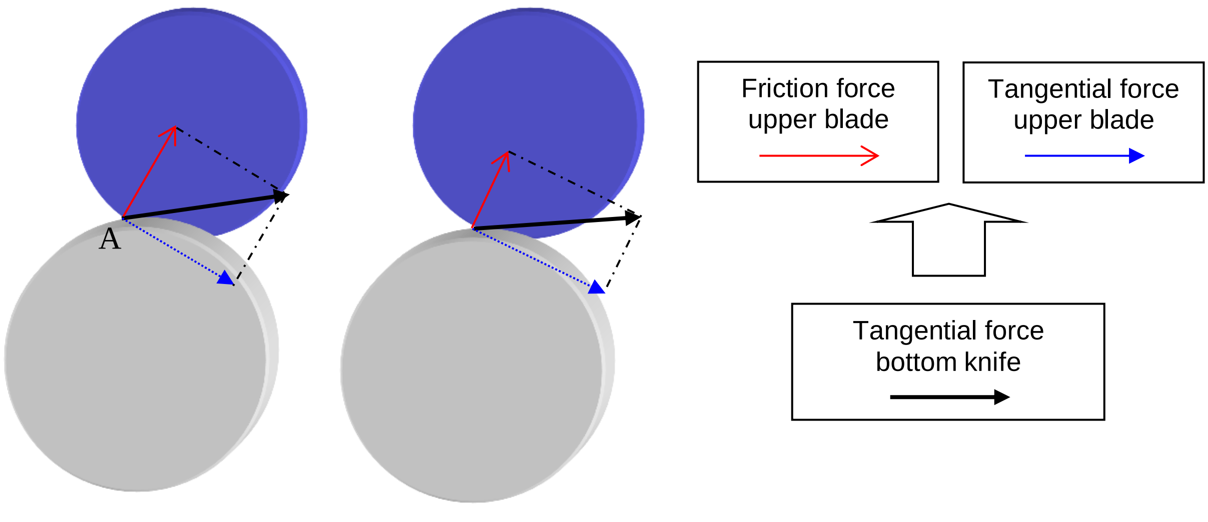


Figure 100: Transformation of the driven force delivered by the bottom knife ring on the upper shear blade with high (left) and low (right) chord length

The bottom knife transfers a force at the contact point between both knives (point A). This force is split into two distinguished parts:

- *Pure friction component: force perpendicular to the tangent of the top blade at the contact point which is the only direction where the top blade is fixed and therefore in result in pure friction.*
- *Pure tangential force: tangent to the top blade which drives the top blade.*

Schable [57] presented for simplified slitter geometry, considering both knives being positioned on top of each other and having the same diameter, the loss of speed of the upper shear blade based on the blade's overlap. He found that the loss of speed increases when increasing the blade's overlap. In the same time, the friction forces become higher which leads to a shorter blades lifetime. He also showed that, for a defined overlap, blades presenting a small diameter are more sensitive to the loss of speed and are getting worn faster. Under the assumptions that there is no loss of energy and that all the force transferred by the bottom knife ring are converted to friction force and tangential force, these two components can be calculated. With these two force components, an efficiency of the system can be defined as the amount of forces used to make the top knife run divided by the total amount of forces in the system. Of interest is the calculation of the percentage of initial forces delivered by the bottom knife ring that is transferred to the upper shear blade (a% for friction and b% for tangential force) may be evaluated. This can be calculated by measuring the norm of the vectors. Schable's simplified model was adapted to our slitter configuration: different position of the upper shear blade compared to the bottom knife ring.

In paragraph 4.5.2.2, the chord length is calculated including the position of the knives. Taking the same slitter configuration, the force generated by the bottom knife ring and the resulting forces on the upper shear blade are drawn in **Figure 101**:

- Initial speed vector ($\overrightarrow{S_{ring}}$) delivered by the bottom knife ring: black arrow
- Speed vector ($\overrightarrow{S_{upp}}$) transmitted to the upper shear blade: blue arrow
- Friction forces ($\overrightarrow{R_{fric}}$) transmitted to the upper shear blade: red arrow

To facilitate the calculation, different coordinate system was used: the origin being the centre point of the chord length and the y-axis, the line passing through both blade centres. Then the x-axis is naturally the line (PQ). Considering φ_b as the angle between the tangent at the bottom knife ring in P and the x-axis, it is also equal to the angle $\widehat{PC_2Q}$ divided by 2.
Considering φ_u as the angle between the tangent at the upper shear blade in P and the x-axis, it is also equal to the angle $\widehat{PC_1Q}$ divided by 2. Previously, the distance between the point P and Q, $|\overrightarrow{PQ}|$, has been calculated and defined as the chord length "r".

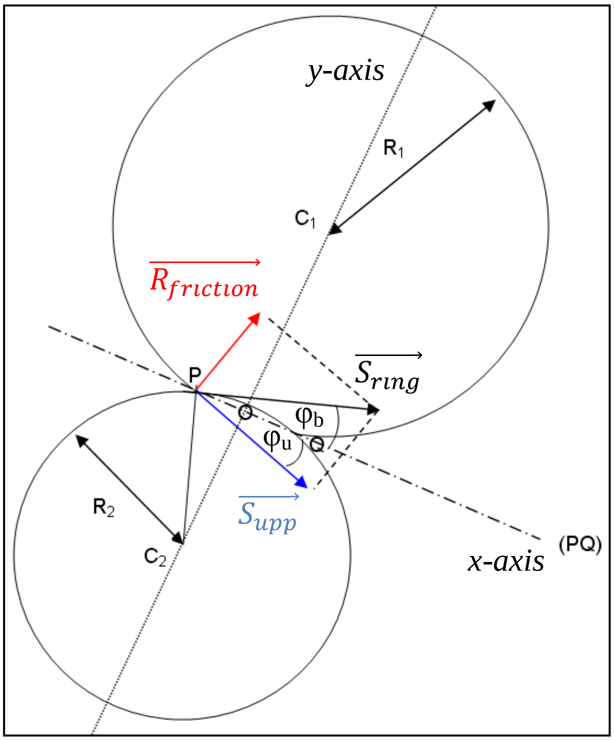


Figure 101: Speed vectors at the slitter

Therefore, it can be shown:

Equation 28: Expression of φu

$$\varphi_u = \sin^{-1}\left(\frac{A}{2} \cdot \frac{1}{R_2}\right)$$

and

Equation 29: Expression of φb

$$\varphi_b = \sin^{-1}\left(\frac{A}{2} \cdot \frac{1}{R_1}\right)$$

The norm of the speed vector of the upper shear blade can then be calculated as a function of the norm of the speed vector of the bottom knife ring:

Equation 30: Norm of the speed vector of the upper shear blade

$$\left|\overrightarrow{S_{upp}}\right| = \left|\overrightarrow{S_{ring}}\right| . \cos(\varphi_u + \varphi_b)$$

In the same way, the norm of the friction vector can be calculated as a function of the norm of the speed vector of the bottom knife ring:

Equation 31: Norm of the speed vector of the bottom knife ring

$$\left|\overrightarrow{R_{friction}}\right| = \left|\overrightarrow{S_{ring}}\right| . \sin(\varphi_u + \varphi_b)$$

To check the influence of the chord length on the speed of the upper shear blade, the speed of the upper shear blade was calculated and also measured with the help of a stroboscope for different chord lengths. In general, a decrease of speed can be observed which confirms the explanation mentioned before (see **Figure 102**).

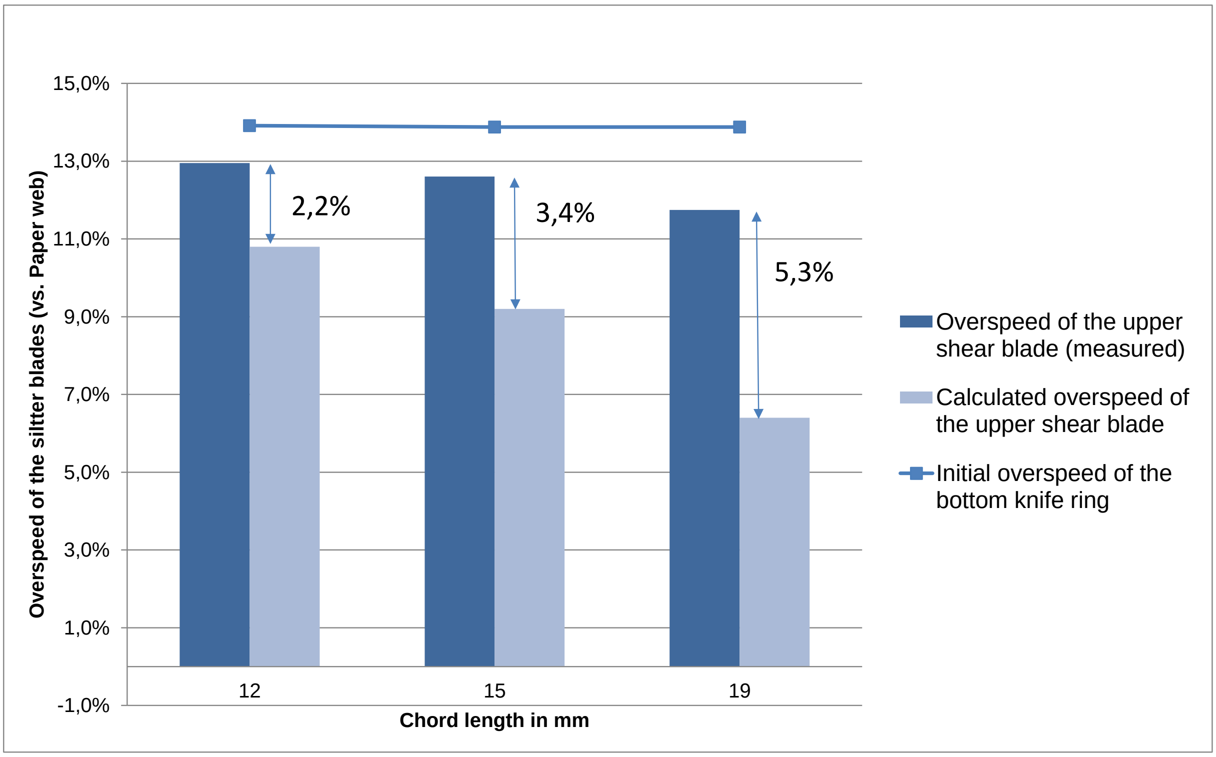


Figure 102: Effect of the chord length on the upper shear blade speed

The effect of the chord length was not as high as pronounced as expected from our calculation. The differences observed are most probably due to:

- The fact that the normal pressure applied between both knives to keep them in contact is not taken into consideration in our calculation. Obviously, this pressure strongly reduces the reduction of speed due to friction between the materials. Indeed, the higher the chord length is, the more important is the effect of the pressure applied between the blades. At a short chord length, when the friction component is lower, the difference between the theoretical model and the actual measurement is smaller.
- The limited accurateness of the calculated results for the chord length due to the fact that the input variables also might show some deviations.

4.5.2.3. Blade wear

Slitter blades undergo wearing and become dull with time or more precisely with the number of rotations. The wearing of the blade has been intensively studied as well by knife suppliers, paper producers and the manufacturers of sheeters. The main targets of these studies were to develop new raw materials and to analyse the influence of the blade geometry in order to determine how blade life time could be extended. In his PhD thesis: "*The wear of paper slitting blades*" **[58]**, Antice found that the predominant wearing mechanism was abrasion due to the action of hard particles such as silica. The wear of the blade was identified as a change in the cutting action from a shearing mechanism to a tensile-tearing mechanism, which limits the running time of the blade due to unacceptable cut quality resulting from such a mechanism. Schable made a troubleshooting guide based on this topic **[59]** emphasizing the symptoms which can be observed on the blades such as the aspect of the wear band and its location, and he listed the possible reasons for them. Paper producers are changing the paper composition generally in the direction of reducing the amount of fibres and increasing the amount of fillers. This has a significant impact on the abrasiveness of the produced paper and it is likely that the paper itself is wearing the blade due to the constant friction of the paper edge against the blade side of the upper shear blade (see **Figure 103**).

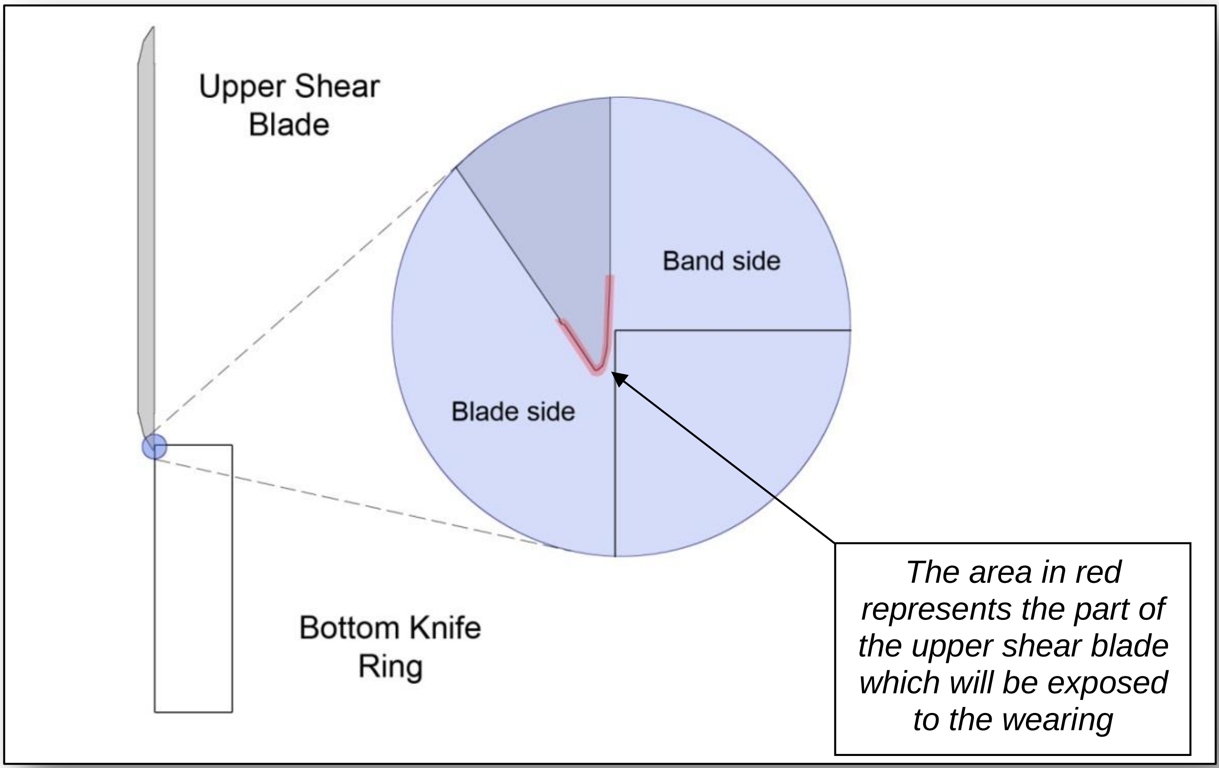
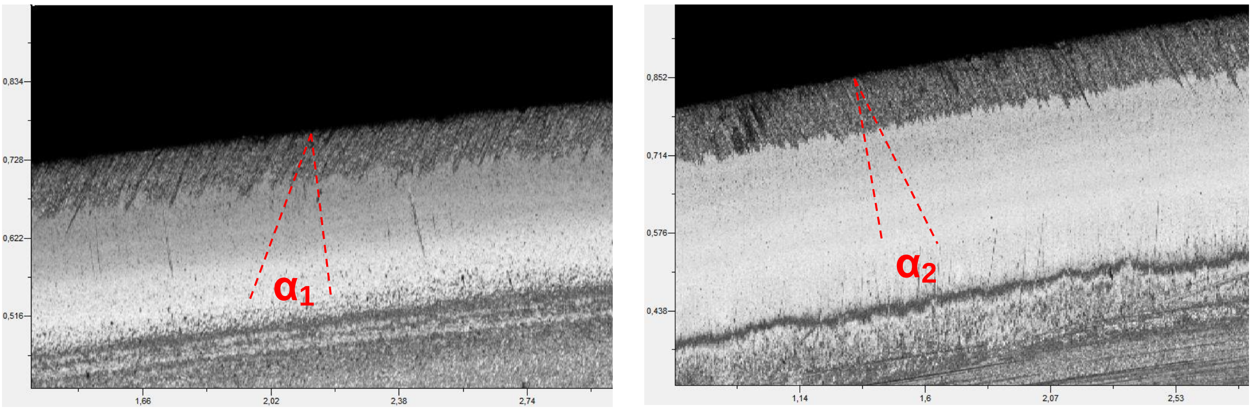


Figure 103: State of the upper shear blade after wearing

Precise analysis of the upper shear blade topography has been made with the help of the Nanoscope [34] in order to study how these blades have been worn and whether the information found in literature could be confirmed. Based on these analyses, several conclusions were drawn:

- The contact area between the upper shear blade and the bottom knife ring, the overlap area, presents a smooth wear. This wear can be directly linked to the chord length adjustment at the slitter. The higher the chord length is, the more oriented towards the centre of the blade will be the marks due to contacts between both knives ($\alpha_1<\alpha_2$). The orientation of the marks depends on the direction of the speed vector of the bottom knife ring (see 4.5.2.2.3).



a) Effect of a chord length of 17 mm b) Effect of a chord length of 19 mm

Figure 104: Microscopic pictures, obtained with the topography device [34], of the band side of the upper shear blades after 4 weeks running at the sheeter with two different settings for the overlap of the blades

α_1 and α_2 quantifying the orientation of the friction marks between both blade

- Several observations have confirmed the fact that the paper due to its composition, also contributes significantly to the blade wear. **Figure 105** shows the wearing action of the paper: the paper webs are sharpening the blade during the cutting process.

