Graz University of Technology

Institute for Paper, Pulp and Fibre Technology

Master Thesis

Simulation of the cutting process within a laboratory

by

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In cooperation with Sappi Fine Paper Europe

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Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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14th of April 2011

Mario Penaso

Simulation of the cutting process within a laboratory

by

Mario Penaso

The work outlined in this thesis presents a new development of a device to cut wood free coated papers in a laboratory scale. The aim of the thesis was to develop in the lab a method which reproduces the cutting mechanisms from the sheeter. The main target is to be able to study the paper influences on cutting in the future.

The Zwick® material testing machine, in combination with the optional creasability module, has been used to construct a cutting device which performs a guillotine cutting action. The main part of the work was to design a knife holder together with a knife based on the knife geometries / materials used at the sheeter. One of the first tasks was to determine adequate settings of the machine and to test the reliability of the results. To check the applicability of the method, a test was carried out to compare the cutting quality obtained at the sheeter with the cutting quality obtained at the Zwick®.

To implement the cutting device, the influence of different paper properties on the cutting parameters was studied. The cutting parameters include not only the measurements from the Zwick® (cutting force, energy ...) but also the cutting quality evaluated with the microscope.

An evaluation of the cutting quality gives the possibility to predict to some extent whether the printing quality might be disturbed in the surrounding area of a cutting edge.

Consequently, the impact of new raw materials which should be used in the paper process can be tested.

Keywords:

Simulation of cutting, paper finishing, sheeter, guillotine, wood free coated papers, long cut, cross cut, cutting quality, cracks in the coating layer, raggedness of the cutting edge, fibre pull, cutting force

Simulation des Schneideprozesses im Labormaßstab

von

Mario Penaso

Die vorliegende Arbeit beschäftigt sich mit der Entwicklung einer neuen Methode den Schneideprozess von holzfrei gestrichenen Papieren im Labor zu simulieren. Ziel der Arbeit war es ein Gerät zu entwickeln, welches den Schneideprozess eines Formatquerschneiders reproduziert. Mit Hilfe dieses Gerätes soll es in Zukunft möglich sein, den papierseitigen Einfluss auf den Schneideprozess zu untersuchen.
Die Zwick® Materialprüfmaschine mit dem dazugehörigen Rillwerkzeug wurde genutzt, um ein Schneidegerät zu entwickeln, das einen Guillotine-Schnitt ausführt. Die Hauptaufgabe lag darin, einen Messerhalter samt Messer (basierend auf den Messermaterialien bzw. Messergeometrien des Querschneiders) zu konstruieren. Danach wurden die Grundeinstellungen der Maschine bestimmt und die erhaltenen Messwerte der ersten Testreihen wurden auf ihre Relevanz geprüft. Um die Anwendbarkeit des Gerätes zu überprüfen, wurde ein Test durchgeführt, bei dem die erzielte Schnittqualität am Querschneider mit der erzielten Schnittqualität des Laborschneidegerätes verglichen wurde.
Um das Gerät in der Praxis anwenden zu können, wurde der Einfluss verschiedener Papierparameter auf die Schneideparameter getestet. Die Schneideparameter enthalten die Messwerte des Laborschneidegerätes (Schnittkraft, Arbeitsaufnahme …) sowie die Qualität der geschnittenen Proben, welche unter Anwendung eines Mikroskops untersucht wurden.
Eine Untersuchung der Schnittqualität ermöglicht eine teilweise Vorhersage der Druckqualität im Bereich der Schnittkante der getesteten Probe.
Zukünftig soll mit dieser Methode der Einfluss neuer Rohstoffe auf die Schneideeigenschaften des Papiers überprüft werden.

Schlagwörter:
Simulation des Schneideprozesses, Ausrüstung von Papieren, Formatquerschneider, Guillotine, holzfrei gestrichene Papiere, Längsschnitt, Querschnitt, Schnittqualität, Strichbrechen, unregelmäßige Schnittkante, Faserrupfen, Schnittkraft

1 Introduction

Finishing is an important step in the production of high quality wood free papers. One of the aspects is to ensure a perfect cutting quality for the end customers. Bad cutting quality can cause runnability problems on the printing press such as edges sticking together and dust formation. Moreover, a poorly adjusted cutting process can be at the origin of an important amount of dust at the sheeter. Therefore, controlling and improving the cutting process will have a positive impact on the environment at the sheeter.

Evaluating the cutting quality is a complex procedure and a lot of efforts have been spent in the past to find an adequate method. No appropriate evaluation method was available to adequately classify the cutting quality of wood free coated papers, therefore the “Cutting quality project” was started within Sappi Fine Paper Europe to conduct research on this subject.

By now, a test method has been developed. The reliability of this method was proven by print trials to study the effect of the edge quality on the printing process.

It is known that the machine parameters as well as the paper properties have an influence on the cutting quality. To study the influence of the machine parameters, an on-site inspection at the sheeter has been carried out. Analyzing the impact of the paper itself is a more complex procedure. For every trial at the sheeter, the paper parameters have to be changed and this is unrealistic due to the very high costs involved. Therefore, a cutting device which can be used in the lab is mandatory.

1.1 Motivation

The costs required to finance the development of a cutting device in collaboration with an external institute are very high. Therefore, it was decided to find / develop internally a laboratory cutting system which reproduces the processes of the sheeter adequately.

The main advantage of a laboratory system is that it will allow making research without being dependent from the paper production. Secondly, a lot of paper properties such as the impact of raw materials can be studied in an easier way and of course, it is the cheapest solution.

Moreover, it is intended by Sappi Fine Paper Europe to spend a lot of effort to tackle the cutting issue. Therefore, a suitable lab method for cutting would advance the fundamental research regarding this issue.

In the beginning of the work the prior art regarding cutting was studied. In the case that no suitable system should exist, a new method to simulate the cutting process has to be developed. In the start-up phase the necessary machine parts had to be manufactured, in order to perform test series in the second phase of the work. Finally, the correlation between the lab method and the cutting at the sheeter should be found out to allow the comparison of the different papers manufactured in Sappi Fine Paper Europe on a lab scale.

1.2 Conceptual formulation

Task of the project work is to find a cutting device, to reproduce the shear cutting process of coated papers in the lab. In the following, the intended operating sequence is shown:

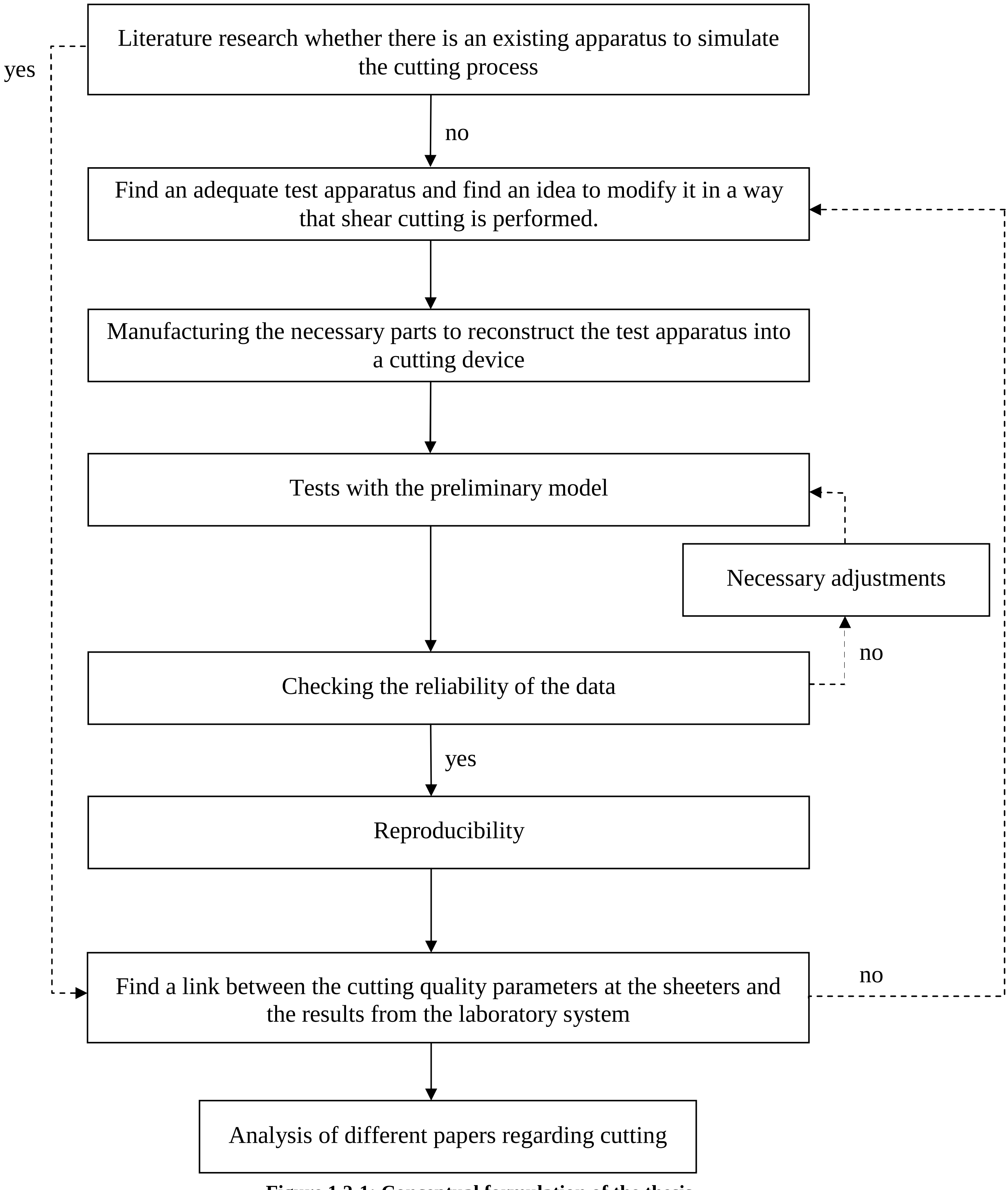


Figure 1.2-1: Conceptual formulation of the thesis

2 Cutting of paper

In this chapter the results of the literature research related to cutting of paper are outlined. At the beginning, the theory of both cutting technologies, slitting and cross cutting, is covered. Furthermore, the paper influence on cutting in general is described. Problems which are emerging due to cutting issues are also presented in this chapter. As a last step, the existing laboratory cutting methods and the evaluation methods of cutting edges are presented.

2.1 Theory of cutting

During the cutting process, the substrate is exposed to three different mechanisms. The so called "*three steps of cutting*" are explained in more detail in the following part:

- *Deformation- or compression-phase:* The compression-phase starts when the knife comes in contact with the paper surface. Due to pressure forces, the paper structure will be damaged and this leads to decrease the strength properties in the area of deformation.
- *Pre-shearing-phase*: Further forces applied by the knife on the paper cause a shear stress which results in elastic / plastic distortions. The resulting forces around the tip of the blade enable the penetration in z-direction.
- *Shear-off-phase:* The complicated state of stress and the high compression forces lead to a final separation of the substrate.

2.1.1 Theory of slitting

Most of the information contained in this section was collected from the PAPIERBUCH [1], from the homepage of CAROLINA KNIFE COMPANY [2] and from an article dealing with finishing defects [3] .

According to the PAPIERBUCH [1], slitting is the separation of paper in machine direction done by rotating circular knives (see *Figure* 2.1-1).

To ensure that shear cutting is performed, the top knife has to rotate at the same or marginally higher speed than the path speed [2]. In most of the cases, the top knife is driven by the bottom knife. Due to the fact that the top knife is decelerated during the cutting action, the bottom knife has to run with a certain over speed compared to the top knife. Usually 3 to 5% over speed is applied. A top knife velocity below synchronous speed results in cockling of the edges.

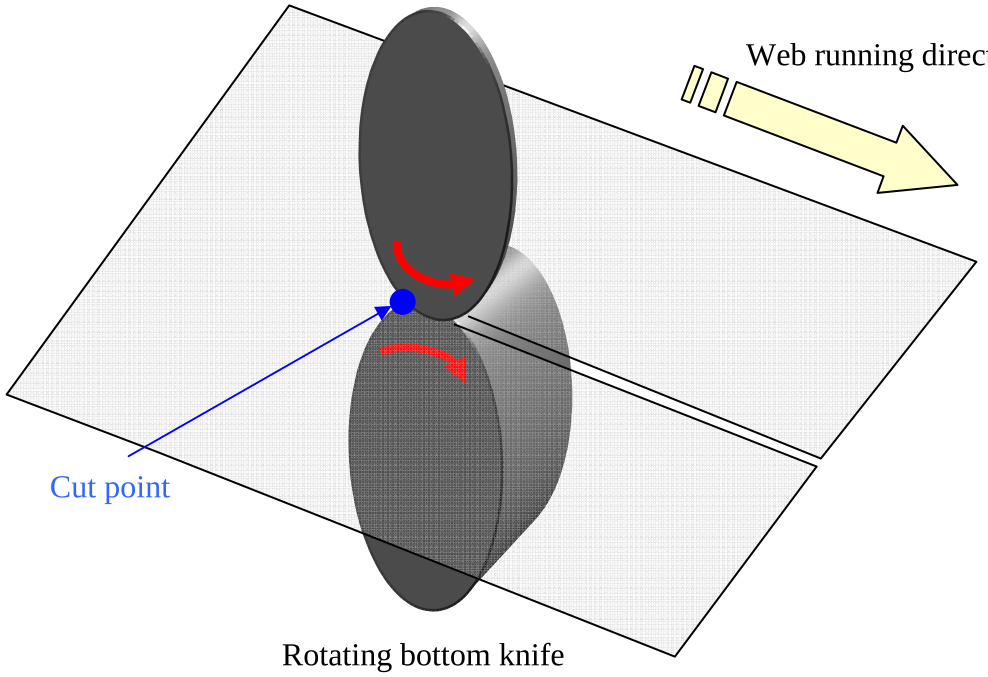


Figure 2.1-1: Configuration of a slitting unit

Field of application for slitters:

- producing paper reels at the winder station,
- finishing of format papers,
- trimming the paper web on paper / coating machines.

As outlined in the PAPIERBUCH [1] the cutting process can be divided in three phases (see *Figure* 2.1-2):

a) Paper web is compressed before the real cutting action starts.
b) Web is laterally displaced by the knife.
c) Knives are getting in contact in the cut point and the web is pushed away by the shear stresses. At the same time the contact pressure between the blades increases, this leads to an extended wearing of the top- and bottom knife.

In order to achieve an adequate edge quality, the compositions of the substrate and also the machine parameters have to be optimized.

Due to the distinctive rubbing action between paper and knife during slitting, the components of the paper influence dusting to a large extent. The level of dust creation depends on the amount of fines, elastic fibres, brittle material and fillers in the paper. Using raw materials such as pigments or starch results in a brittle fracture and many fine particles are released [1].

Next to the paper, the machine parameters play a major role in slitting. The most important systems and settings for slitting units are discussed in the following part.

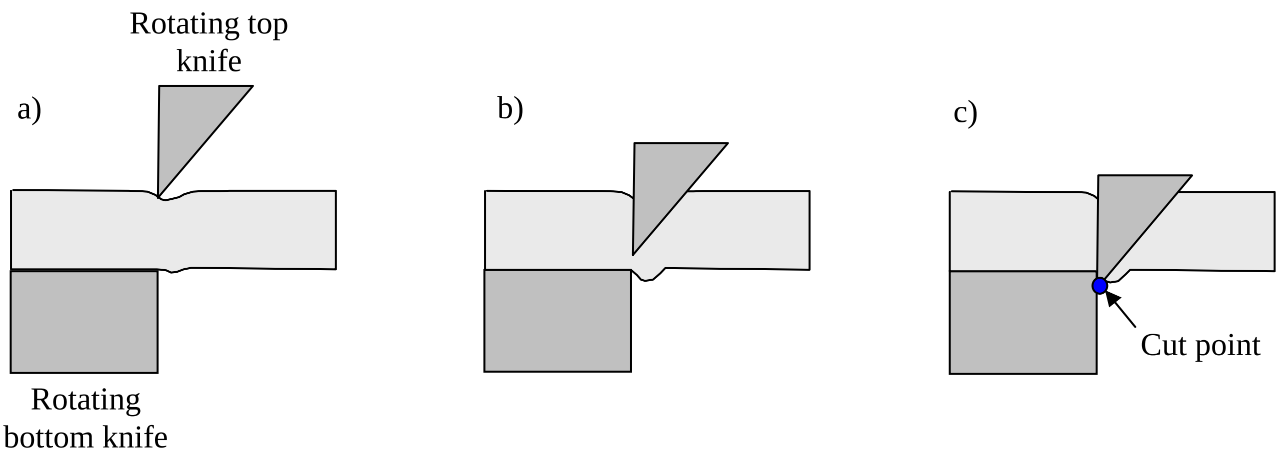


Figure 2.1-2: Steps of the slitting process - Redrawn according to [1]

As presented in [2], there are two main shear slitting systems to separate paper in machine direction, the *tangent slitting* and the so called *wrap slitting* (see *Figure* 2.1-3). In tangent slitting the web is passed directly to the cut point while in wrap slitting the substrate touches the bottom blade over a larger area before it is being cut.

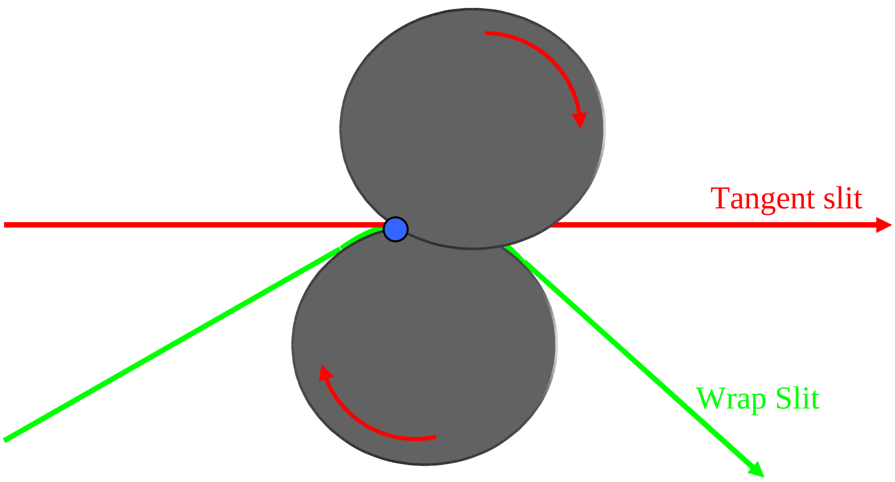


Figure 2.1-3: Tangent vs. wrap slitting - Redrawn according to [2]

The results of FRYE [3] showed a negative impact on the cutting quality, if the resulting strains during the cutting action are too high. The origins of these strains and how to handle them are discussed in the following part.

Using small *bevel angles* (see *Figure* 2.1-4) leads to lower displacement of the web and for this reason the friction action decreases. A drawback of this configuration is that the knives are thinner and therefore they have to be changed sooner.

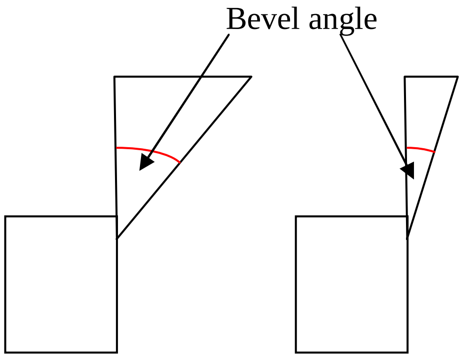


Figure 2.1-4: Possible configurations of the bevel angle

A second possibility for reducing strains is to correct the *toe-in angle or cant angle* (see *Figure* 2.1-5). According to [2], the toe-in is very important for the optimal cut point. To find the perfect setting is a complex procedure. Therefore, the adjustment is usually kept constant when the desired result is achieved. It is of utmost necessity, that the toe-in is accurately adjusted after installing new blades, incorrect angles lead to irregularities. The toe-in angle can run on three different types. The angle either can be positive, zero or negative. A positive angle favours the cutting result, but the knife wears out faster. Setting a negative toe-in means that there is no defined cut point anymore and the web isn't cut properly.

Similar to the toe-in angle, three possibilities for top knife's *rake angle* exist (see *Figure* 2.1-5). The negative, zero or positive angle is often built into the top knife. In order to reduce the cross machine strain a zero rake angle is the adequate setting for the top knife, because the deflection of the web is lowest in this case.

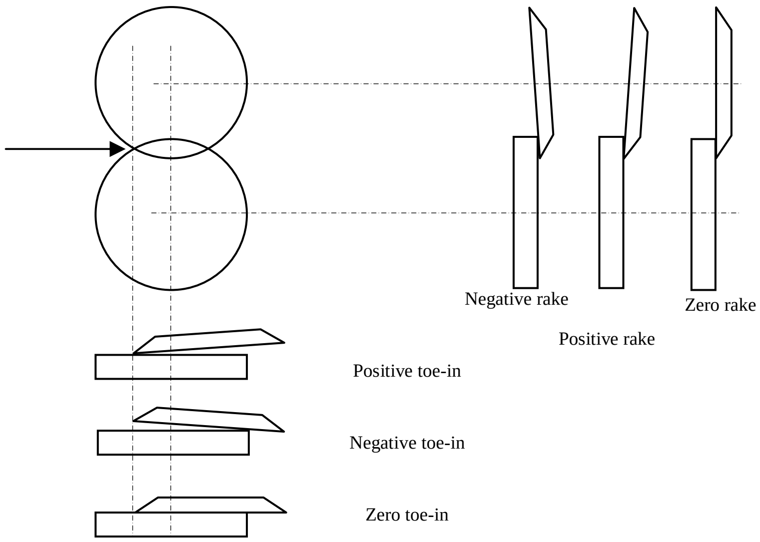


Figure 2.1-5: Toe-in and rake angle for slitting units - Redrawn according to [3]

The rate of *penetration or overlapping of the blades* (see *Figure* 2.1-6) is defined by the substrate properties and the type of slitters used (tangent or wrap) [2]. When using tangent slitting, the paper and the knives have to come in contact in a single point. Only one cut point is available for this system, in fact the tangent of the highest point of the bottom blade. The use of wrap slitting system allows different settings.

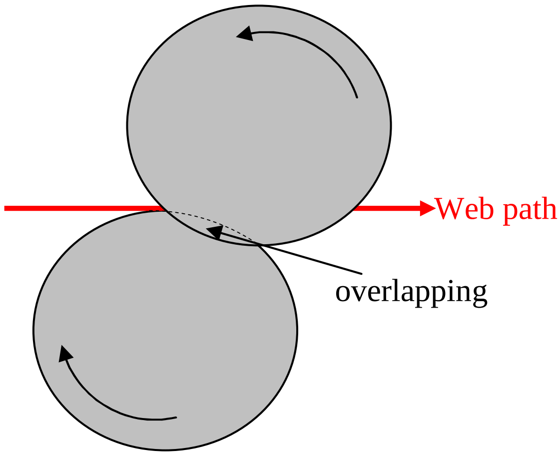


Figure 2.1-6: Overlap of top and bottom knife

According to [2], the contact force in the overlapping area is adjustable. The *side loading pressure* is just the force which acts on the surface between top and bottom knives. The ideal setting is the minimum pressure needed to achieve a good cutting quality. A too high contact pressure leads to faster blade wear. Also, adapting the side load does not increase the functionality of worn blades.
It is mentioned that sometimes more side load is required. This is an indication that one of the parts in the machine is not working in a proper way anymore.

2.1.2 Theory of cross cutting

WITTENBERG [4] defined, cross cutting as a separation of paper perpendicular to the main fibre orientation. The cross cutter acts like a pair of scissors. The full width of the web is not cut in one moment, the cutting stroke moves from the tender to the drive side. Would the paper be cut at once, the cutting force would reach a maximum and cause negative impacts on the cutting quality as well as on the stability of the system. There are two basic concepts which can be applied:

1) Cross cutters with a rotating top drum cylinder, on which the knife is installed in an angle to the drum axis (see *Figure* 2.1-7). The bottom knife is stationary. To achieve a square cut, the stationary bottom knife has to be mounted in a way that it compensates the inclination of the top knife.

   When using a *non synchronous cutter* (circumferential speed of the top drum cylinder is not equal to the path speed during the moment of cutting), it is essential to adapt the position of the cutting machinery in a way, that it matches with the favoured format.

   By contrast, *synchronous cutter*s are synchronizing to the format to be cut. The circumferential speed of the top drum is equal to the path velocity in the moment of cutting. Between the cutting actions, the drum accelerates or decelerates depending on the format length.