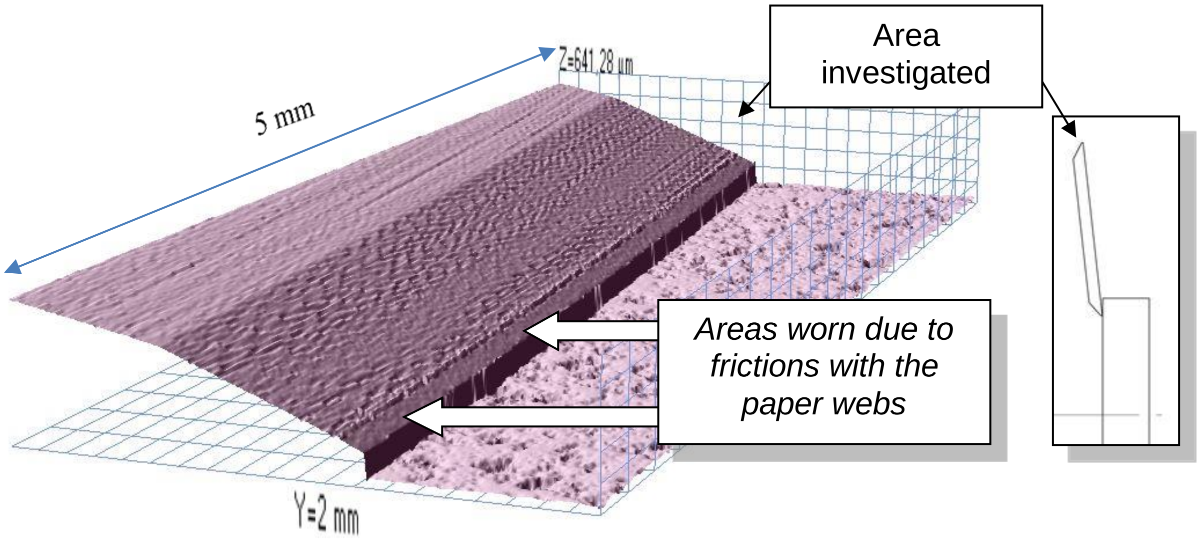


Figure 105: Topography measurement [34] of the tip of an upper shear blade presenting a worn area on the side in contact with the paper webs (blade edges).

In order to study the impact of worn blade on the cut quality of wood free coated papers, several tests were carried out on a commercial sheeter. A suitable amount of papers were produced and cut at the same sheeter with the same settings at different time interval. By doing so, it was possible to evaluate the influence of different materials but also the effect on the cut quality. For each test, paper samples were collected and analysis of cut quality was carried out in the laboratory.

The first test was dedicated to the generation of dust at the slitter during the cutting process. New knives were installed at the slitter and for a period of five weeks papers from the same production run were cut with the same machinery settings. Before each test, the areas around the sheeter were cleaned and after a specific period of time, dust was collected and measured for a defined collection area by weight (see **Figure 106**). The results show that the amount of dust is linked with the age of the blade. It increases by a factor of three with three weeks and seems to follow an exponential development. A change of blade resulted in a significant decrease of collected dust.

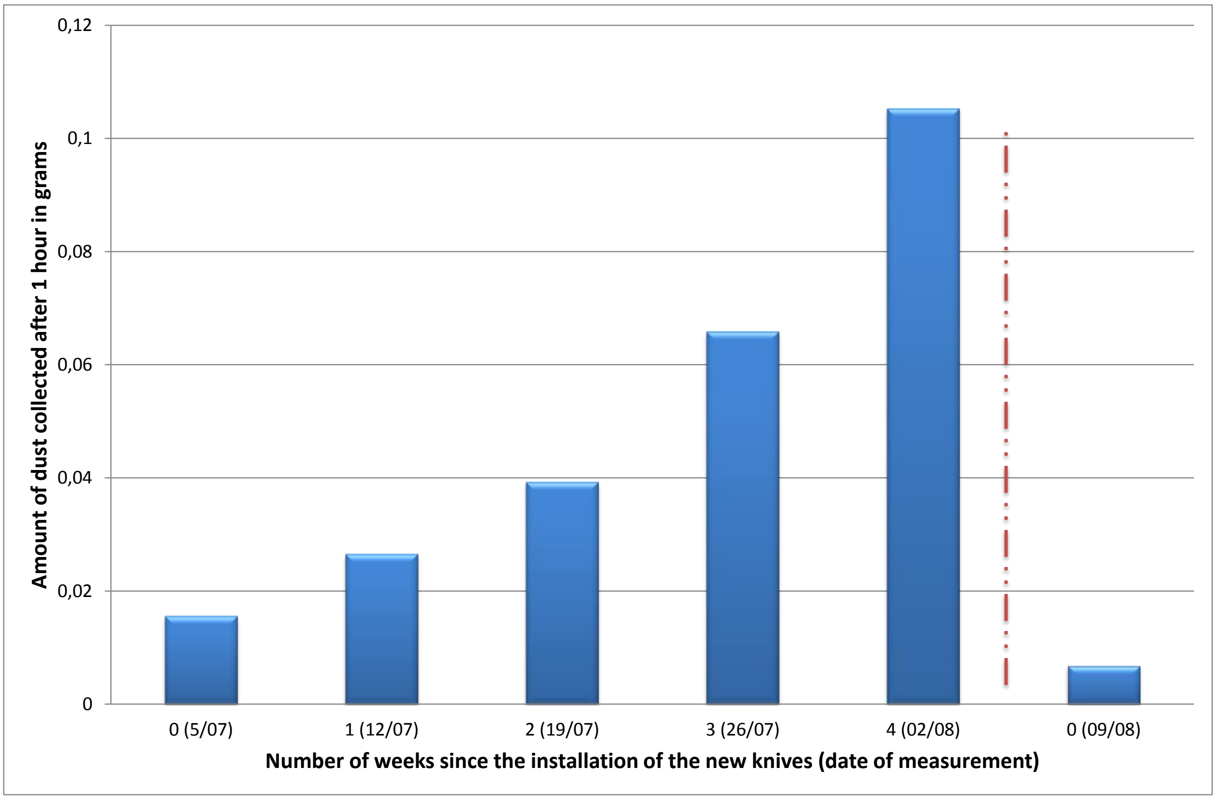


Figure 106: Evolution of the dust generation at the sheeter with the wear of the blade

The location of the cracks within the paper stack is also strongly influenced by the wear of the blades. In another trial, papers were collected at intervals during a period of two weeks and their cut quality was evaluated. Of the three parameters used to define cut quality, the raggedness is the most affected by the wearing of the blade: it deteriorates by a factor of 2 in two weeks. The number of cracks is mainly influenced by the blade positioning and the initial blade quality. However, an increase with “wearing” of the blade was also noticed. The number of cracks depending on the location of the sheet in the stack was even more affected. For example, on the blade edges, mainly the sheet in contact with the blade was found to deteriorate over time. The tip of the knife might get dull and scratches the surface of the first layer. This theory was confirmed by analysing the knife surface at the end of the trial (see picture in **Appendix E**). In the same way, it was also confirmed by the observations made with the amount of dust collected over time. These observations have been represented in **Figure 107**.

Figure 107: Number of cracks depending on location of sheet within stack as a function of the blade wears (on the blade side)

On the band edges, the first two layers in contact with the upper shear blade (layer 1,2,5 and 6) are exposed to a folding action characterized by the presence of a higher number of cracks on the inner fold (see paragraph). After few days, only the first layer in contact with the upper shear blade (layer 1 and 6) still presents this asymmetry of the number of cracks between top and bottom sides. It is likely due to the fact that the upper shear blade is not as sharp anymore. Due to that, the compression and the stress within the paper stack increase and the layer located in the middle of the stack is not folded anymore but just compressed. These observations have been represented in **Figure 108**.

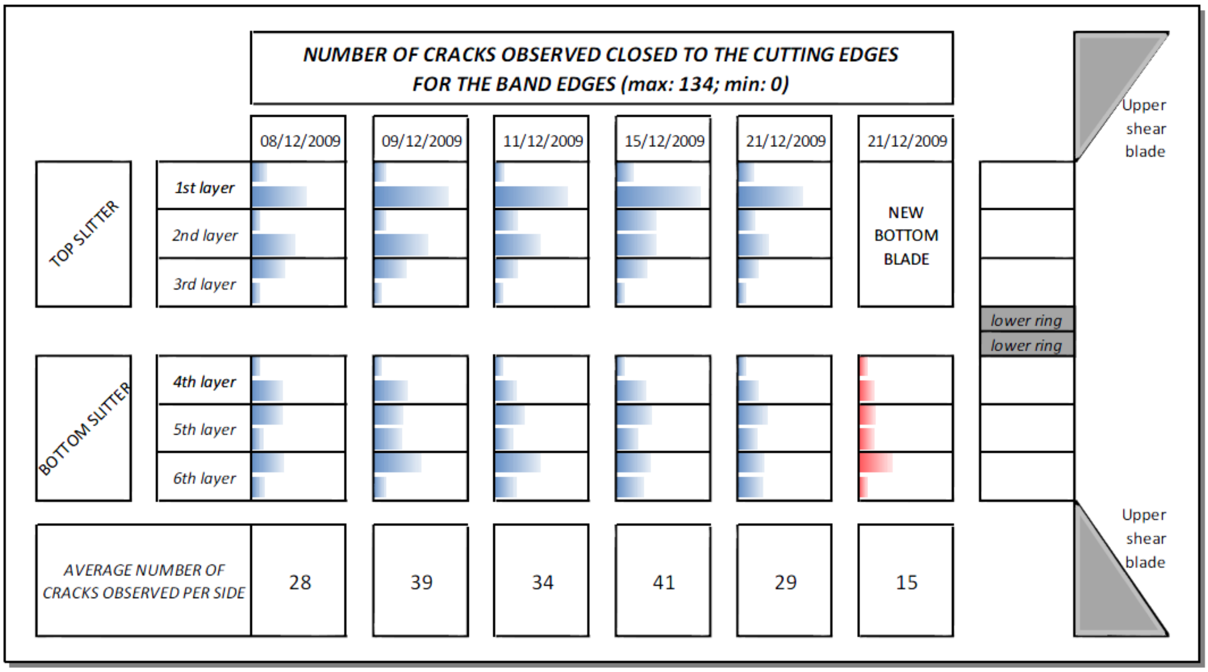


Figure 108: Number of cracks depending on location of sheet within stack as a function of the blade wears (on the band side)

To summarize, we have seen a significant influence of the blade adjustment and of the wear of the blades on the cut quality. For the operators, a new system was put in place on all sheeters to facilitate the correct positioning of the blade at the slitter. This system consists of a plastic stencil used by the operator in order to check the chord length. This stencil is made of two parts which are sliced on both sides of the blades. The correspondence of the line indicates to the operator a good position for the blades (see Appendix F for more details). All employees were trained to work with this system and a video was made to train new employees.

4.5.2.4. Blade geometry: angle and sharpness

Blade aspects are an important factor to consider before starting to cut paper. Indeed they have a strong influence on the paper behaviour during the cutting process. Moreover, depending on the material being cut, they can influence the cut quality. Before starting to study these factors, it is important to define the blade geometry which can mainly be described by the angle of the blades and the sharpness of the blade. Indeed the sharpness of the blade has nothing to do with the blade angle. The sharpness of a material can be defined by the width of the line created at the intersection of two areas. This width is in general small for a sharp blade and depends mainly on the quality of the grinding processes and on the material itself. Sharpness can be measured accurately by the help of an electronic microscope. Due to the difficulty to correctly monitor sharpness in a commercial finishing department, it was decided to focus exclusively the knife angle in this thesis. The sharpness of the blade is also decreasing with the wearing process of the blade which was covered in the previous paragraph (see paragraph 4.5.2.3). All knives were manufactured from the same material and reground at the same place by the same person and were considered to present a standard quality regarding sharpness.

In order to study the bevel angle impacts, three types of blade geometry currently in use were selected: 27°, 45° and 60° (see **Figure 109**). Only the primary blade angle was varied while the secondary grind angle was kept to 15° (see **Appendix G**). Small blade angles (below 30°) are normally avoided due to the weakness of the tip of the knife. Indeed a blade with a small bevel angle presents a high risk of rupture. Moreover, it wears faster. On the other hand these small angles have the advantage of decreasing the cutting forces and also the deformation of the material in front of the cut point. Nowadays, due to the increasing number of webs being cut simultaneously, it has become necessary to decrease the bevel angles of the blades but this leads to a new set of challenges and few disadvantages. Going from 27° to 60° is an important change in terms of the cutting process. Indeed with a bevel angle of 27°, it is possible to speak about a "*slitting*" process: the blade going through the paper web, the material is slit by the upper blade. With a bevel of 60°, we are more in the area of a true "*shearing"* process as the material is severed between the top and bottom blades. With tangent slitting, low bevel angles are normally used for sheeters cutting multiple webs. Low bevel angles may also be applied to bulky materials. High bevel angles are normally used with dense materials that are immune to deformation. Information and advices regarding the blade geometries to be used for shear slitting have been summarized by Schable [60]. The cut quality strongly depends on the material being cut. Different observations can be noticed with other materials possessing different mechanical properties. During our experiment, the bevel angle of the bottom knife ring was kept constant at 85°. Then the same paper was cut with the different blades. Finally, the cut quality was evaluated.

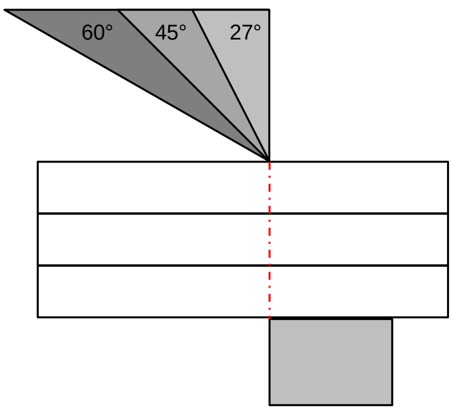


Figure 109: Different blade geometries used for the test

Tests were performed with the same paper grade from one production run (glossy grade of 135 g/m²). The raggedness increases with the bevel angle of the blade (see **Figure 110**). This confirms the theory of Schable that the stress created in front of the cut point influences the cut quality due to the blade position and thickness. It is mainly the layer in contact with the upper shear blade which shows the strongest variation in raggedness. This layer also undergoes the largest stress difference in front of the cut point (see **Figure 99**).

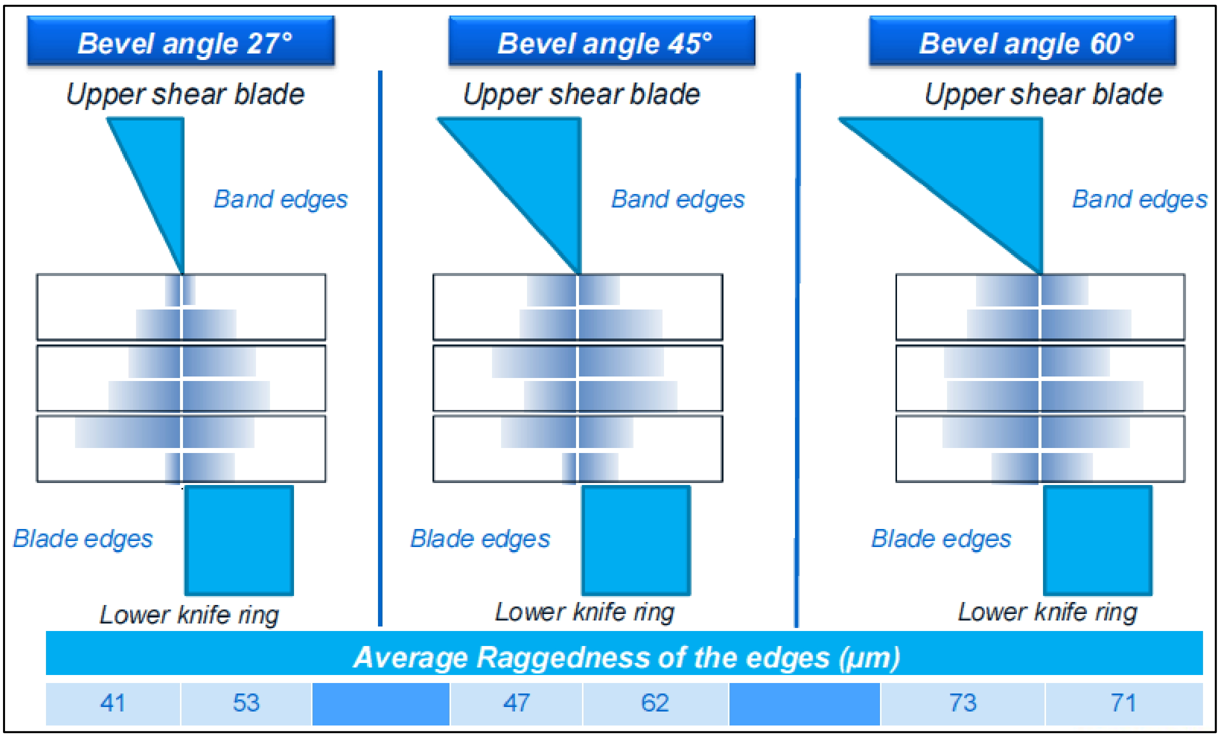


Figure 110: Raggedness of the edges within the paper stack as a function of different blade geometries

The distributions of the cracks through the different layers are shown in **Figure 111**. With a bevel angle of 60°, top and bottom sides of the sheets presented a similar number of cracks. This shows that the layers were definitely not folded but clearly severed between the knives. With regards to the two other geometries (27° and 45°), asymmetry regarding the number of cracks between top and bottom sides of a same sheet confirmed the folding of the webs. This effect was more pronounced with the 45° knife. One explanation could be that with this angle, the paper is not really slit and not really sheared but faces something in between these two actions. With our materials, it seems to combine the negative features of both shearing and slitting. With a bevel angle of 27°, the material is more slit than sheared as the paper web does not have sufficient time to be folded mainly if the knife is very sharp, lowering the force required to penetrate into the substrate.