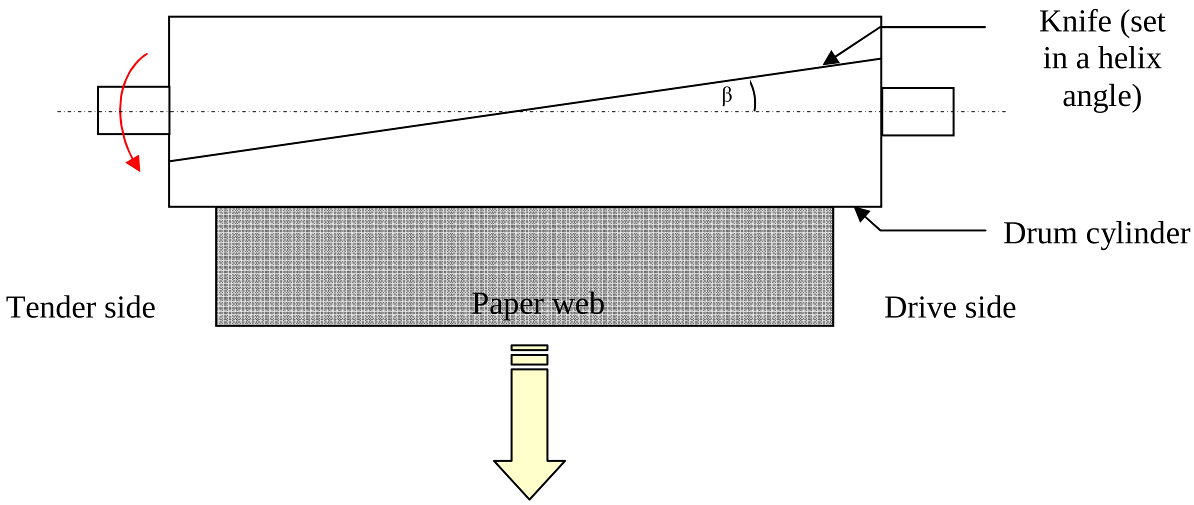


Figure 2.1-7: Configuration with a rotating top knife and a static bottom knife - Redrawn according to [4]

2) Cutters with two rotating drums are so called *double rotary cutters* (see *Figure* 2.1-8). Both, top and bottom drum cylinder are rotating. The knives are set in a helix angle on the drums and furthermore the axis of the drums is set at an angle to the running path. The tangential deviation of the knives is compensated by the displacement of the drums. Due to this setting, it is possible to achieve a straight cutting line.

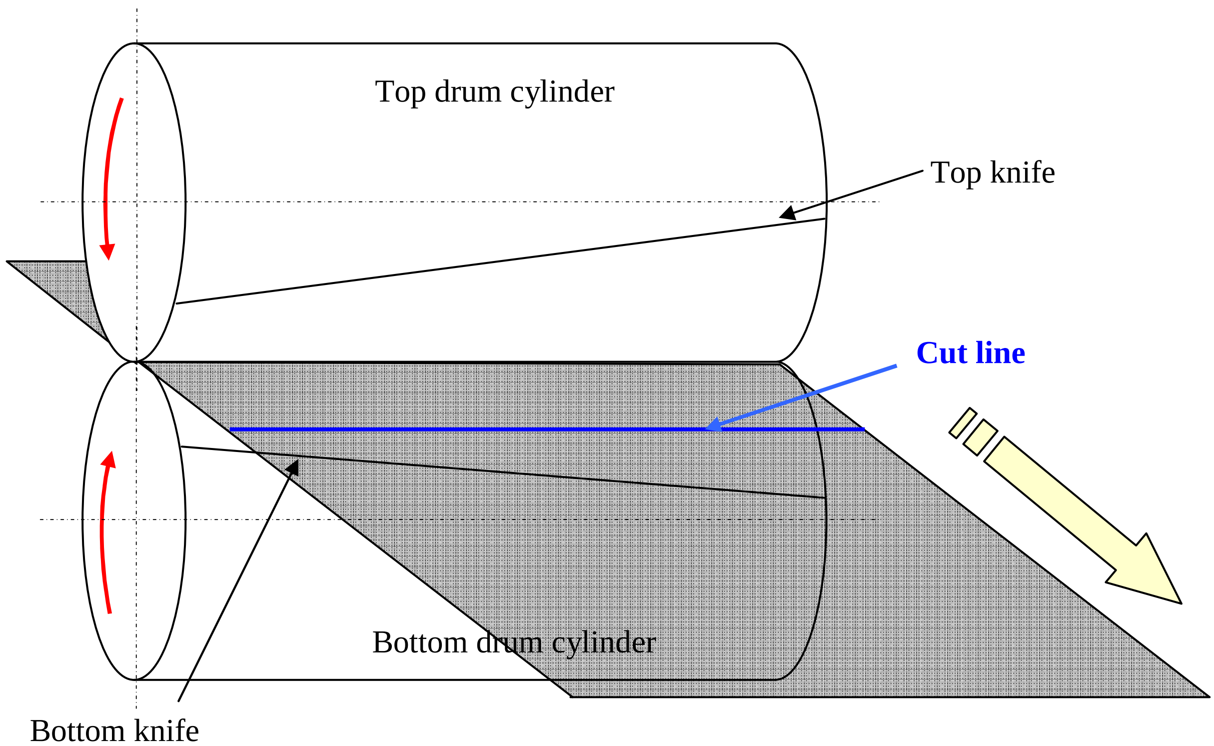
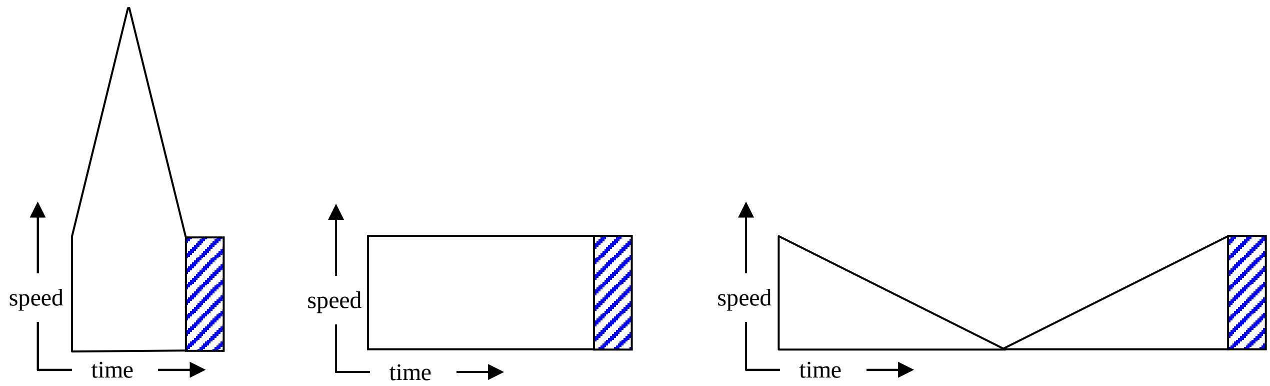


Figure 2.1-8: Double rotary cutter

In accordance with the PAPIERBUCH [5], there are two different driving mechanisms for rotary-synchronous cutter.

1) *Mechanical drive*: Both drum cylinders are driven by a single engine. By adjusting a continuous gear box, the machine can be set to a different format.
2) *Direct drive*: Each rotating component is directly driven by its own engine. The adjustment to the desired format is done electronically.

Figure 2.1-9 shows the interdependence between rotation speed of the drums and the time in between the cutting actions for a **single rotation**. The surface areas of the figures have the same size. The path speed is equal for every case. The corresponding rotation speed for the drum cylinders is varying related to the format. The blue-shaded area represents the moment of cutting.



a) short format b) synchronic format c) long format

Figure 2.1-9: Acceleration and deceleration of the drums at different formats - Redrawn according to [5]

In case (a) the drums have to accelerate between the cutting actions, while synchronic formats (b) allow constant rotation speeds. For cutting very long formats (c), the circumferential speed reaches a minimum.

2.1.3 Industrial cutting of paper

As mentioned in chapter 2.1.1, there are several applications for slitting and cutting operations in the paper industry.

In the production process, the trims of the paper web on paper and coating machines are cut away continuously. On the reel slitters, at the end of the production line, the mother reel is cut into several smaller reels. These reels can be either directly delivered to the customer or they are cut to format sheets in the last step in a paper mill, the finishing. These different fields of cutting applications are discussed in this chapter.

2.1.3.1 Trimming of the edges

To cut away the trims on paper or coating machines, water jet cutters (see *Figure* 2.1-10) are installed at the border of the machines, in most of the cases.

The functional principle is based on a high pressure water jet which separates the edge trim from the paper web [7]. The pressure of the jet is in a range between 600 to 1500 bar, depending on the machine speed and the basis weight of the paper to be cut. To get rid of the trim after it is being cut, a suction system leads it into the broke handling system of the paper machine.

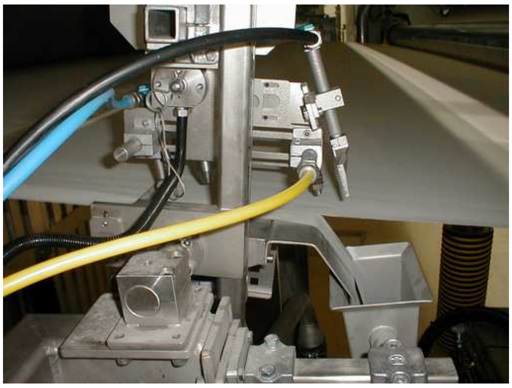


Figure 2.1-10: Water jet cutter [7]

The benefits of a water jet cutter are:

- the higher lifetime of nozzles compared to slitting blades,
- lower dust generation of water jet cutters compared to a slitting knife,
- and the possibility to apply the system also in the wet end of a paper machine.