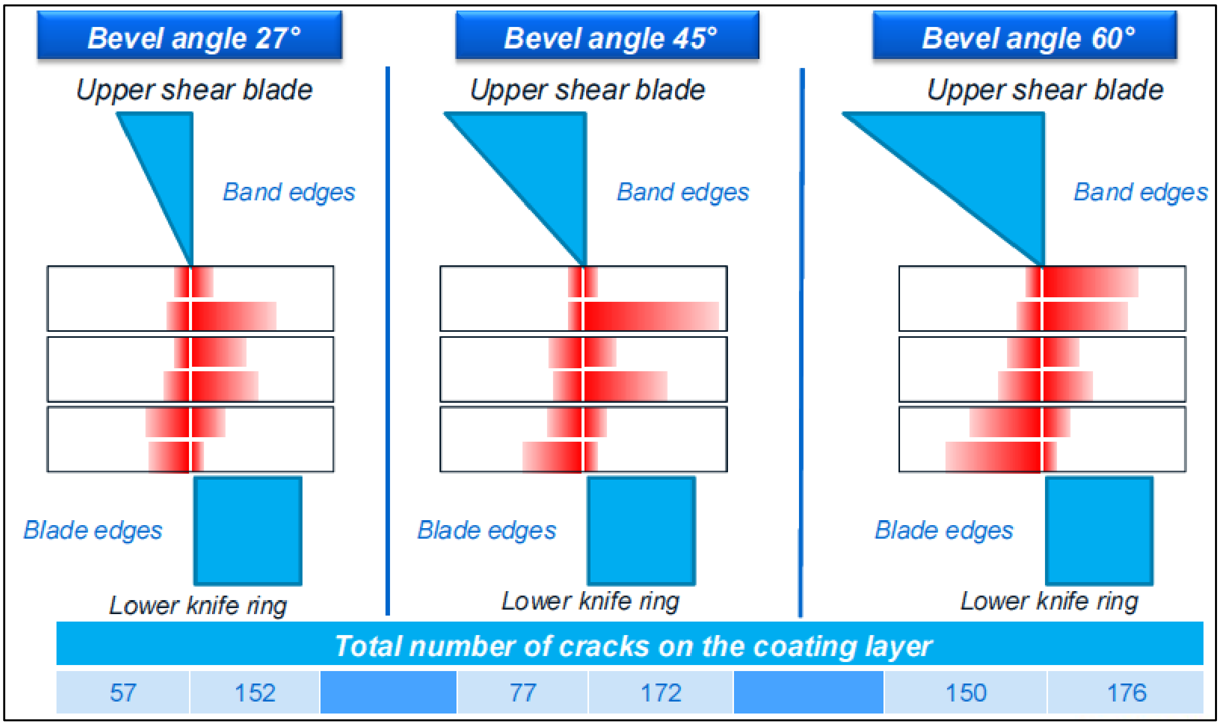


Figure 111: Distribution of the number of cracks within the paper stack as a function of different blade geometries

In conclusion a bevel angle of 27° turned out to be the best blade geometry for cutting WFC paper in terms of raggedness but also in terms of the number of cracks. Our results are based solely on a cut quality analysis of paper samples but one also has to consider the runnability aspects of the blades since stopping the sheeter to change blades results in productivity losses. Obviously the knives with a bevel angle of 27° needs to be changed more often compared to knives with a 60° blade angle. The effects of blade angle, varying from 20° to 30°, on blade stresses during cutting of different kinds of paper materials was studied by Erdogang et Al. [61]. In their study, they simulate the guillotine process. Based on their results, they conclude that for increased durability of the blade in terms of abrasion/breakage, a blade angle of 28° was the optimum and that blade angle below 22° is not advised.

4.5.2.5. Speed

The operation speed is an important parameter of the sheeter as it directly influences productivity. At the same time, higher cutting speed is expected to result in a lower cut quality. In order to check this common assumption, several tests were carried out at the sheeters cutting different paper qualities at significantly varied speeds. Contrary to common belief, no differences were noticed between the papers cut at low speed compared to papers cut at high speed (see **Table 13**).

	Speed (m/min)	Number of sheets	Raggedness (µm)	Number of cracks per 5 cm	Fibre pull (-)
1st test (standard paper quality)	100	7	40	11	2.3
	170	7	38 (~)	12 (~)	2.4 (~)
2nd test (low paper quality)	100	6	44	4	3,5
	220	6	46 (~)	6 (~)	3,3 (~)

Table 13: Cut quality as a function of machine speed on longitudinal edges (average obtained from all sheets cut simultaneously – basis weight 90 g/m² - standard and low paper qualities in terms of tensile strength and tearing strength)

Looking more closely at the cutting process, these results are not surprising. In longitudinal cutting, the paper webs and the knives are all moving and when the paper web is accelerating then the knives are also accelerating in a similar proportion. This means that whatever the paper speed, the cutting action always occurs at a constant speed ratio in the running direction of the web (speed of the blade vs. speed of the paper webs).

Meehan and Burns also observed this behaviour and stated: "*The rate at which the material is slit appears to have minor effects on the measured cutting-force curve and its stability*" and "*The applied stresses in a web and the material's response to these stresses dominate the quality of the cut surfaces*" [38].

4.5.3. Influence of rotary cross cutter settings:

Contrary to the slitter, the rotary cross cutter cut the paper webs perpendicular to the main fibre direction. Double rotary cross cutters differ from the slitters by the fact that the knives are placed on two drum cylinders. In order to avoid cutting the entire width of the paper webs at the same time, the knives are set in a helix angle (see **Figure 112**). The main purpose of the helix angle is to reduce the force of the cutting process. If there was no helix, then the forces and the knife deflection would be at the maximum. By adding a helix, only a small portion of the total web width is cut at any one time. This, however, creates another problem. To create a helix on a cylindrical knife cylinder, the cutting elements must be wrapped in a spiral around the cylinder. The alignments of the blades on the top and bottom cylinders must be perfect to avoid a clash between both knives. For stability and runnability reasons, a draw press roll is installed upfront to blow away the air between the paper webs in order to optimize the alignment and accuracy of the cutting. To obtain sheets having four rectangular angles, the drums cylinders are set at an angle with the web (see **Figure 113**).

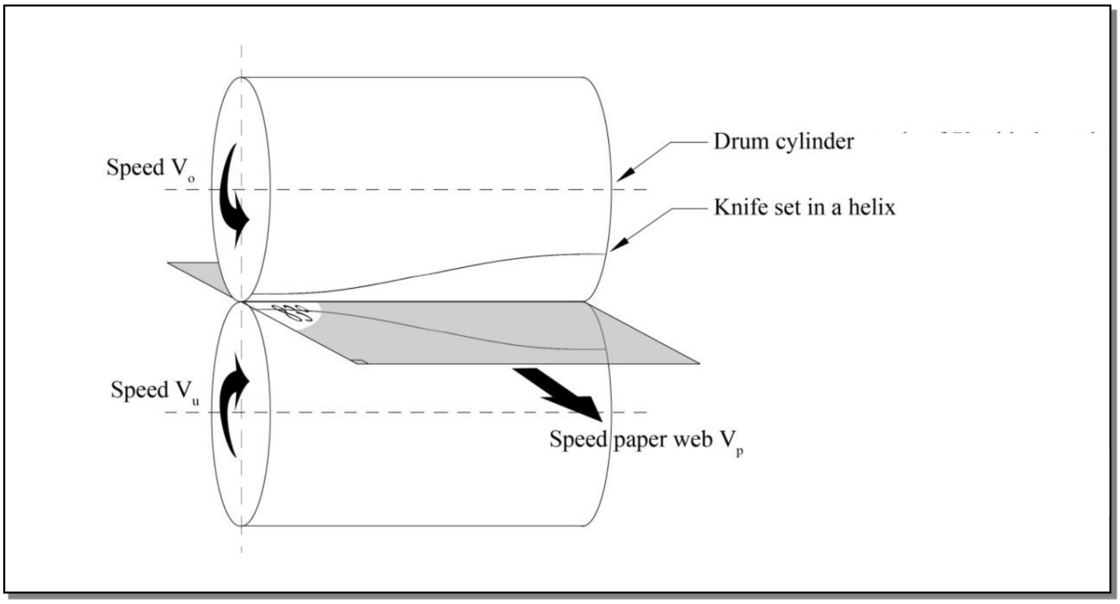


Figure 112: Double rotary cross cutter description

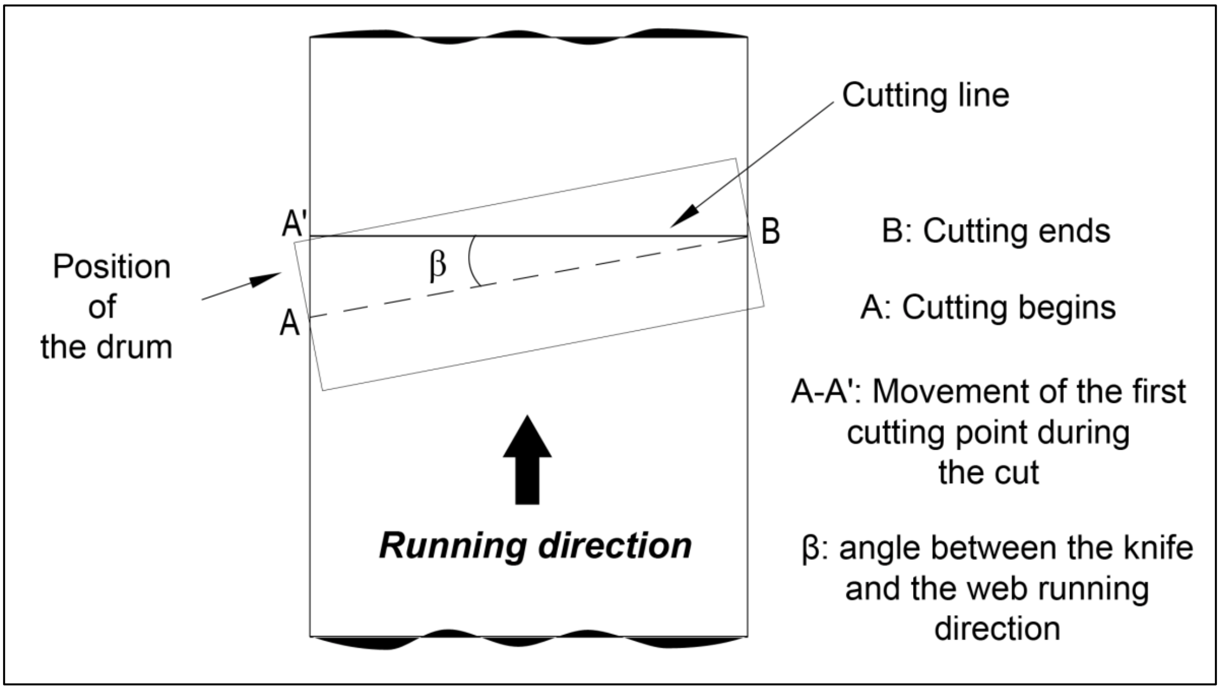


Figure 113: Cutting process on a double rotary cross cutter

During this thesis, only a limited amount of parameters regarding cross cutting were tested due to the difficulty to set up different tests. It was not realistic to test different blade geometries due to the time required, the difficulty to change the blades and the commercial implication on the productivity of the sheeters.

4.5.3.1. Blade adjustments: clearance

Contrary to the slitters, the rotary cross cutter knives are not changed so often and their adjustment is more difficult as there is no way to measure the clearance. In practice, the adjustments of the blades are made as follows:

a. Blades are installed in the blade holders. The bottom blade has a fixed position and the other blade can be adjusted with several screws every 2 cm giving the blade a slight bend to ensure a perfect alignment between the knives (see **Figure 114**)
b. A sheet of paper of high basis weight is placed between the blades and the cylinders are rotated at a low speed.
c. Based on the observed cut quality of the sheet at low speed over the full width, the knife may be adjusted with the screws in the area presenting a bad cut quality.

The last two operations are repeated with different basis weights from high to low with the aim to reduce the clearance between the blades while staying within a clearance zone which avoids the blades from overlapping. Finally, the rotary cross cutter rotates during a specified time and the clearance is checked again and readjusted if required. This blade adjustment takes up to 4 hours and can be performed several times during the life time of the blade. Besides this, the height of the blade is also very important and needs to be adjusted with the aid of a metal bar each time the blade is reground to ensure that the blades are meeting in one point.

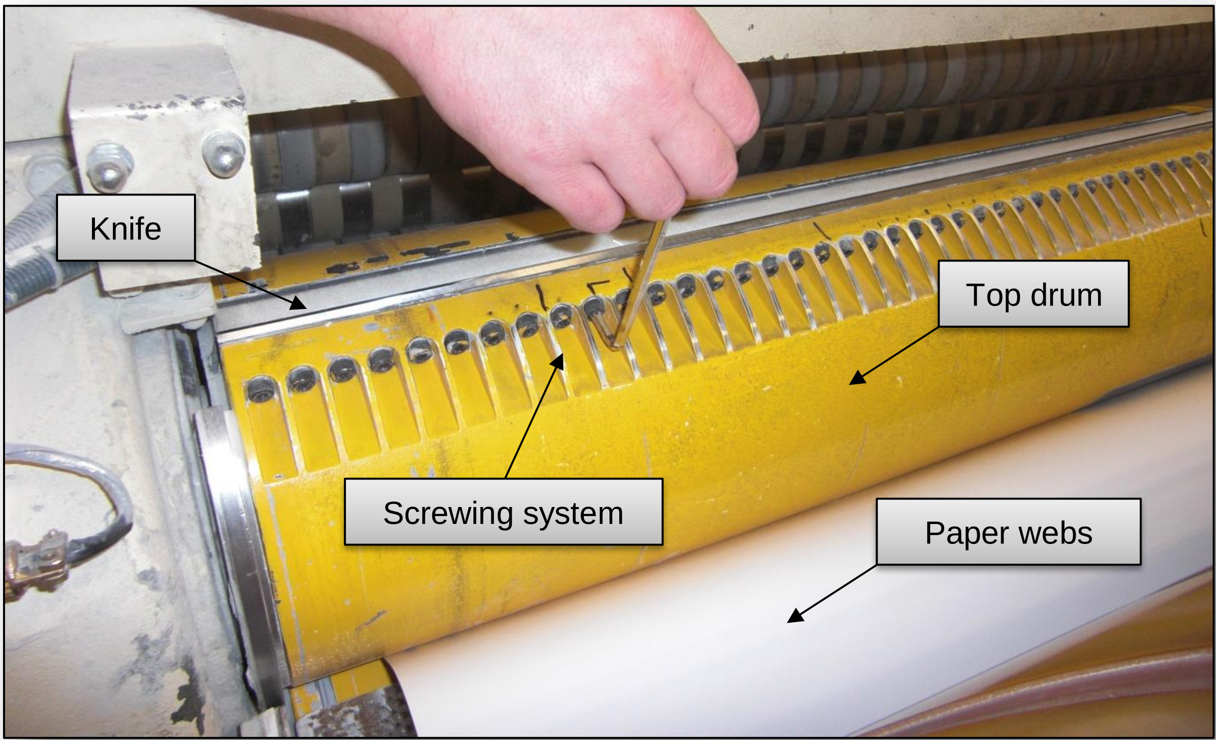


Figure 114: Rotary cross cutter knife and system to adjust the clearance

The clearance defined as the distance between both knives (see **Figure 115**) significantly influences cut quality. The influence of the clearance on the out of plane shearing characteristics of coated paperboard was studied by Nagasawa et al [62] and Veenstra [63]. Investigations in the course of this thesis also show the clear trend of reduced cut quality at higher clearance values. This is mainly due to the fact that at higher clearance the paper is not cut (sheared) anymore but is "torn". In fact, the freedom of the paper increases with increasing clearance and this allows the paper stack to be twisted and torn instead of being cut. This tendency to tearing is greatest in the sheets located in the middle of the paper stack because they are the last ones to be cut resulting to high raggedness and dust generation (see **Figure 116**). The edges of the sheets located outside the paper stack are strongly folded before separation occurs. In the case of a low clearance, the two forces created by the knives coming in contact with the paper are opposite and similar: They will therefore superpose each other. Due to this, the paper is more stable in the case of a low clearance.