Even if it is mentioned in literature [7] that a water jet cutter provides an adequate cutting quality, several investigations in Sappi Fine Paper Europe presented opposite results. When checking the edge quality of papers which were cut by water jet cutter, a bad cutting quality was observed. It seems that the water jet is not strong enough to cut single fibres, only the bondings in the fibre matrix are released.

2.1.3.2 Reel slitters

The paper which is wound on the mother reel at the end of the production line has to be converted, either in marketable reels or in reels which are workable for the finishing department.
This is done at reel slitters by using the principle of slitting with rotating circular knives. That means that the paper is cut in long direction, at paper web speeds up to 2500 m/min. This "overspeed" of the reel slitters compared to the paper machine ensures that there is no bottleneck at the end of the production chain.
There are two main types of reel slitters [9]:

- Two-drum winders: Just after the paper is unwound from the mother reel, the web is cut by the rotating knives. After this cutting action, the paper reels are built up on two bearer drums. In most of the cases, the bearer drums are equipped with grooves to get rid of the air boundary layer which is transported into the nip by the web. The roll hardness is controlled by the dead weight of the reel. The disadvantage of this configuration is that the progressing reel weight during winding can cause failures in the finished product, like over expansions or burst areas in the external areas of the reels.
- Single-drum winders: For this type of machines, the produced reels are pressed laterally against a supporting roll. Compared to the two-drum winders, the roll hardness can be controlled independently from the dead weight of the reels. The contact pressure between the reels and the supporting roll is adjustable. Therefore, constant roll hardness across the full diameter can be achieved.

2.1.3.3 Cutting the paper to format sheets

For the production of printing and writing papers the paper reels, produced at the reel slitters, are cut into sheets. This operation is carried out at sheeters (see *Figure* 2.1-11), where in a first step the paper is cut in long direction to achieve the desired width of the sheet. In a second step, the paper is separated in cross direction to set the correct length of the sheet.
An important difference with the cutting processes mentioned before is that several layers can be cut simultaneously at the sheeter.
Sheeters for wood free coated papers can handle up to seven reels at the same time. That means that it is possible to cut up to seven sheets simultaneously. Before the webs are getting in contact with each other to form a compound, a decurler presses against the single webs to

eliminate the tendency to curl. After the decurler, the webs are brought together and led into the slitting unit. The slitting unit can be arranged in two different ways:

- *Single slitting unit*: The paper compound is cut in one slitting unit. For this application, slitting knives with a low bevel angle are used to reduce the rubbing action between the knife and the substrate to cut and also to reduce the penetration forces.
- *Twin slitting unit*: The twin slitting unit consists of two parallel slitting units which are on top of each other. The paper compound is separated in front of the slitting units in two parts. After the cut the webs are led together again.

Sometimes the slitting units are equipped with a dust extractor system to remove the dust generated during the cutting action.

After the webs were cut in long direction, the cross cut follows as the next step. In contrast to the slitting unit, the entire paper compound is cut without separation before the cross cutting unit. Sole exception is the Duplex-sheeter where also the cross cutting unit is split in two parts. The advantages of this configuration is the fact that two different format lengths can be produced simultaneously [5] and a separation of the paper compound at the cross cut leads to a better cutting quality due to the reduced overall thickness of the compound.

Subsequently, the cut sheets are transported via belts to the stack preparation. The number of sheets to cut is counted by an automatic system.

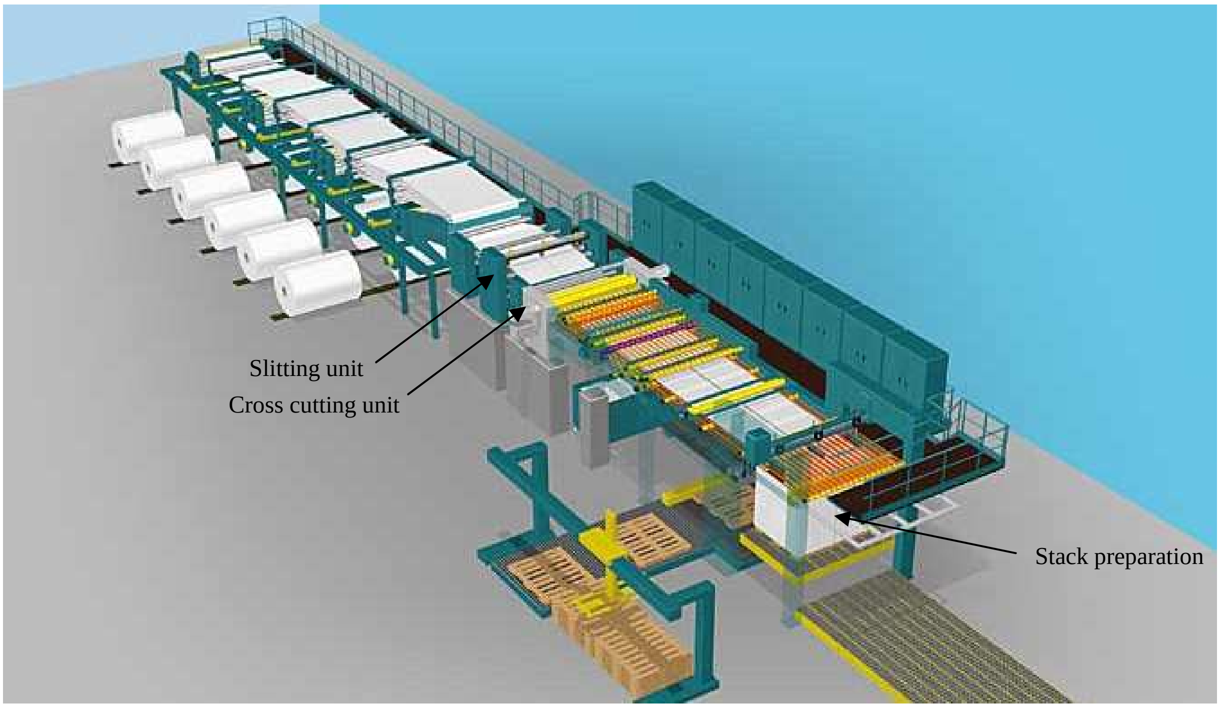


Figure 2.1-11: Sheeter for fine papers [8]

In the case of irregularities of the cutting edge (too ragged edge, format errors …) the paper stack has to be reworked. This is done at the guillotine cutters. Due to the downward movement of the upper knife the paper stack which is located below the knife is cut. The upper knife is set in a certain angle to avoid too high cutting forces when the knife reaches on the paper surface. This angle causes a shear cutting action, the cut point moves from the left side to the right side of the paper stack. After the cut is completed the knife moves upwards to its initial state.

2.1.4 Material influence on cutting

The theory in this chapter is based on research by VEENSTRA [10].

2.1.4.1 Influence of the fibre length

The fibre length has a big influence on the cutting quality. If we assume that paper is single layered and only composed by fibres, two different cases regarding fibre length are possible:

a) b)

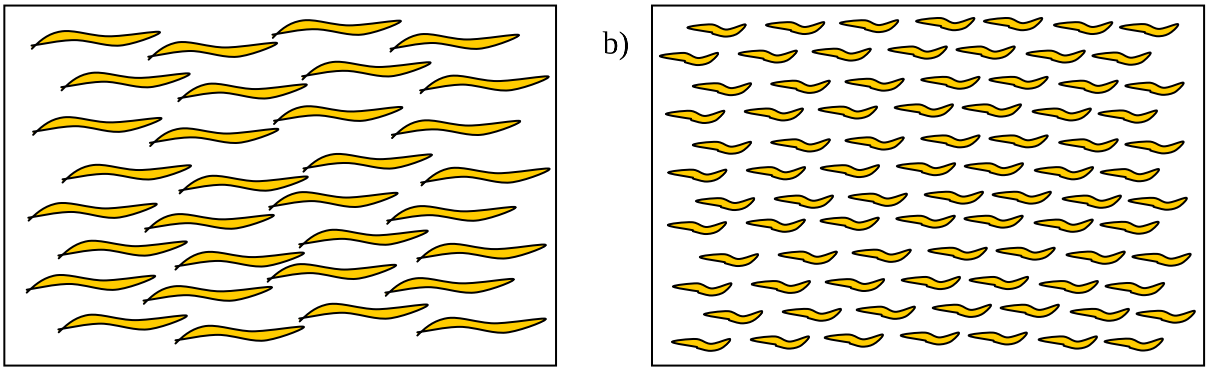


Figure 2.1-12: Simulated fibre length distribution of two papers - a) with long fibres - b) with short fibres Redrawn according to [10]

The total fibre length of paper a) is equal to the total fibre length of paper b) (see *Figure* 2.1-12). The outcome of a cutting action perpendicular to fibre’s principal direction is a cut line with sufficient quality, in both cases.