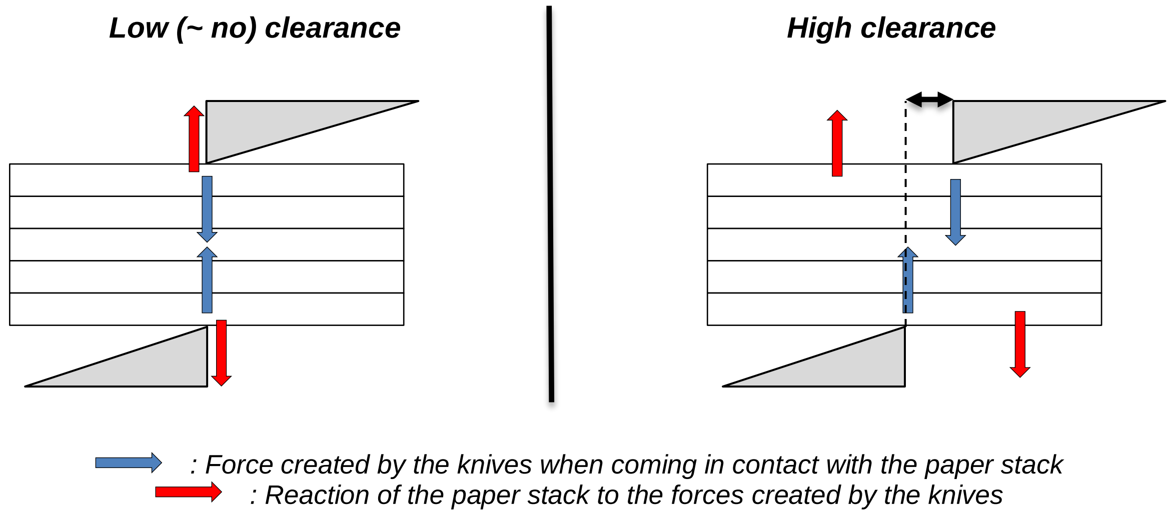


Figure 115: Impact of the clearance and reaction of the paper stack against these forces induced by both knives coming in contact with the paper stack at the rotary cross cutter

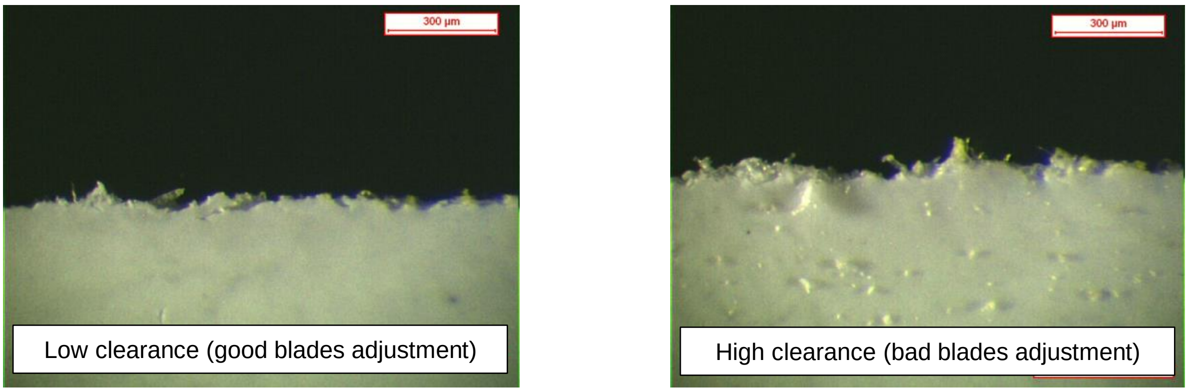


Figure 116: State of the sheet located in the middle of the paper stack with low and high clearance adjustments (5 sheets cut simultaneously, 150 g/m², glossy paper)

For a given clearance, strong differences are noticed between gloss and silk/satin papers. Gloss and satin papers differ mainly in their surface properties. A gloss paper has normally undergone an additional converting process which is calendering. The aim of this process is to obtain a specific gloss and smoothness to meet printing requirements. In order to achieve this and to optimize the paper properties, also the coating composition of gloss and satin papers is different in terms of pigments type, binder amount… Therefore, the observations made at the sheeters regarding the difference between gloss and satin grades cannot be associated with one specific cause and are often a consequence of several parameters. For these reasons, only repeatable and proven observations are outlined below:

- Gloss papers create more dust than silk papers. The higher dusting from gloss papers is explained by the brittleness of gloss coating layers. During the cutting process, the paper is compressed and/or folded depending on the location within the paper stack before being cut. During the calendering process, the coating layers are compressed and compacted and the coating structure loses part of its elastic properties.
- Gloss papers are also more sensitive to burr generation than silk papers. A comparison between gloss and silk papers showed that gloss papers at similar total load are much more sensitive to this phenomenon. Observations of the burr with a microscope shows that the coating layer near the coating edges is clearly pulled out from the base paper. **Figure 117** and **Figure 118** show this feature to occur always on the same cut edges positions: bottom side of the first layer at the leading edge and top side of the last layer at the trailing edge. Those layers correspond to the layer undergoing a strong folding during the cutting process. On the inner fold, the forces generated are much higher than on the outer fold [54], and the coating layer is not able to absorb these deformations. The significantly better cut quality of silk paper becomes evident in **Figure 118**. Again we attribute this to calendering where the coating layers are compressed resulting in the coating layer becoming more brittle and less deformable.

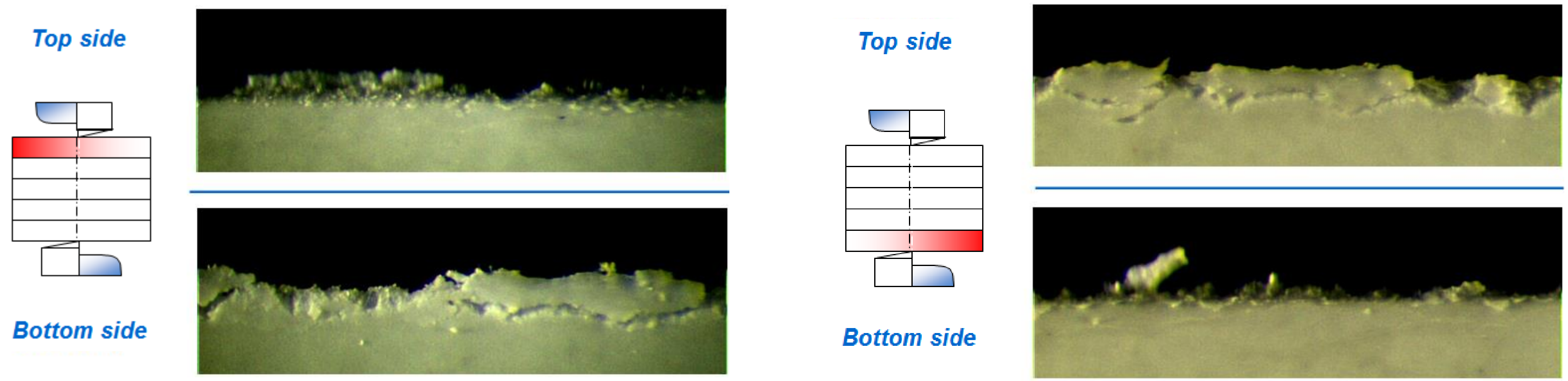


Figure 117: Burr observed at the cross cut when cutting 5 sheets - gloss paper 170 g/m² (left: first sheet leading edge / right: last sheet trailing edge)

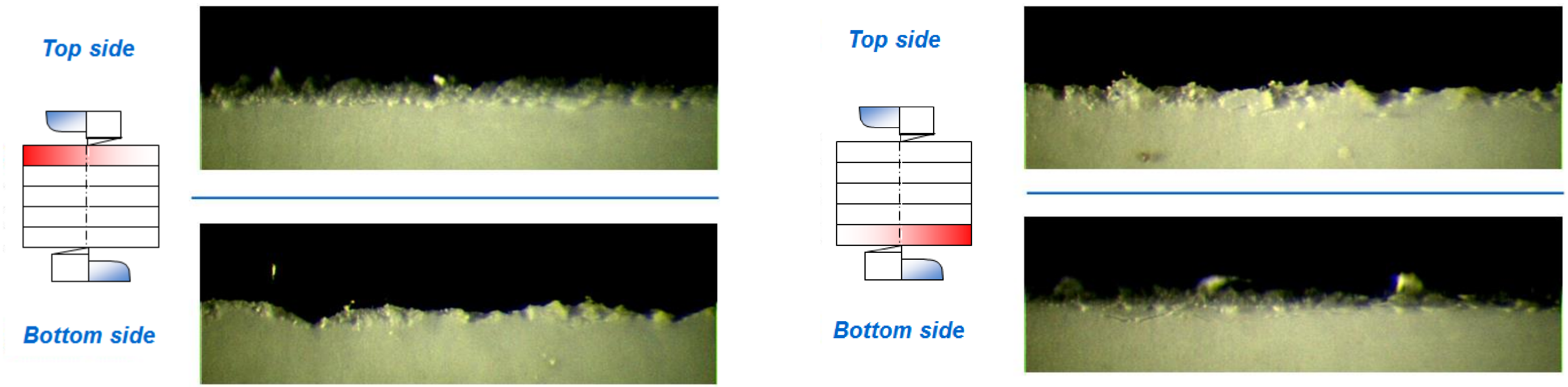


Figure 118: Burr observed at the cross cut when cutting 5 sheets - silk paper 170 g/m² (left: first leading edge / right: last sheet trailing edge)

As presented in paragraph 4.5.3.1, the clearance plays an important role in the force required to perform the shearing process by increasing the surface of the transversal cutting section. For a given clearance, the higher the amount of material is cut, the lower the impact of the clearance on the cutting force. Using the **Equation 14** and considering a standard paper thickness of 100 µm, we can calculate the development of the cutting force with the number of sheets for different clearances: 0, 10 and 100 µm.

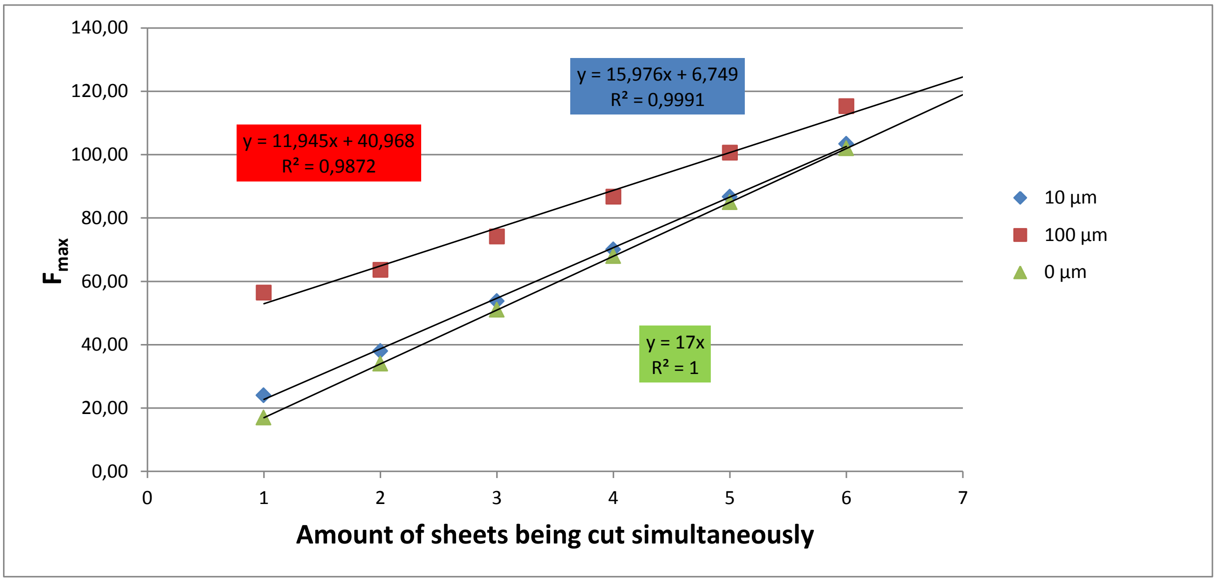


Figure 119: Impact of clearance on the cutting force as a function of the number of sheets cut simultaneously

Figure 119 shows that the higher the number of sheets or the thicker the paper stack, the lower will be the impact of the clearance on the cutting force. This confirms practical observations: the lower the clearance, the better the cut quality within a safe clearance zone.

These observations are very important for the operators at the sheeter who often neglect the blade adjustment due to the difficulty of positioning and measuring but also due to time constraints during production. It also shows the importance of adjusting the clearance for a single sheet because this is where the effect of a bad clearance can be best minimized.

4.5.3.2. Blade age

Studying the influence of the wear of the blades at the rotary cross cutter on cut quality is difficult due to the longer life time of these blades compared to the slitter: up to 18 months compared to few weeks. Studying the influence of this parameter carefully would require a large amount of paper being stored from the same production run as it was done for the slitter investigations but in much higher quantity. Keeping the same conditions of cut, at regular intervals, would also be difficult as the blades are readjusted several times during their lifetime. Due to these complexities and the time required to undertake this study, we decided against a detailed evaluation via such a test. Given the large number of analysed paper samples and the experience acquired during this thesis, we still are able to make several conclusions. The average raggedness of the paper stack and the number of cracks were found out to increase over the full life time of the blades. A readjustment of the blade tends to improve the situation for a certain period of time. One interesting observation, made at several occasions, concerns the burr which is generally very pronounced with brand new blades and tends to decrease with their age. The explanation for this observation is:

- *"Sharpness of the blade":* With brand new or reground blades, the sharpness of the blades is very high. This causes the stress created when coming in contact with the paper to be much more localized than with old knives presenting a higher contact area. After a given running period, only limited burr is noticed on the cutting sheet. In **Figure 120**, this effect is simulated by using a sponge and pressing it with a sharp object (representing a brand new knife) and a round object (representing an old knife). It is obvious that the deformation of the sponge is more "smooth" with the round object

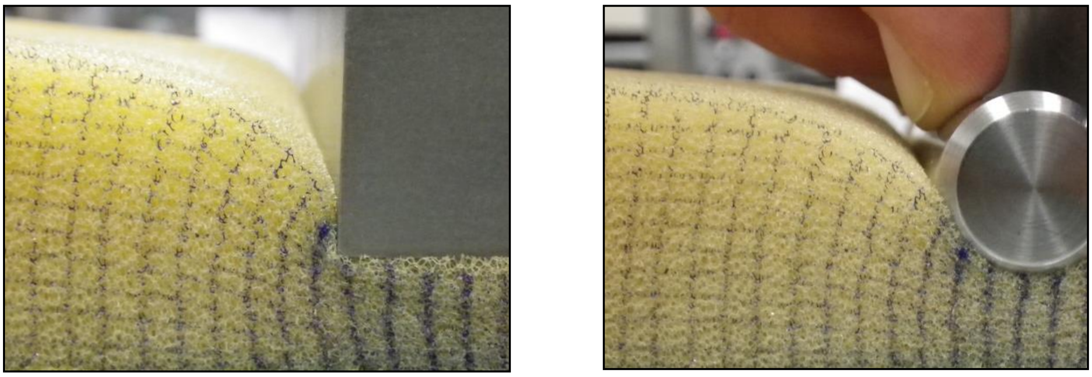


Figure 120: Difference in deformation created with a sharp angle and a round angle object

Another important observation is the fact that when the blade becomes dull, the rubbing contact area of the blade and the paper becomes larger (see **Figure 120**). If the blade is damaged, it may mark the paper surface and create dust. **Figure 121** below illustrates such damages.

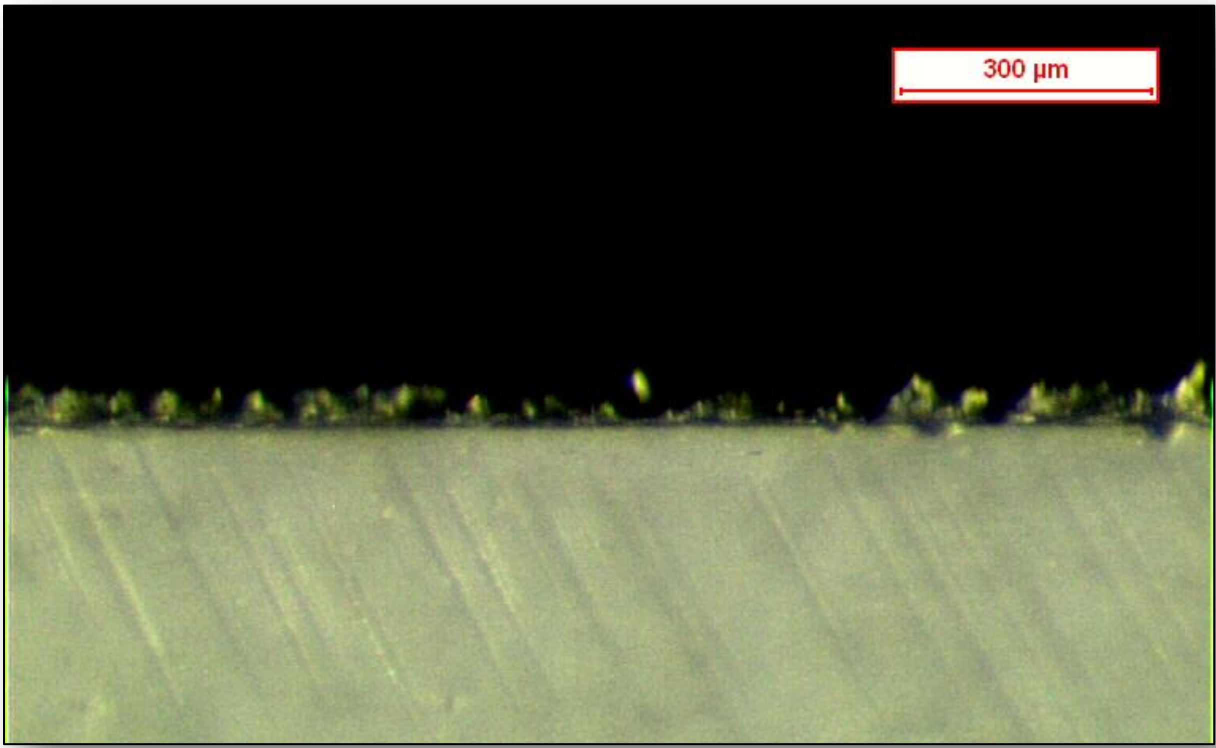


Figure 121: Marks observed on the sheets in contact with the blades at the cross cut when blades are becoming dull

4.5.3.3. Speed effect

With synchronous rotary cross cutter, the speed of the drums is almost equal to the speed of the web (when looking in the paper webs direction) during the cutting process. In order to obtain the desired format, the drums are accelerated or slowed down between two cutting periods: the cutting period corresponds to the time where the knives are cutting the paper webs. Nowadays, synchronous double rotary cross cutters are predominantly used. With this system, we still distinguish two different types of technology: mechanical or direct drive. The differences concern the way the drum is accelerated or decelerated: “oscillation” or “direct” (see **Appendix H**). The main advantage of the direct drive technology is the fact that during the full cut width, the knives have exactly the same speed as the paper web. It is always quite complex to define what the cutting speed is when dealing with rotary cross cutting system as this term could refer either to the speed of the cut point displacement, to the average penetration speed of the blade in the paper material in Z-axis, or to the width of the paper cut divided by the time required to cut this distance? The difference between these three “cutting speeds” is explained below.

The following numerical values are considered:

- *the paper webs are running at a speed of 200 m/min*
- *the paper web width is 2 m*
- *the angle of the drum cylinders with the paper web is 7°*

- *the drums have a diameter of 30 cm*
- *6 webs with a thickness of 100 µm are cut simultaneously*

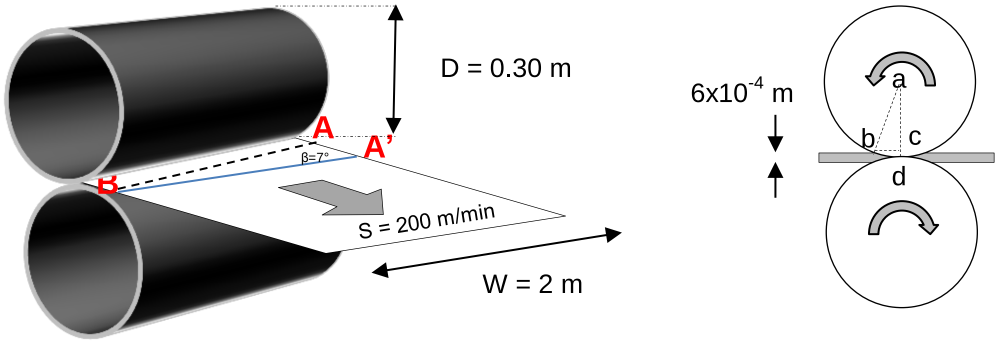


Figure 122: Cross cutter representation and condition for speed calculation

Then, the different speeds are calculated as follows:

- Speed of the point going from A to B in **Figure 122:**

$$Cut\ point\ speed\ in\ m/min = \frac{200\ m/min}{\sin(7)} = 1641{,}10\ m/min$$

- Cut speed: width of the paper web divided by the time to go from A to A' in **Figure 122**:

$$Cut\ speed\ in\ m/min = \frac{200\ m/min}{\tan(7)} = 1628{,}87\ m/min$$

- Penetration speed of the blade in the stack (z-component of the speed at b in **Figure 122**):

$$Penetration\ speed\ in\ m/\min = \frac{0{,}0003}{\frac{\frac{2\,.\,\pi\,.\,0{,}15}{200\ m/min}\,.\cos^{-1}\left(\frac{0{,}15-0{,}0003}{0{,}15}\right)}{360}} = 6{,}324\ m/min$$

It can be seen that the penetration speed differs quite a lot from the other speeds. It is also important to notice that the penetration speed (z-component of the knife speed) is not constant during the penetration of the blade in the paper stack. Indeed this speed is decreasing until it reaches 0 m/min in d (see **Figure 122**).

Several tests were carried out to evaluate the effect of the speed of the rotary cross cutter on the cut quality. Tests were performed with 2 different basis weights: 90 g/m² and 170 g/m². With the lower basis weight, a low and high paper quality in terms of tensile strength and tearing strength were used (see **Table 14**).

	Basis weight (g/m²)	Number of sheets	Machine speed	Raggedness in µm	Number of cracks per 5 cm	Fibre pull
1st test (standard paper quality)	90	7	100 m/min	97	31	3,5
			170 m/min	100	30	3,5
2nd test (low paper quality)	90	6	100 m/min	63	4	3,4
			220 m/min	67	8	3,4
3rd test (standard paper quality	170	5	100 m/min	78	29	3,5
			150 m/min	82	31	3,4
			175 m/min	83	28	3,5
			200 m/min	80	31	3,5

Table 14: Evolution of cut quality with different the machine speeds on cross cut edges (average obtained from all sheets cut simultaneously - standard and low paper qualities in terms of tensile strength and tearing strength)

No important effect of the speed has been noticed on the cut quality. The results were not dependent on the basis weight. With the low quality paper grade and a speed increase of 120%, a slight decrease in cut quality was seen but the overall quality level remained very good. With regards to the number of cracks, the increase in percentage might appear high but the absolute number of cracks is still very low. The results show an increase of going from 4 to 8 cracks which means that 4 extra cracks were noticed over 5 cm.

To ensure a perfect cut over the full paper width, both knives have to be perfectly adjusted ensuring a smooth move of the cut point. The knives must not be in contact because, at high speed, this may result in their destruction. However, the clearance between the knives has to be kept as low as possible for optimal cut quality reasons. Everyone who ever tried to cut a sheet of paper with scissor having losses knives knows that the resulting cut quality is terrible. In practical terms, in the case of cut quality issues (if the blades are ok), it is much more efficient to remove one web from the paper stack than reducing the speed. The rotary cross cutters have made significant improvements during the last decade and research is still on-going by the sheeter manufacturers to optimize this process. Their main aim is still to increase the amount of paper being cut simultaneously in order to improve productivity whilst maintaining a high cut quality.

Chapter 5

Conclusions & Outlooks

5.1. Test methods developed

A new test method for the evaluation of cut quality of WFC paper grades has been developed that takes into consideration three independent parameters: raggedness of the edges, number of cracks, and fibre pulled out at the cutting edges. The obtained results prove that the measurements are repeatable. Contrary to existing test methods, it also takes into account the state of the coating layers near the cutting edges. A practical printing test validated the method and showed the importance of the new parameter and the efficiency of the dust extractor system.

This method, which is suitable to assist in understanding and quantifying the effects of the machine settings and paper properties on the cut quality of WFC papers, has proven its efficiency during this thesis. The analysis of the cut quality of WFC papers using a set of fixed routines provides valuable information which are not found for uncoated papers or board alone. Indeed, the high sensitivity of the coating layer with regards to cutting allows a better understanding of the process mechanisms in some aspects. Particularly, the importance of the blade positioning and the efficiency of the dust extractor system have been established.

As observed during the printing test, the cut quality has an important impact on the printability of the papers. Looking at the evolution of the industry, with papermakers increasing their productivity by cutting more and more paper webs simultaneously and the printers running their machine faster to reduce costs, this topic might become more and more important in the future. The fast test with the black rubber roll, developed during this thesis, to evaluate the dust at the sheeter is now used on demand by the operator to check the cut quality. It has also been very useful to study in detail the impact of the machinery parameters.

5.2. Impact on the process

Due to practical reasons, paper properties and process parameters were studied separately. However it became clear during the course of this thesis that these two elements are interdependent. In a first theoretical part, the impact of the transversal cutting section on the cutting force was clearly established. The higher the transversal cutting section is, the higher the cutting force.

The construction of a laboratory cutting device enabled the identification of some factors influencing the shear cutting force such as the cumulative basis weight, the bulk and the clearance. Very often these factors are directly influencing the transversal cutting section. One interesting parameter which was studied with the laboratory cutting device is the impact of fibre orientation. The shear cutting force correlates to the number of intercepts between the cutting blades and the fibres. Due to this finding, it was also possible to explain the fact that the cutting force in CC increases faster than the cutting force in LC when increasing the total load.

The experiments carried out with the different furnish mixtures (fibre types and filler content) proved the influence of the material being cut. With decreasing paper strength, e.g. due to the replacement of fibres by inorganic fillers, the influence of some parameters such as the chord length is likely to be even higher due to the paper being more sensitive to the stress created in front of the blades.

The effect of the sheeter settings on cut quality were clearly underlined in all the tests realized during this thesis. All these findings are of great interests for the operators in the finishing departments but also for the papermakers. Indeed, all these information can be turned into practical solutions and advices when confronted with cut quality issues. Some of these practical information/advices are listed below:

- The number of cracks is critical to ensure a good print quality and therefore, blades should be changed when the amount of dust generated at the sheeter is too high and not when the visual aspect of the cut is bad because it is often too late. This can be controlled either visually by keeping clean the surrounding area of the sheeter, because any dust generation will then be detected very quickly, or by running the test with the black rubber roll.
- The blade adjustment is of utmost importance to ensure not only a good cut quality but also to extend the life time of the blades. Therefore, at the shear slitter but also at the cross cutter, this operation must be carried out as well as possible.
- The speed of the sheeters has very little impact on the cut quality compared to the total basis weight cut simultaneously at the sheeter, so it is better to reduce the total load than to reduce the speed of the sheeter when confronted with cut quality issues.
- Increasing the filler content of the paper while decreasing the fibre content without keeping the strength of the material at the same level will result in a decrease of the cut quality due to the lower capability of the paper to withstand the stress created in front of the cut point. Therefore the blade adjustment will become more and more important in the future.
- Due to the fibre orientation, the cut quality at the cross cut is more sensitive to changes such as basis weight increase and should therefore be carefully controlled.
- Bulky papers require more force to be cut than glossy papers and are resulting to a poorer cut quality at similar total load. As their runnability is normally better due to

their higher stiffness, it would be advisable to reduce the total load and increase the sheeter speed when possible.

Finally, the stability of the paper webs and the behaviour of the paper stack during the process were found to play an important role. This “instability” is the origin of several weaknesses in the cut quality, such as the burr at the cross cutter, and subsequently of a non-negligible part of the cutting dust. Looking at other sectors where cutting processes are performed such as the metal industry, this factor has already been considered and some solutions, such as fine blanking, to ensure better stability of the material during the cutting process have been implemented [64]. These new systems clearly result in better cut quality. Making a comparison in the paper industry, it is closest to the observations made with the guillotine cutter. In this case the paper webs are maintained with the back gauge during the cutting process. As observed during the trials, the guillotine is also producing the best cut quality in terms of coating cracks, raggedness and fibre pull. Clear improvement could be achieved if means of supporting the paper webs during cutting can be worked out and applied to the slitter and also at the cross cutter due to the existence of a bigger clearance.

5.3. Evaluation of customer complaints during the project

An advantage of this work is that most of the findings could be directly implemented in a production scale. The outcome may be used to evaluate the efficiency of the proposed and implemented actions.

Complaints from the customers, printers or merchants, are received and dealt with on a daily basis. Depending on the type of complaints and based on the analysis of the samples received, these complaints are categorized and are either accepted or rejected.

With regards to cutting issues, these complaints can be classified into three categories:

- *Edges sticking together:* This issue can clearly be a problem for the printer and is due to two or more sheets with torn edges.
- *Poor cutting:* Poor cutting is mostly a visual issue for the printer. In this case, the edges present a high degree of raggedness. Of course, this raggedness can also result in poor paper runnability on printing machines.
- *Cutting dust:* This is a printability issue. Depending on the printing system the free paper/coatings particles can accumulate on the printing blanket. After few hundred sheets the print quality starts to decrease. This is particularly visible in raster areas.

The number of customer complaints due to cutting issues is monitored constantly in the mill (see **Figure 123)**. It can be seen that the number of complaints decreased during the project period from May 2009 until December 2011 to reach 0,010 complaints per 1000 tons of papers in BY2011.

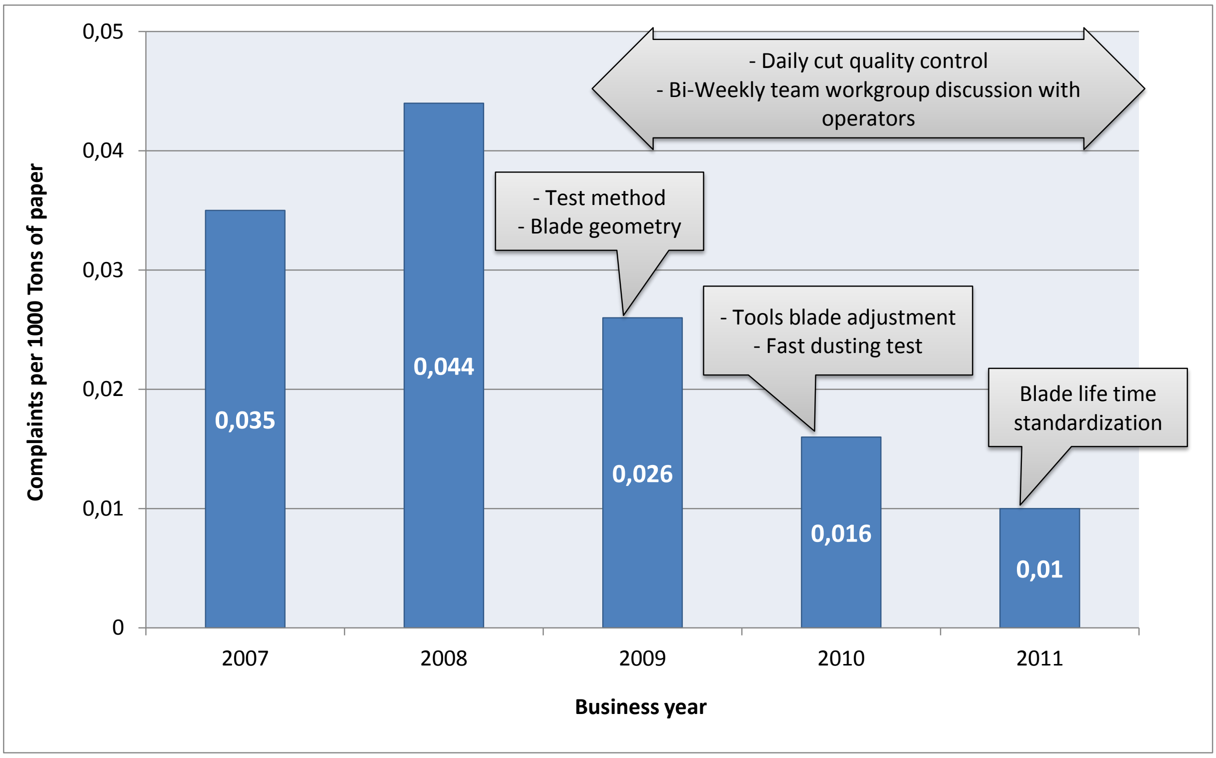


Figure 123: Evolution of the number of complaints related to cut quality during the period of the project.