On the other hand, a cutting action not perpendicular to the main fibre direction will result for paper a) in a bad cutting quality. Fibres which are not ideally oriented to the main fibre direction bend away if the knife pushes against them. After the cut is completed, the fibres are moving to their initial state. These fibres are sticking out from the cutting edge and decrease the quality of the cut. The negative impact on cutting quality is increasing with the average fibre length. This would mean that a decreased fibre length leads to a better cutting edge, but on the other hand long fibres are requested to ensure good strength properties.

2.1.4.2 Paper humidity

According to VEENSTRA [10], the paper's absolute humidity influences its strength. As a consequence of this, the ability to cut is also influenced by humidity.
The cutting forces increase with decreasing humidity. The higher stability of the fibre matrix at lower moisture content leads to a more regular cutting edge.
Recently, an investigation of the impact of paper humidity on the cutting quality was carried in Sappi Fine Paper Europe [11]. It was intended to investigate the influence of the natural aging process of papers on the cutting quality. The same paper was cut at the same sheeter in certain time intervals within two weeks and the edge quality was analyzed. The outcome of this test was, that the cutting quality was slightly decreasing for the long cut. Regarding the cross cut, no real changing in the cutting quality was observable. The negative development of the cutting quality in long direction was mainly caused by the faster blade wearing of the knives of the long cutting unit. The lifetime of these blades is limited to approximately five weeks whilst a cross knife can stay over one year. Thus, the wearing of the cross knife is negligible for the mentioned period and we can conclude that there is only a minor influence from the humidity on the cutting quality. But, it has to be mentioned that the natural ageing of the paper only caused an increase in humidity of around 3 %.

2.1.4.3 Specific volume

Using the same kind of fibres, papers with a higher specific volume are more critical to cut. Especially bulky papers are subjected to a high compression during a cutting action. The lower breaking elongation for voluminous papers (see *Figure* 2.1-13) causes that some fibres to be torn out of the paper when the knife penetrates into the fibre matrix. This fact results in a decreasing quality of the cutting edge for papers with a higher specific volume.

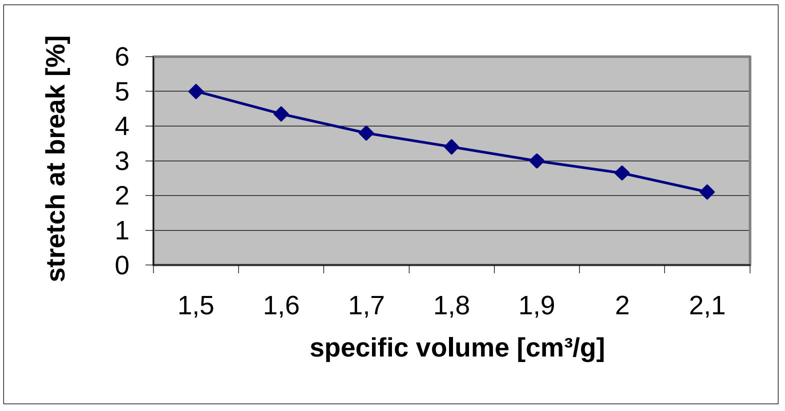


Figure 2.1-13: Relationship between the spec. volume and the breaking elongation - Redrawn according to [10]

2.1.4.4 Material thickness

Figure 2.1-14 describes the influence of the material thickness. It is clearly visible that a thicker paper or a compound of several sheets becomes more deformed by the knife. This results in:

- larger areas of friction associated with increased dust creation,
- higher strains,
- higher deformation of the cutting edges.

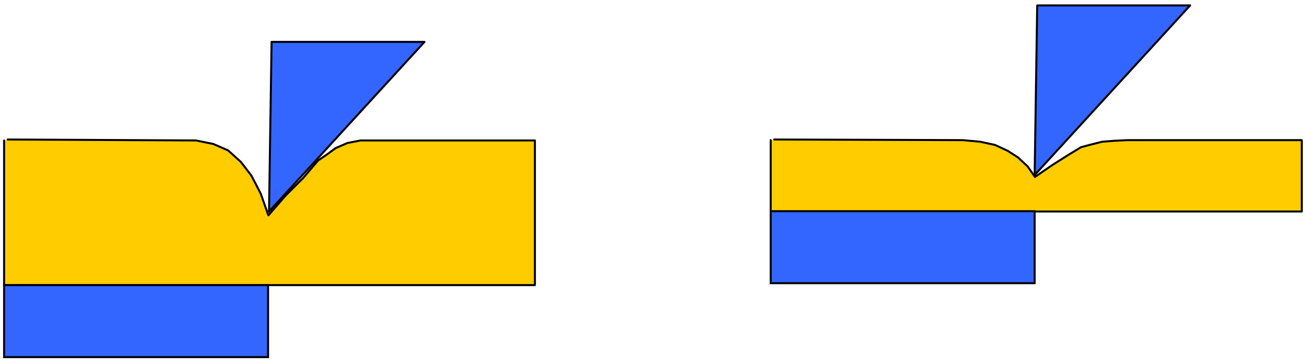


Figure 2.1-14: Behavior of thick respectively thin papers during cutting - Redrawn according to [10]

VEENSTRA [10] calculated the paper stresses under the blade in the elastic state, as a function of the distance to the paper surface in z-direction. He assumed that paper is an elastic material which is supported on bottom side.

In case A (see *Figure* 2.1-15), the substrate presents a high potential for compression. Before the bottom knife starts to act as a support, the full paper thickness will be compressed.

In case B, part of the substrate has already been cut. Therefore, the "compression potential" of the substrate is lower. After a penetration of 500 µm, a new state of elastic deformation appears and the tensions were calculated again. The tensions of case B are lower compared to case A, the effect of the support from the bottom knife is much more distinctive.

This difference in stress condition will have an important impact on the cutting quality of the substrate. The top layers, subjected to high stress (case A), present in general a worse cutting quality than the bottom layers which are subjected to the lower stress (case B).

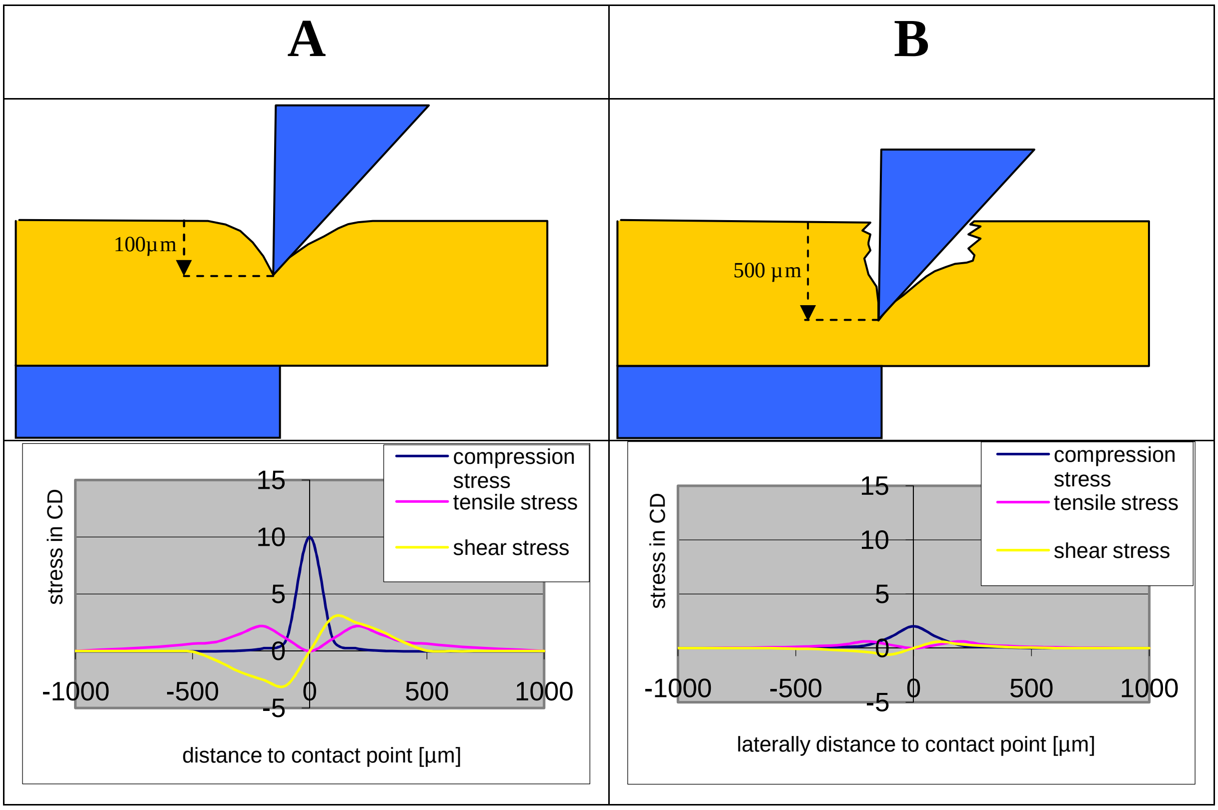


Figure 2.1-15: Calculated stress distributions related to different distances of the knife to the paper surface - Redrawn according to [10]

2.2 Evaluation of the cutting quality

Evaluating the cutting quality is a difficult process. The problem related to this topic is that there is no correct definition for the term "cutting quality". The most prevalent method is to measure just the raggedness of a cutting edge.

According to the ISO 22414 test method [6], the shape of the raggedness of the edges is measured at a magnification of 42 times. The templates used to determine the results, are parallel lines of varying gaps between 1 and 6 mm. The template is put on top of the cutting edge. The number of the template (which corresponds to the gap), at which the amplitude of the raggedness fits in between the lines, is used as the result (see *Figure* 2.2-1)

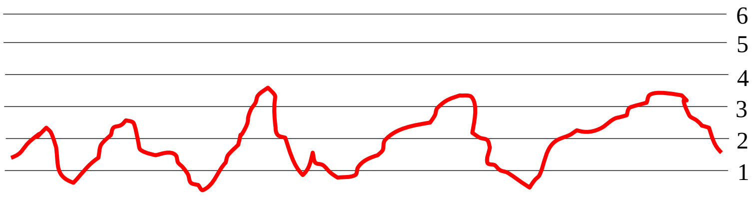


Figure 2.2-1: Evaluation of a cutting edge - Redrawn according to [6]

An image analysis tool was introduced in Sappi Fine Paper Europe to measure the raggedness of a cutting edge and the amount of fibres pulled out at the cutting edge. A series of pictures of a cutting edge is read into the program and an algorithm calculates the maximum raggedness[1] as well as the averaged raggedness of the edge.

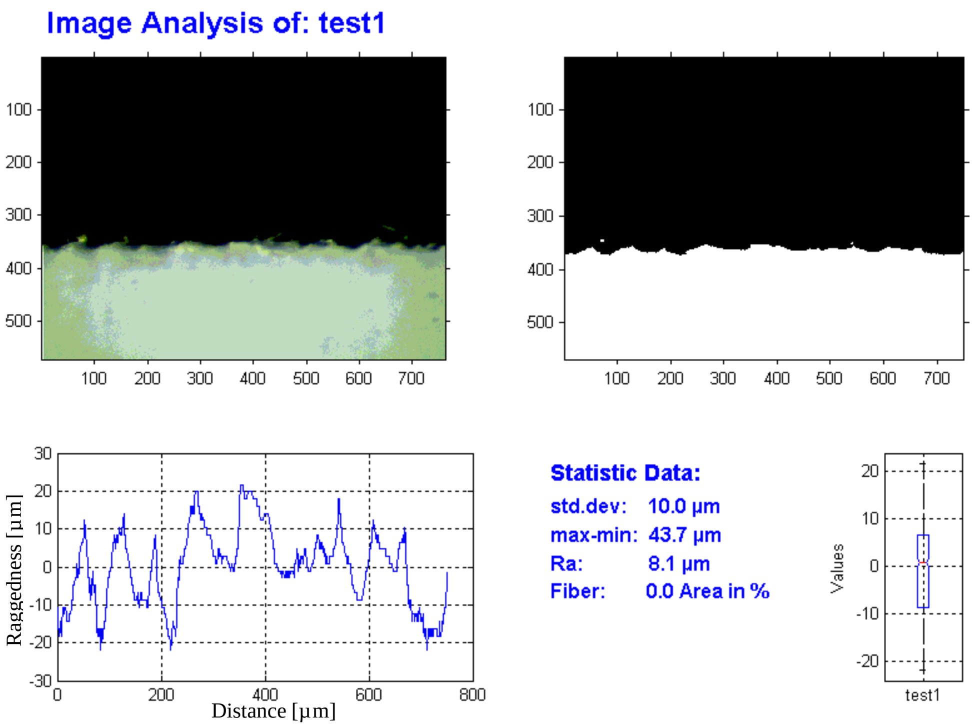


Figure 2.2-2: Image Analysis Tool developed within the cutting quality project in SFPE

Figure 2.2-2 shows the principle of the Image Analysis Tool. For the calculation of the results, the pictures are turned into black and white images to detect the shape of the cutting edge. The mean max-min distance determines the zero line to calculate the average roughness of the cutting edge (R_a). A peak greater than 100 µm above the mean value, with a certain vertical alignment, is detected as a fibre. A box plot is used to interpret the distribution of the calculated values. 50 % of the total values are located in the box and due to the separation at the median the spread of the values around the median can be determined.

The introduced methods are suitable to measure the raggedness of the cutting edges for uncoated papers. Limitations come up when determining the cutting quality of wood free coated papers by means of these methods, because there is no parameter to estimate the shape of the coating layer around the cutting edge.

[1] Distance between the highest and the lowest point of a cutting edge

Therefore, a new test method is being developed within Sappi Fine Paper Europe (Confidential test method in development). Besides the *raggedness* (the maximum distance between the lowest valley and the highest peak is recorded), the *fibres pulled out at the cutting edge* and the *cracks in the coating layer* are considered.

The term fibre pull represents the amount of fibres which have not been cut and were pulled out at the edge during a cutting action. For the fibre pull, a scale has been set up to evaluate visually the amount and size of the fibres, from 1 (very good) to 5 (bad). To evaluate the length of the fibres, a "0,5" is set to the value if there is at least one fibre which is longer or equal than 100 µm. *Figure* 2.2-3 represents a result of 3,5.

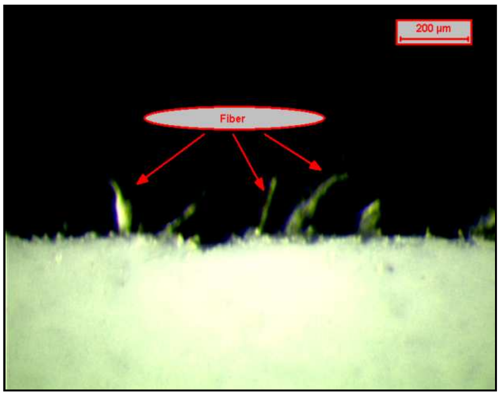


Figure 2.2-3: Fibre pull

Cracks in the coating layer are created during the cutting process and represent particles which are only partly linked to the cutting edge.

The quantity of the cracks in the coating layer is evaluated. For this reason, the number of cracks per 5 cm is recorded. By definition, a crack has to fit the following criteria:

- the minimum length of a crack amounts to 50 µm,
- the minimum width of a crack is at least 10µm.

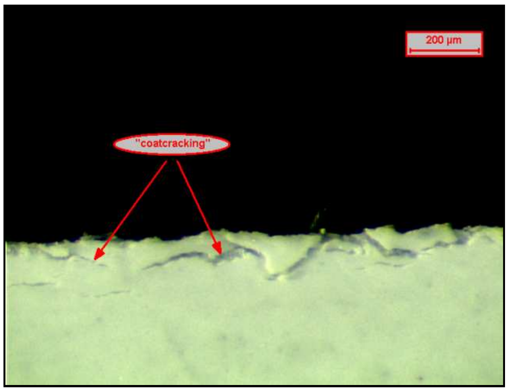


Figure 2.2-4: Cracks in the coating layer

In *Figure* 2.2-4, six cracks are apparent.

2.3 Influence of cutting on paper quality

The cutting quality impacts the value of the finished product to a great extent. Some issues related to this topic are specified in the following part:

- *Poor cutting* is one issue which often leads to complaints. The customers criticize the disturbed visual impression of the cutting edge. A poor cutting edge is often caused by worn knives or bad machinery settings. *Figure* 2.3-1 shows an example of a bad cutting edge.