5.4. Outlook

This thesis has shown the main parameters which play an important role in the shear cutting process. The test methods developed within this project set the basis for qualifying and quantifying the cut quality of WFC Papers. This is a first step towards understanding and improving the process. Several aspects of the cutting process have not yet been investigated due to time restrictions during this thesis and might be interesting for further developments.

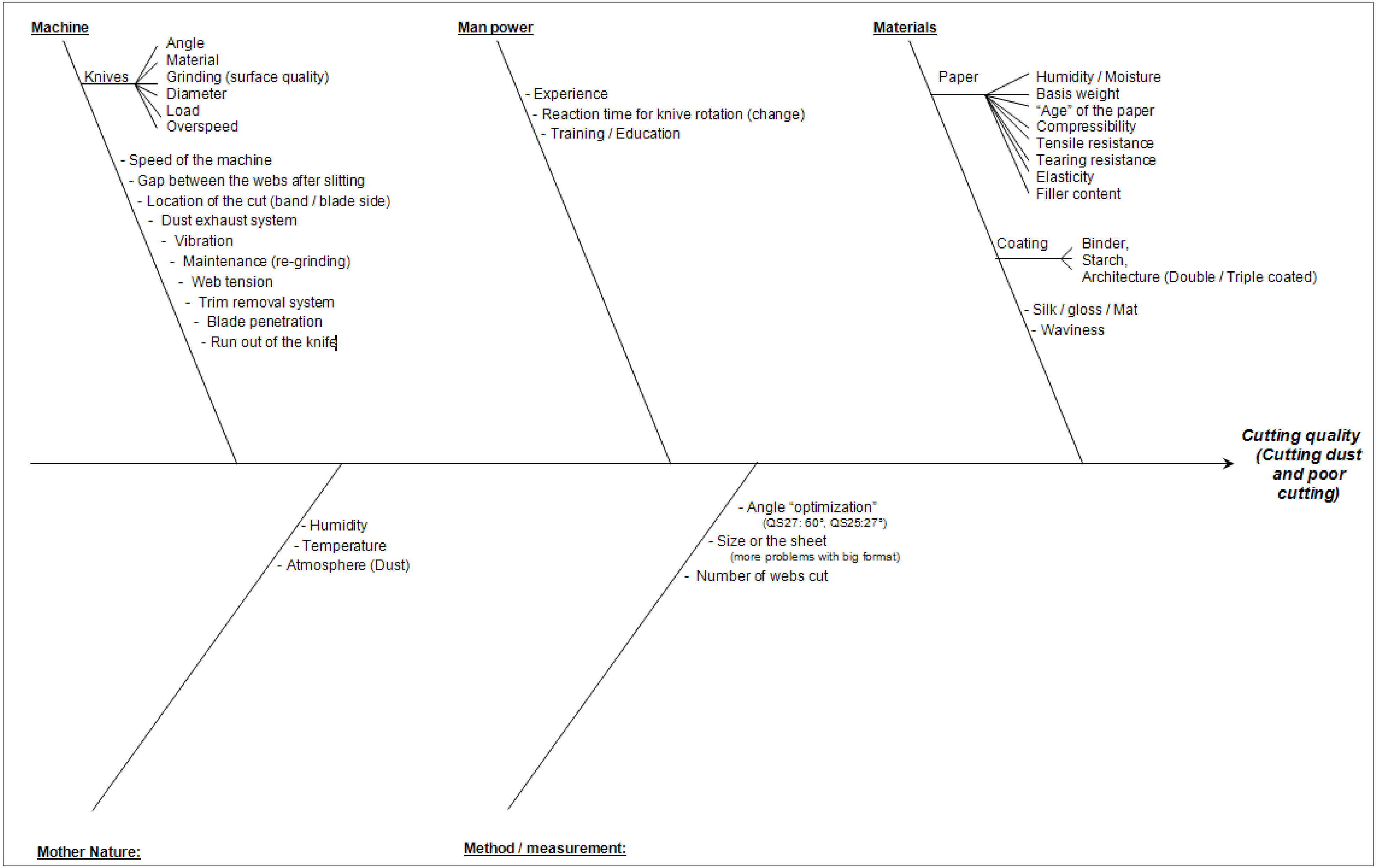
- The first point concerns the negative effect of clearance at the cross cutter. One idea could consist of finding a way to stabilize the paper stack during the cutting process to avoid any possibility for it to be twisted between the knives. This could reduce the burr on the cross cut and the cutting dust. It is also expected to improve the productivity at the sheeter and the runnability on the printing press.
- The second point concerns the effect of the paper itself. During my work, the laboratory cutting device that was developed to study the cutting process was found to have some limitations when looking at the influence of specific parameters such as the coating components. Although it was not proven during this thesis, I strongly

believe that the elasticity of the coating could play a part in limiting the development of coating cracks thereby reducing the amount of dust generated during the process. To study this aspect, it would require a more precise device. A high definition camera may give the opportunity to observe and record the coated layer's physical changes during the process.

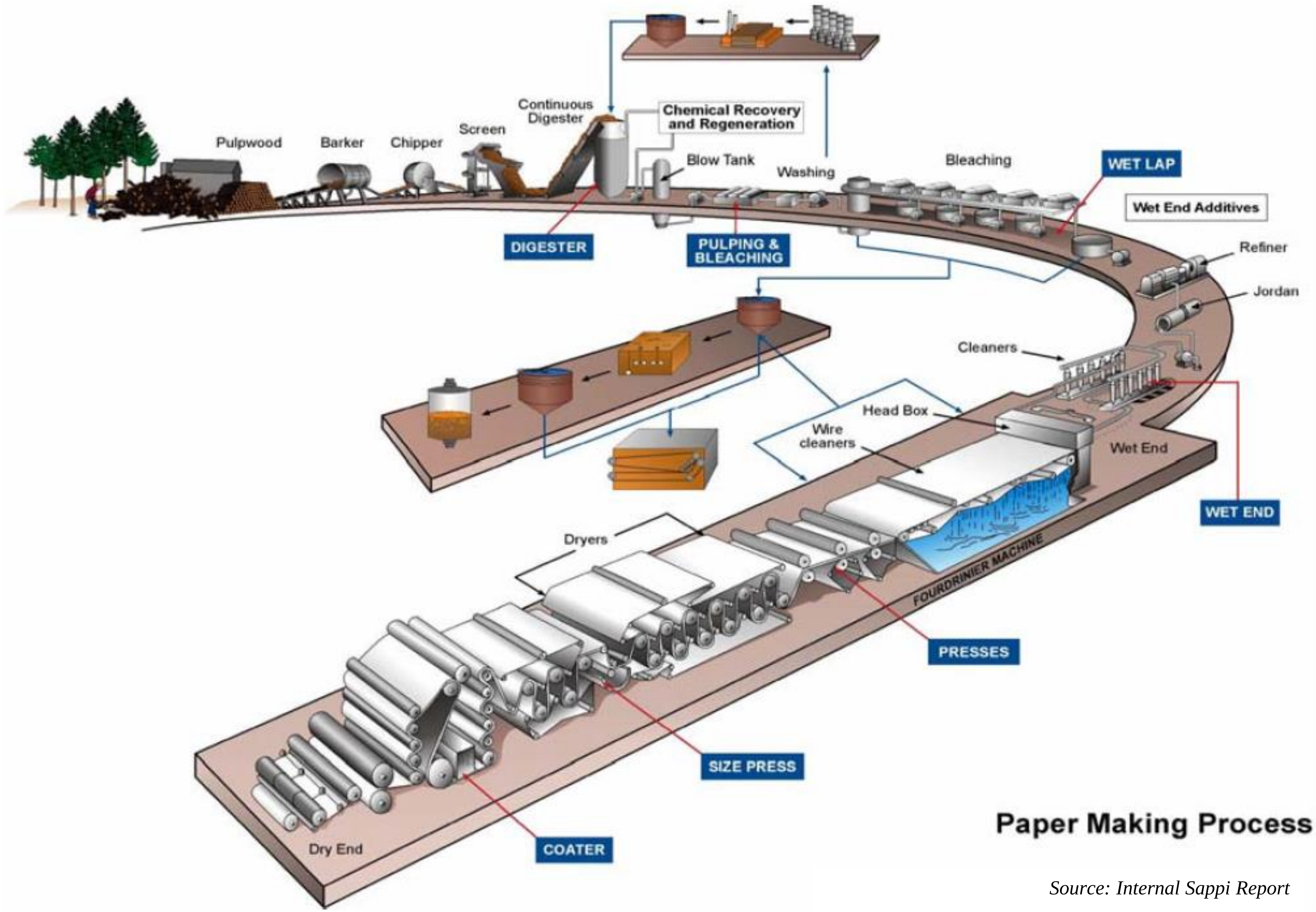
- Finally, the impact of the fibre orientation and fibre material on the cutting process has also been touched and some extra work could be further carried out to check the impact of fibre furnish.

Chapter 6

Appendix


Machine
Knives
Angle
Material
Grinding (surface quality)
Diameter
Load
Overspeed
- Speed of the machine
- Gap between the webs after slitting
- Location of the cut (band / blade side)
- Dust exhaust system
- Vibration
- Maintenance (re-grinding)
- Web tension
- Trim removal system
- Blade penetration
- Run out of the knife
Man power
- Experience
- Reaction time for knive rotation (change)
- Training / Education
Materials
Paper
Humidity / Moisture
Basis weight
"Age" of the paper
Compressibility
Tensile resistance
Tearing resistance
Elasticity
Filler content
Coating
Binder,
Starch,
Architecture (Double / Triple coated)
- Silk / gloss / Mat
- Waviness
Cutting quality (Cutting dust and poor cutting)
- Humidity
- Temperature
- Atmosphere (Dust)
- Angle "optimization"
(QS27: 60°, QS25:27°)
- Size or the sheet
(more problems with big format)
- Number of webs cut
Mother Nature:
Method / measurement:

Appendix B: Paper making process representation



Source: Internal Sappi Report

Appendix C: Detailed results of the cut quality obtained with the pallet for the print trial

RAGGEDNESS OF THE EDGES ON THE BLANKET SIDE (top side of the paper)

GRIPPER SIDE

Appendix C: Detailed results of the cut quality obtained with the pallet for the print trial

NUMBER OF CRACKS ON THE BLANKET SIDE (top side of the paper)

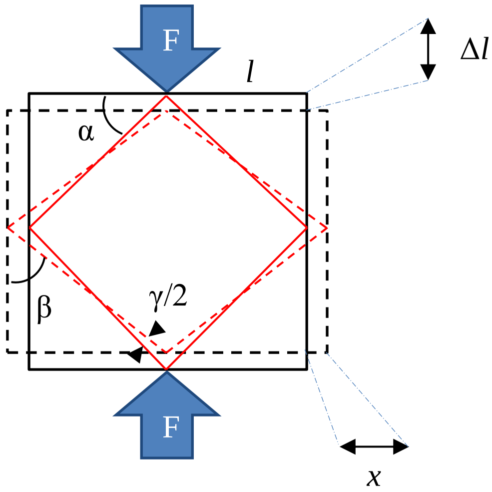
GRIPPER SIDE

Appendix D: Shear strain in case of pure shear stress

Calculation of the strain in case of pure shear stress:

We consider a square of material with a width of l, and a similar shear force F is applied on both sides of the square (top & bottom). This will result in a deformation of the system. The resulting rectangular shape has a width of (l-2Δl) and a length of (l+2x).

Representation of the system:



As defined in literature and represented in the figure above, the pure shear strain can be expressed as 2 times the difference between the angle β and α.

So, we have:

$$\gamma/_2 = \beta - \alpha \qquad \& \qquad \tan(\alpha) = \frac{l/_2}{l/_2} = 1 \qquad \& \qquad \tan(\beta) = \frac{l/_2 + x}{l/_2 - \Delta l} = \frac{l + 2.x}{l - 2.\Delta l}$$

Due to the law of conservation of matter, stating that: *matter cannot be created or destroyed in an isolated system,* the area of the initial system is equal to the area of the new resulting system:

$$l.l = (l - 2.\Delta l).(l + 2.x)$$

By developing this equation, x can be expressed as a function of l and Δl:

$$l + 2.x = \frac{l^2}{l - 2.\Delta l}$$

It is now possible to express tan(β) only as a function of l and Δl:

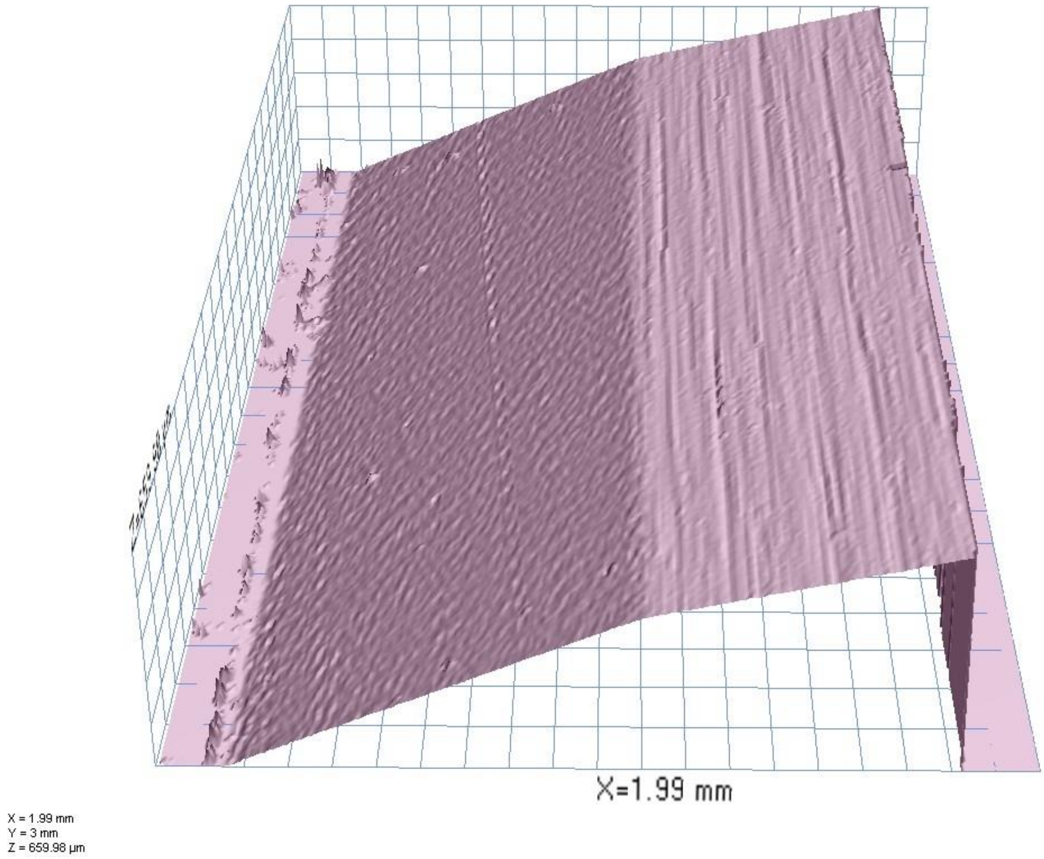
$$\tan(\beta) = \frac{l^2}{(l - 2.\Delta l)^2}$$

Considering Δl << l, it will result that γ will be very small and then we can consider $\gamma \sim \tan(\gamma)$:

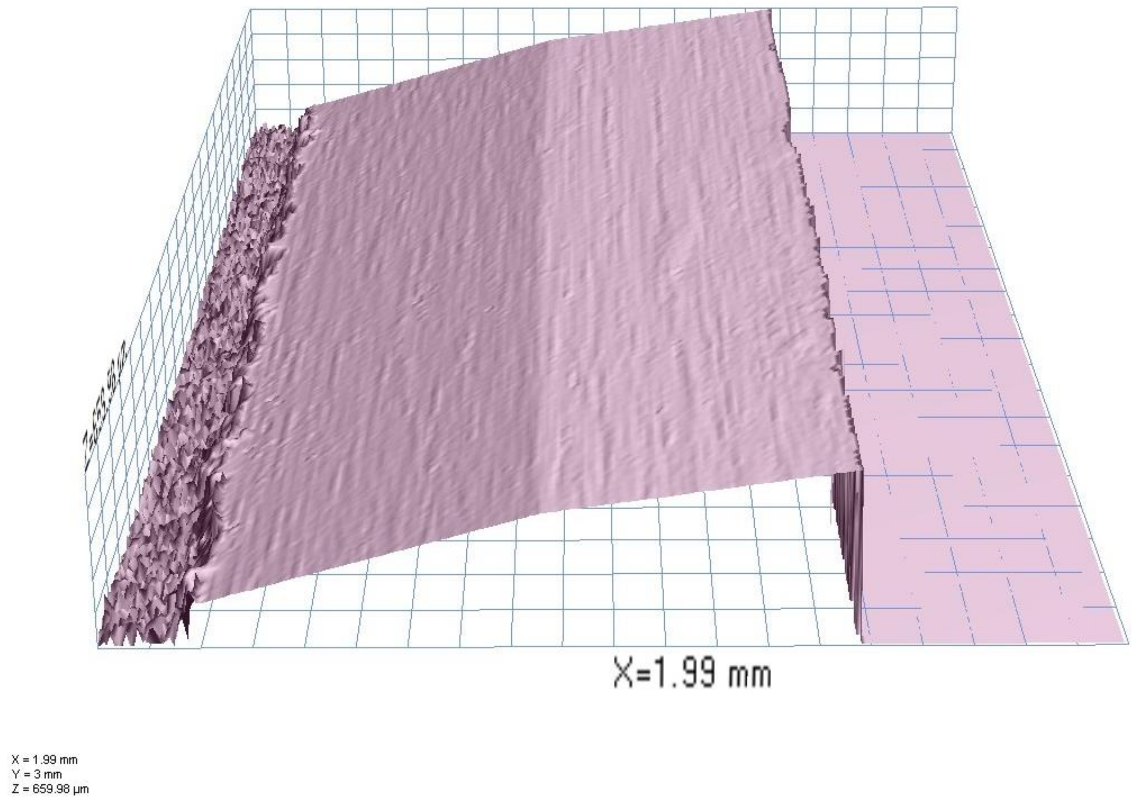
$$\tan(\gamma/_2) = \tan(\beta - \alpha) = \frac{\tan(\beta) - \tan(\alpha)}{1 + \tan(\beta).\tan(\alpha)} = \frac{\frac{l^2}{(l - 2.\Delta l)^2} - 1}{1 + \frac{l^2}{(l - 2.\Delta l)^2}} = \frac{2.(l.\Delta l - \Delta l^2)}{l^2 + 2.\Delta l^2 - 2.l.\Delta l}$$

Appendix E: Upper shear blade topography changes

Brand new blade:

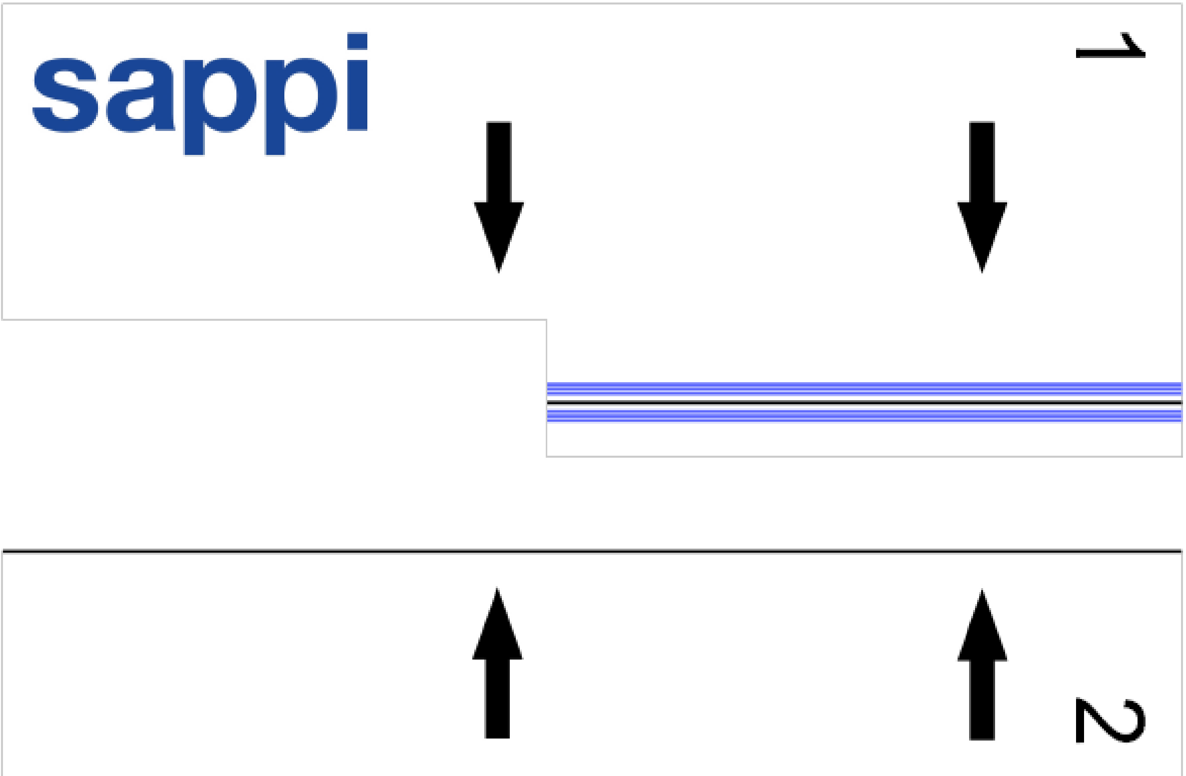


Worn blade:



Appendix F: Stencil for chord length adjustment

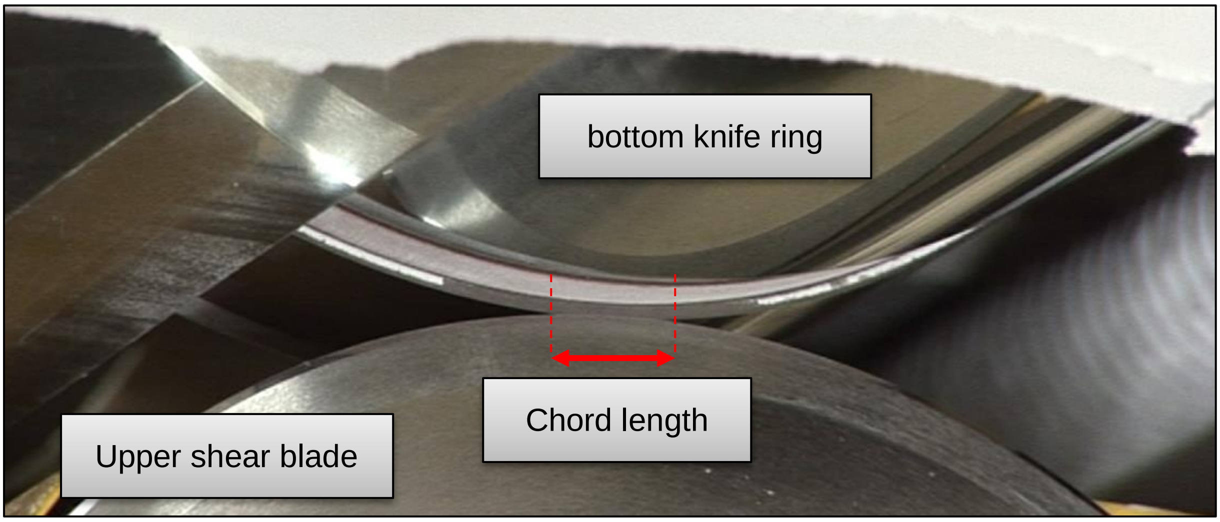
Stencil created to facilitate the blade positioning at the slitter (adjustment of the chord length):

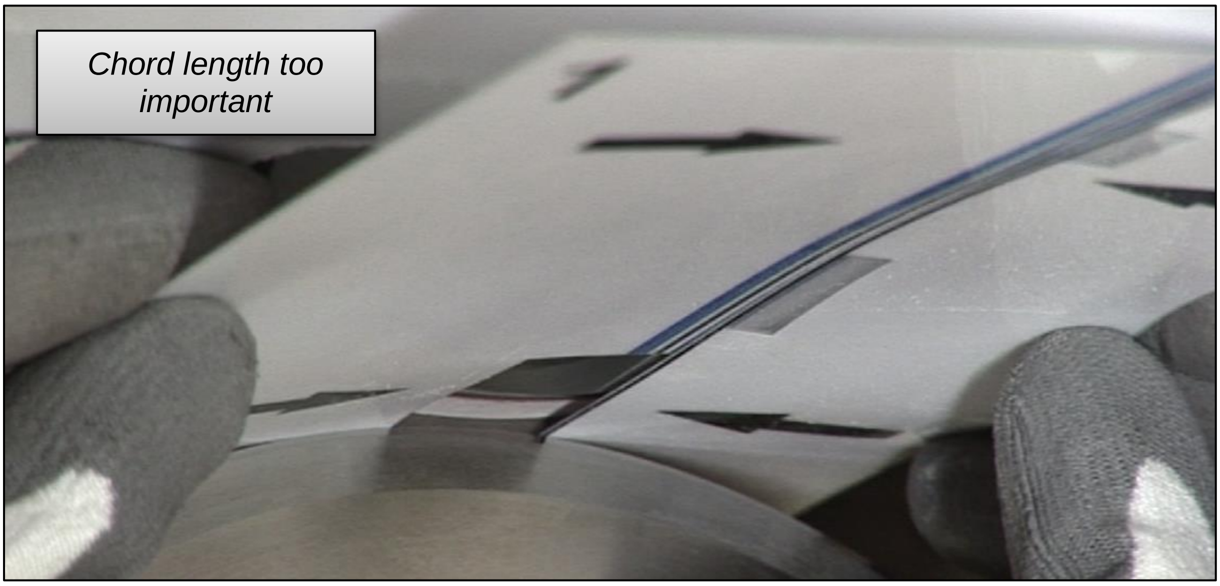


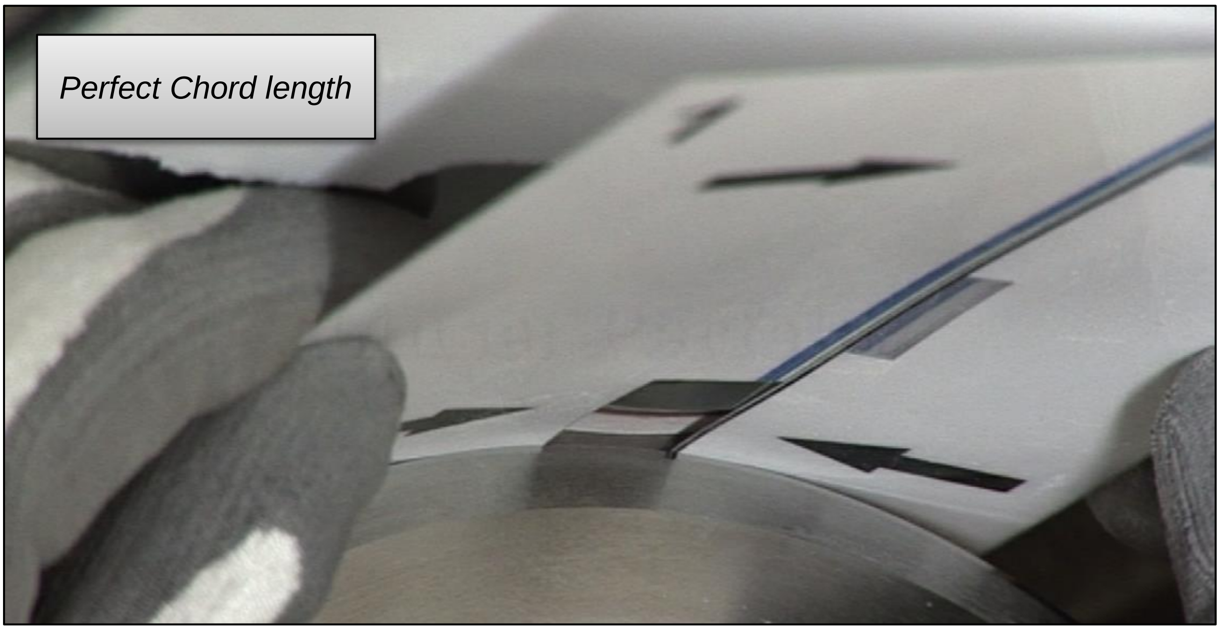
<u>Remark:</u> See picture on next pages to see how it works.

Appendix F: Stencil for chord length adjustment

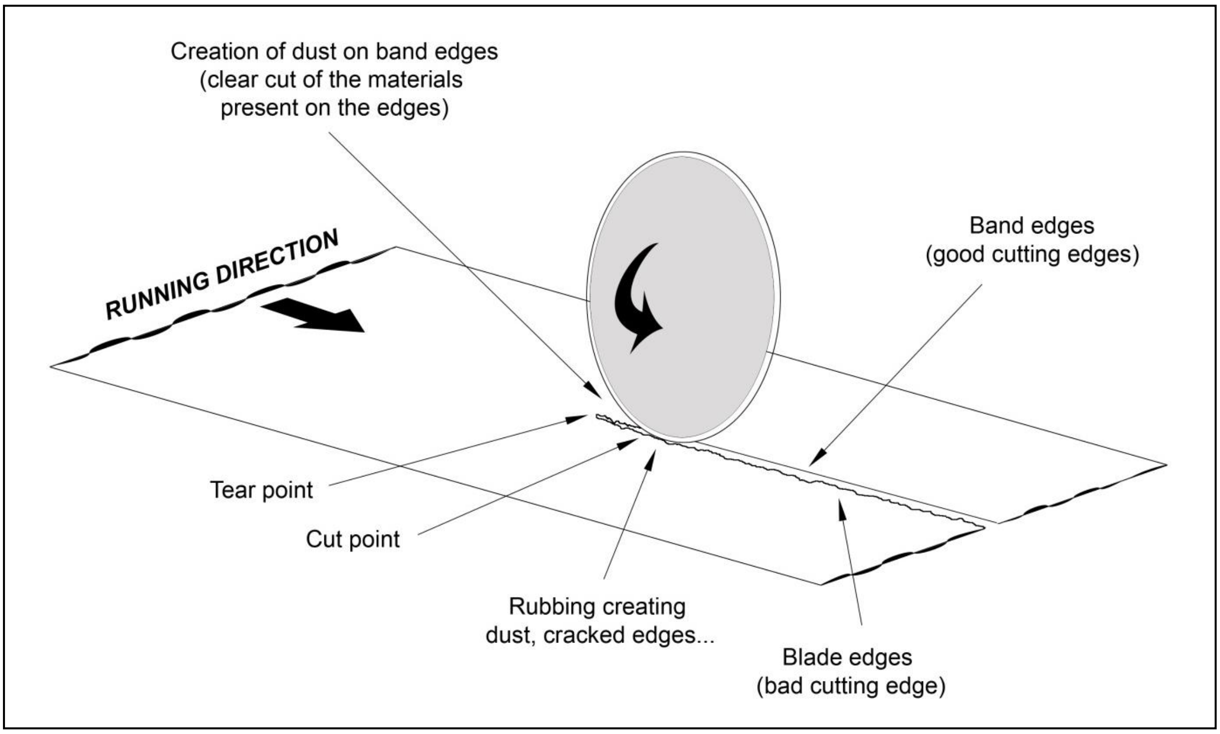
Adjustment of the chord length in practice:

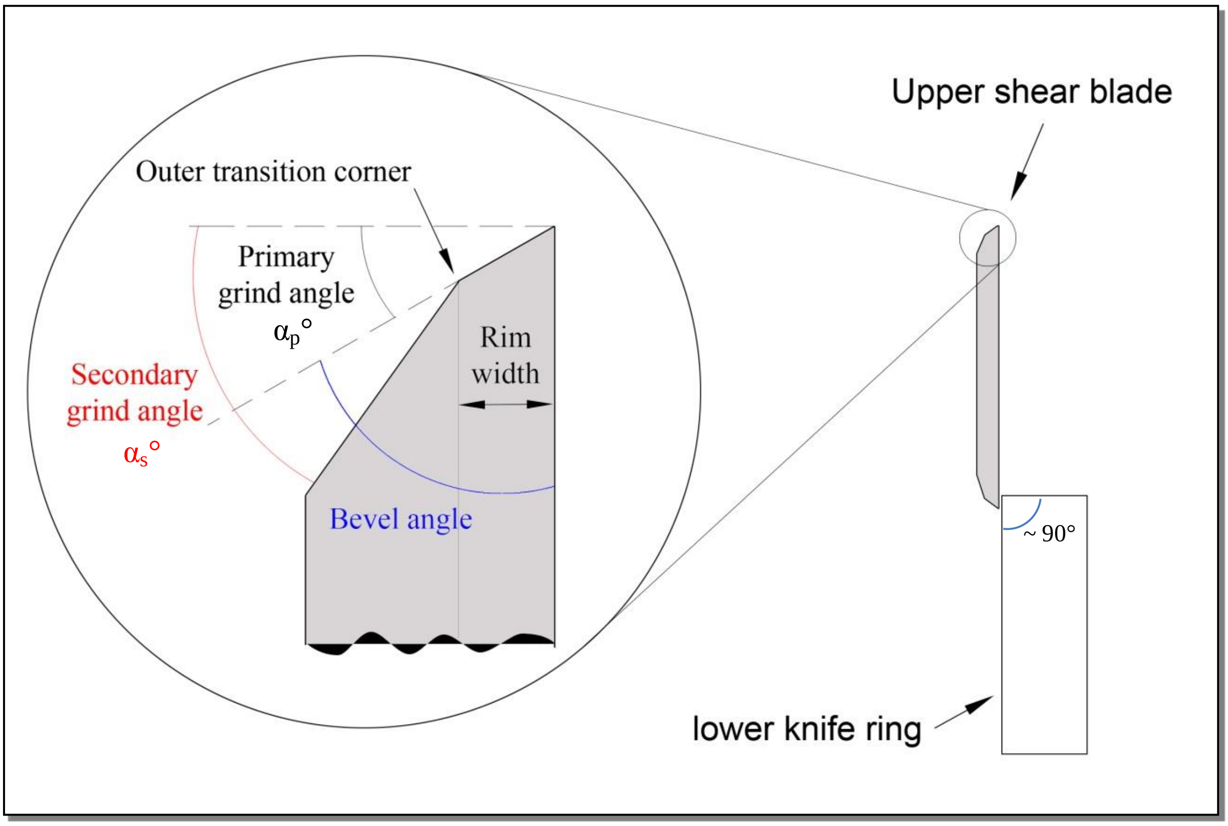




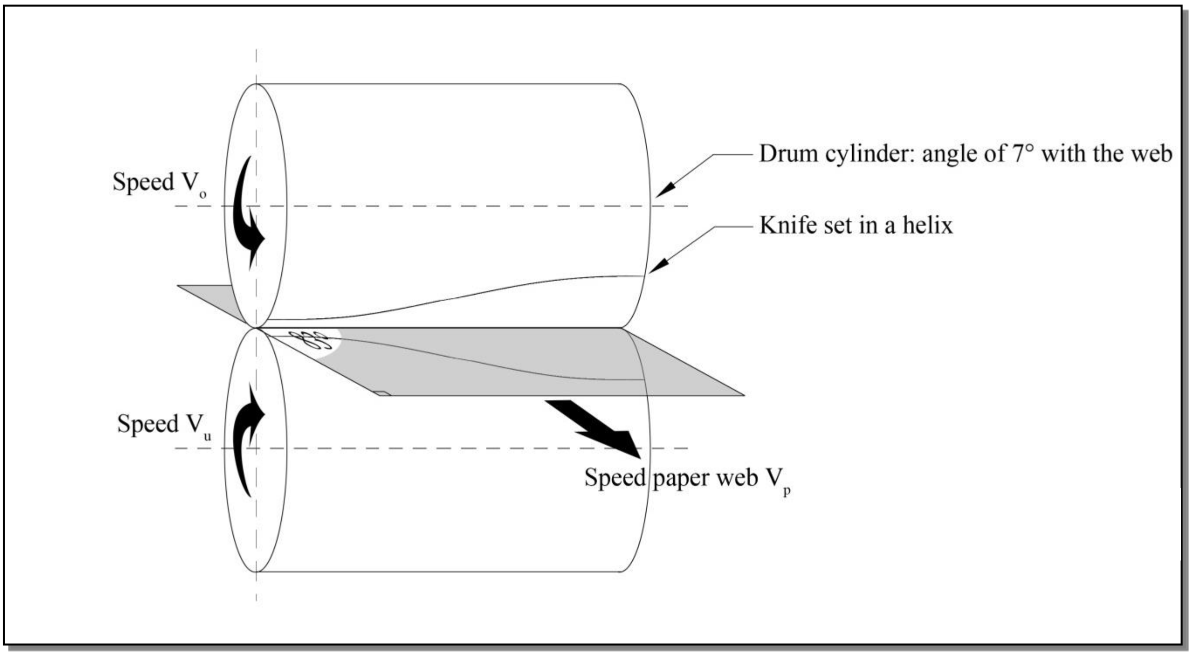


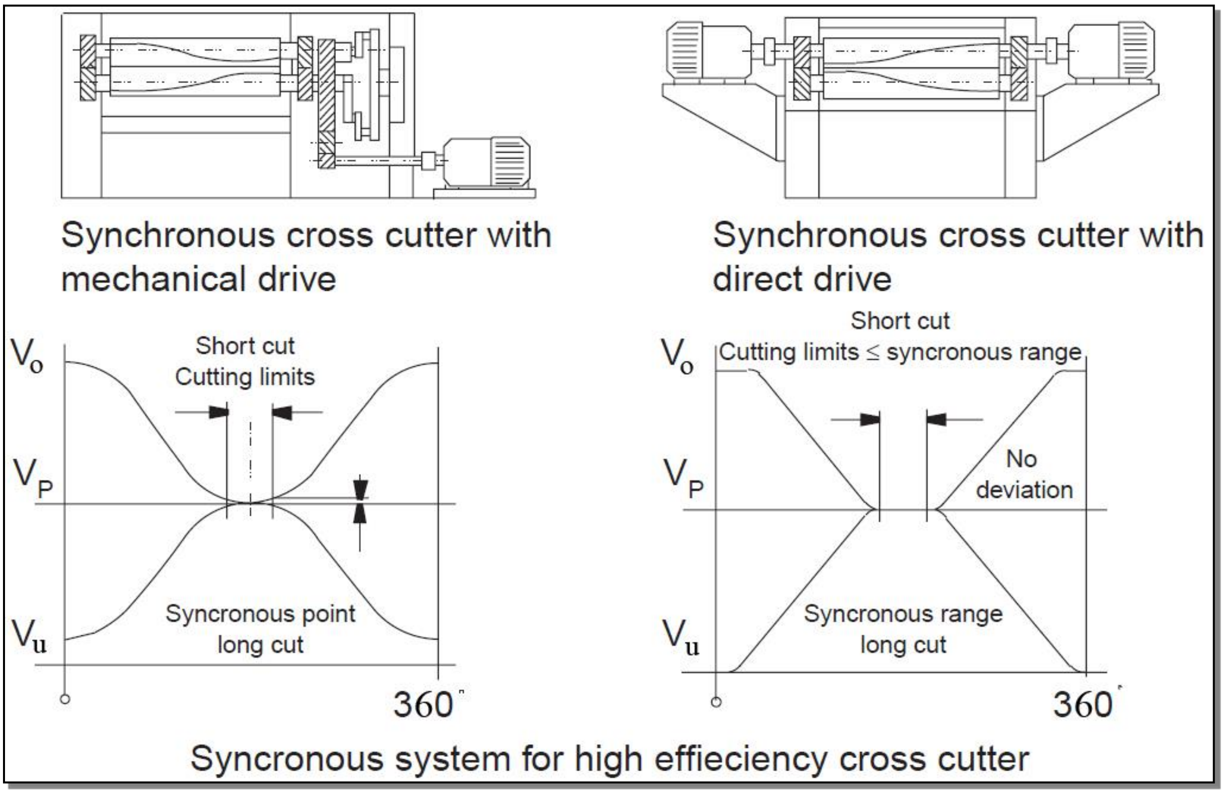
Slitter configuration and terms used:





Appendix H: Rotary cross cutter details





Sources: Paper Science and Technology [65]

Bibliography:

[1] Heidelberg France, *CutStar - Les avantages de la rotative adaptés à la feuille*. Available from: http://www.fr.heidelberg.com/www/html/fr/content/articles/product/stars/cut_star [2012, April]

[2] McCormack, D., *Online Etymology Dictionary*. Available from: http://www.etymonline.com/index.php?term=paper [2012, August]

[3] Jeffries I., *Political Developments in Contemporary China*.: Taylor & Francis, 2010, ISBN: 9780415580854.

[4] VDP (Verband Deutscher Papierfabriken), "Statistik, Weltdaten 2008-2009," 2011.

[5] Pulp & Paper Resources on the Web, *Paper on Web*. Available from: http://www.paperonweb.com/grade.htm [2012, August]

[6] Orsena E., *Sur la route du papier*, Stock, Ed., 2012, ISBN 2234063353.

[7] De Biasi P.-M., *Le papier, une aventure au quotidien*.: Gallimard (Editions), 1999, ISBN: 2-07-053445-6.

[8] Greenpeace, *www.greenpeace.org*. Available from: http://www.greenpeace.org/international/en/campaigns/forests/asia-pacific/ [2012, Avril]

[9] FAO (Food and Agriculture Organization), *www.fao.org*. Available from: http://www.fao.org/docrep/013/i1757f/i1757f.pdf [2012, Avril]

[10] Council European Parliament, DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL ON WASTE AND REPEALING CERTAIN DIRECTIVES, November 19, 2008.

[11] Old and Sold, *Old and Sold*. Available from: http://www.oldandsold.com/articles10/paper-making-12.shtml [2013, May]

[12] Einlehner Tester Instrumentation Manual, Abrasion tester AT2000, 1975.

[13] Voith, *www.voithpaper.de*. Available from: http://www.voithpaper.de/media/twogether-article-31-en-16-hainan-pm-2.pdf [2012, Avril]

[14] SCA: Svenska Cellulosa Aktiebolaget, *www.sca.com*. Available from: http://www.sca.com/en/media/news-features/archive/2010/sca-has-the-fastest-paper-machine-in-the-world/ [2012, Avril]

[15] Carolina Knife co., *www.cknife.com*. Available from: http://www.cknife.com/educational_materials/ [2010, Avril]

[16] Metso, *www.metso.com*. Available from: http://www.metso.com/pulpandpaper/MPwPaperBoard.nsf/WebWID/WTB-080911-2256F-A79C4?OpenDocument#.UevOtm0o45A [2013, July]

[17] Ebel T. J., "MODERN TECHNOLOGY MAKES DUPLEX SHEETING A VALUABLE ALTERNATIVE," in *1991 Finishing and Converting Conference*, Houston, TX, 1991, pp. 213-222.

[18] Schable R., *Spotlight on slitting*, Paper, film & foil converter ed., Robert A. Zuck, Ed. Chicago, IL, Illinois, USA: Maclean Hunter Publication, 1993. Available from: http://tidland.maxcessintl.com/sites/default/files/documents/SlittingSubstrates_Tidland.pdf

[19] Schable R., "A Guide to Slitting," *Converting magazine*, pp. 1a-13a, September 2003.

[20] E.C.H. Will GmbH, *Paper Converting Machines - E.C.H. Will GmbH*. Available from: http://www.echwill.com/en/folio-cut-size-stationery/board-sheeting-gfs-pro.html [2012, July]

[21] Wittenberg H., "Rotary Cross Cutting Systems," *Paper Technology and Industry*, vol. 19, no. 7, pp. 240-243, September 1978.

[22] Appleton and Charles M. Pearson Charles A. Fourness, "Paper metering, cutting, and reeling," Brevet n°: 2,006,499, July 2, 1935.

[23] Amundsen, E., Kleisser B., "Ultra high pressure water jets – Are they right for you?," *Proceedings, TAPPI: Finishing & Converting*, pp. 91-104, 1990.

[24] Malmberg and Veli Kujanpää, *Industrial laser solutions for manufacturing*. Available from: http://www.industrial-lasers.com/articles/print/volume-21/issue-7/features/application-report/cutting-paper.html [2012, January]

[25] Lappeenranta University of Technology, Available from: http://www.lut.fi/en/technology/lutmechanical/research/laser/laserprocesses/lasercutting/non-metalliccutting/Pages/Default.aspx [2012, January]

[26] Micro Laser Tech, Available from: http://www.microlasertech.com/downloads/en/mlp-50twin_10_2008_engl.pdf [2013, January]

[27] Ramsay, B.A., Richardson I.A., "Workington tries laser slitting on coated paperboard," *Paper Technology*, pp. 17-22, September 1992.

[28] International Organization for Standardization, ISO 22414:2004, 2004.

[29] Frye K. G., "Web separation and slitter dust," *Tappi Journal*, pp. 52-54, December 1986.

[30] Rycobelgroup "Spec*Edge", *www.rycobel.be*. Available from: http://www.rycobel.be/attachments/pdf/specedge.pdf [2012, Avril]

[31] Brandt, F., Herrig, A. Krolle, B., Ramcke E., "Improving sheeting quality with new dust control system," in *Finishing & Converting Conference*, Houston, 1991, pp. 229-239.

[32] Gericke, S., Sarbach, M., Pietsch, and J., Eckl R., "Optimierung von Scherschneideeinrichtungen in Papierausrüstung hinsichtlich der Schnittqualität," PTS (Paper Technology Specialist), Munich,.

[33] ACA System Oy, *www.aca.fi*. Available from: http://www.aca.fi/product-dpa.php [2012, Avril]

[34] COTE:M Control Technology GmbH, *www.cotem.de*. Available from: http://www.cotem.de/ [2013, Sep.]

[35] Frye K. G., "Web separation - A basic study of slitting and cutting," in *TAPPI Finishing and Converting Conference*, Nashville, 1979.

[36] Oxford Dictionaries definition of "burr", Available from: http://oxforddictionaries.com/definition/english/burr [2013, July]

[37] IGT Testing system, *www.igt.nl*. Available from: http://www.igt.nl/igt-site-220105/index-us/w-bladen/AIC/W33.pdf [2012, Avril]

[38] Burns, S.J., Meehan R.R., "Mechanics of Slitting and Cutting Webs," *Experimental Mechanics*, vol. 38, no. 2, pp. 103-109, June 1998.

[39] Stenberg N., *On the Out-of-Plane Mechanical Behaviour of Paper Materials*. Stockholm, Sweden, 2002, Doctoral Thesis.

[40] Arcona, T.A., Dow C., "The role of knife sharpness in the slitting of plastic films," *Journal of Materials science*, vol. 31, pp. 1327-1334, 1996.

[41] Dupeux M., *Introduction à la mécanique des matériaux et des structures*. Paris, France: Dunod, 2009, ISBN 978-2-10-053023-6.

[42] Naceur H., Available from: http://naceurh.free.fr/occ3/cours/cours03.pdf [2012, February]

[43] Strength of Materials, Available from: http://www.eformulae.com/engineering/strength_materials.php#pureshear [2012, June]

[44] Kalpakjian, S., Schmid S., Manufacturing Processes for Engineering Materials, 5th ed., 2008, Pearson Education, ISBN: 0-13-227271-7.

[45] Stenberg, C., Fellers N., "Out-of-plane Poisson's ratios of paper and paperboard," vol. 17, no. 4, pp. 387-394, August 2002.

[46] Wisselink H., *Analysis of Guillotining and Slitting - Finite Element Simulations*. Twente, The Netherlands, 2000, PhD Thesis.

[47] Penaso M., *Master Thesis: Simulation of the cutting process within a laboratory*. Graz, Styria, Austria, 2011.

[48] Interknife, Available from: http://www.interknife.com [2012, January]

[49] Silvy J., *Etude Structurale de milieux fibreux*. Grenoble, France, 1980, thèse de Doctorat d'Etat, INP.

[50] Holmstad R. and al, *Modelling the paper sheet structure according to the equivalent pore concept*. COST Action E11 Final Workshop, Espoo, Finland, 2001.

[51] Drouin, R., Gagnon, A., Schroder, M., Butel, J., Silvy B., "L'orientation des fibres et les propriétés mécaniques du papier: méthodes de contrôle de l'anisotropie de la feuille," *ATIP*, vol. 49, pp. 66-72, mars/avril 1995.

[52] Bartsch H. J., *Taschenbuch Mathematischer Formeln*. Leipzig, Germany, 1990, ISBN 3871447749.

[53] International Organization for Standardization, ISO 8791-4:2007, 2007.

[54] Wilberger M., *Development of a FE Model and description of the main mechanisms of the coating crackings of multiple coated offset papers*. Graz, 2008, PhD Thesis.

[55] Schable R., "SLITTER PERFORMANCE Problems and Solutions," *Proceedings, TAPPI: Finishing & Converting*, pp. 65-82, 1990.

[56] Jin, LU, Hongbing, LI, Ming, WANG, Bo MA, "Burr Height in Shear Slitting of Aluminium Webs," vol. 128, pp. 46-55, February 2006.

[57] Tidland, Séminaires Bladerunners: La performance du cisaillage, October 6, 2010.

[58] Antice P.D., *The wear of paper slitting blades*. Bath, 1979, PhD Thesis.

[59] Schable R., "Converting operations: Troubleshooting slitter blade wear," *SOLUTIONS! for People, Processes and Paper*, April 2003.

[60] Schable R., "SHEAR BLADE PROFILES: FACTORS TO CONSIDER," Technical paper for ABTCP 2000.

[61] Erdogan, S., Turkum, K., Abdullah K., "The Effects of Blade Angle on Blade Stresses During Cutting of Different Kinds of Paper Materials," *Journal of Mechanical Engineering*, 2009.

[62] Nagasawa, Yamashita, D., Abdul Hamid, Y., Fukuzawa, A., Hine S., "Out-of-plane shearing characteristics of coated paperboard," no. 52, pp. 1101-1106, 2010.

[63] Veenstra P., "Zu den Einflussgrössen beim Scherschneiden von Papier mit Kreismessern," *Wochenblatt für Papierfabrikation*, no. 11-12, 2004.

[64] CustomPart, *www.custompart.net*. Available from: http://www.custompartnet.com/wu/sheet-metal-shearing [2012, September]

[65] Mikko Jokio, Ed., "Paper Science and Technology," in *Papermaking Finishing, Part 3*., ch. 4.3.1.8, p. 299, Book 10 from the series, ISBN 952-5216-10-1.

[66] Malmberg, V., Kujanpää H., *industrial-lasers*. Available from: http://www.industrial-lasers.com/articles/print/volume-21/issue-7/features/application-report/cutting-paper.html [2013, July]

[67] Wood P., *Optimizing the Shear Slitting Process*. Available from: www.tappi.org/content/events/07/place/papers/wood.pdf [2007, September]