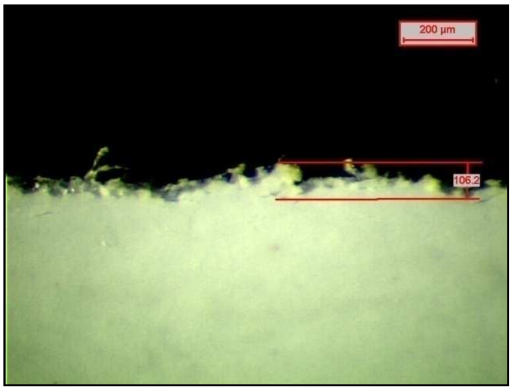


Figure 2.3-1: Poor cutting edge

- Sometimes the cutting *edges are sticking together* (see *Figure* 2.3-2). In this case the cutting edges of the webs are folded by the impact of the knives during a cutting action. This results in an overlapping of the edges. Therefore, the sheet separation at the beginning of the printing process is disturbed. This problem is often related to bad machinery settings.

Figure 2.3-2: Edges sticking together

- Cutting also has a big influence on the quality of the printed samples. The cracks in the coating layer, in combination with the surface dust which is generated during a cut are affecting occasionally the quality of the printed samples. A theory to explain this printing disturbance is that coating particles accumulate on the rubber blanket and furthermore on the plate cylinder. Thereby, the raster transfer from the ink rollers to the plate cylinder is disturbed to some extent. Particles which are sticking on the plate cylinder saturate with black ink[2]. This fault in turn is transferred again to the rubber blanket and furthermore to the sheets. The results of a printing quality for a bad and a good cutting edge after 8000 copies is presented in *Figure* 2.3-3, in which the printing error appears as black dots. After a certain number of copies, the print quality is not acceptable anymore and the printer has to clean the blanket, which leads to a loss of productivity of the printing press.

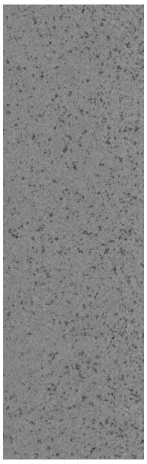
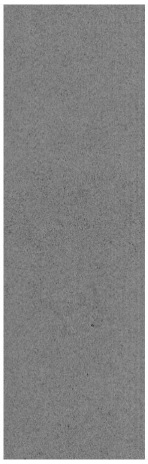
a)  b) 

Figure 2.3-3: Printed sample nearby the cutting edge - a) represents a bad quality - b) represents a good cutting quality

2.4 Existing methods to simulate the cutting process

A lot of efforts have been taken in the past to develop methods which reproduce the paper cutting process.

The attempted approaches can be divided in two main groups:

- *finite element methods* to simulate the cutting operations in a mathematical way by using an adequate software,
- *devices* to execute various cutting processes with paper.

In the following, some types of both species, which have been found during my literature research, are presented.

2.4.1 Finite element method

A research work regarding finite element method was carried out by HOFER [12]. The following part is an abstract of his work.

[2] assumption: black ink used in the first printing unit

The finite element method (FEM) is a tool to assess complex stress – strain interactions. This method is used in several manufacturing industries, as in aircraft- and vehicle construction. For this method, the model is divided in many elements. Each element is defined by equations, whose solution describes the stress and strain behaviour of materials.

By characterizing a punching operation, the finite element method can be explained more in detail.

A punching operation can be divided in three steps:

1. compression phase,
2. separation phase,
3. interpenetrate, respectively pressing the knife against the support table.

Figure 2.4-1 is the result of an experimental determination:

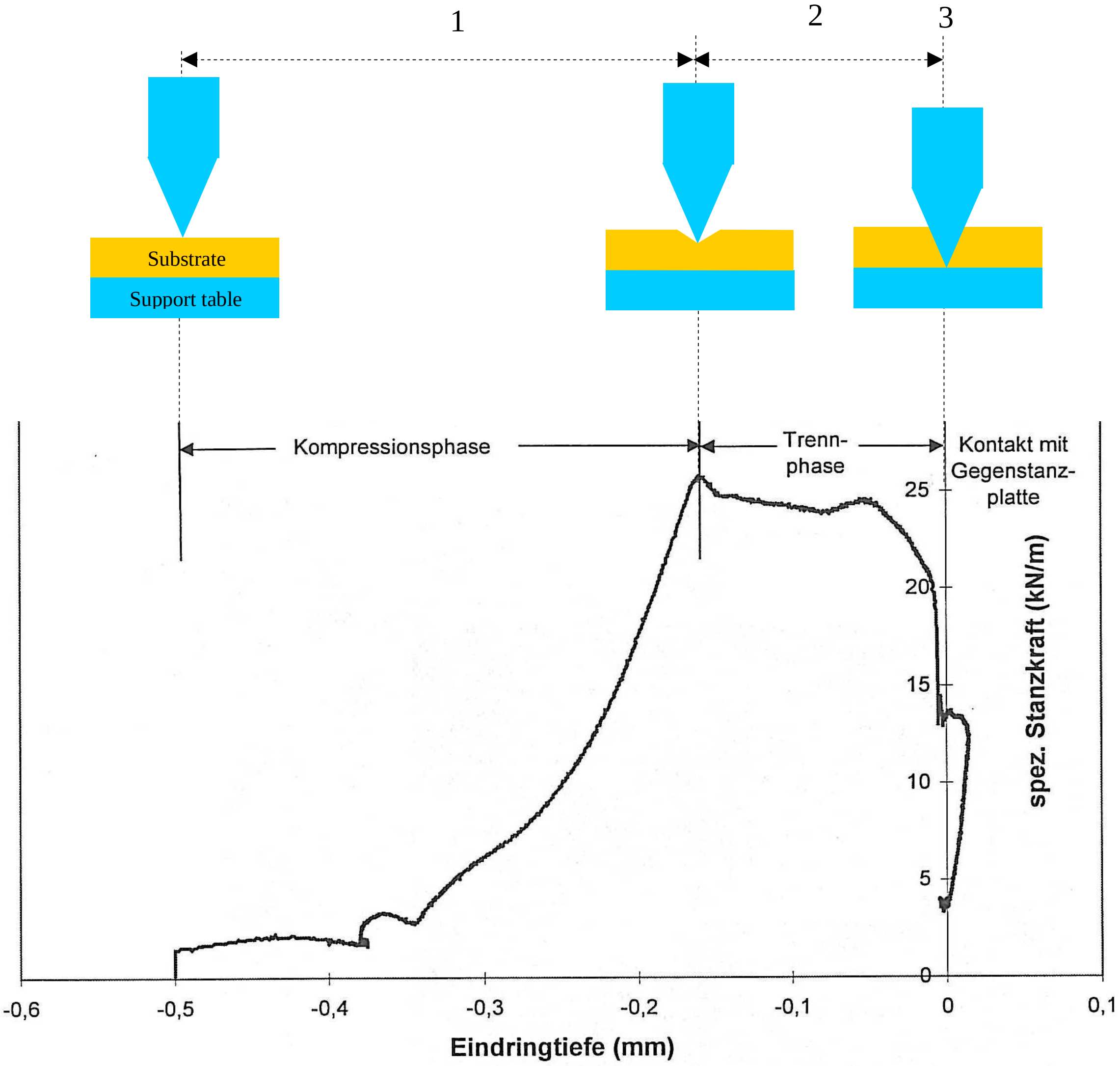


Figure 2.4-1: Progression of the cutting force with increasing penetration [12]

In a first step, the substrate is compacted up to a maximum force (1). The substrate is compressed up to its minimal void volume. Afterwards, the substrate is separated with a lower force (2). At the end of the penetration phase, the knife interpenetrates the substrate completely (3). The contact between knife and support table leads to a slightly increased force.

The different knife – substrate interaction within the three steps has an impact on the finite element method. A separate modeling of the three stages is necessary. With the help of the compression phase, the approach regarding modeling is shown:

1. FEM-Model: Usually, knife and substrate assumed to be symmetrical. Thus, it is possible to calculate only half of the phenomenon to reduce the computing time.
2. Material constants: In the case of punching, the E-modulus in z-direction is increasing with advancing penetration (see *Figure* 2.4-1). In generally, FEM – software offers the possibility to calculate with changing E-modulus.
3. Boundary conditions: In order to set a limit between compression- and separation phase, boundary conditions have to be defined. Starting point of the punching action is, when the knife comes in contact with the surface of the substrate. The end point of the compression phase is determined by the elasticity behaviour of the substrate, in fact the highest peak of the curve in *Figure* 2.4-1, the changeover from the compression phase to the punching (cutting) phase.
4. Calculation and interpretation of the results of a numerical simulation: To calculate the results, the material is separated in a finite number of equations. Each element is defined by such an equation and these elements are linked with each other. Solving this system of equations yields the result of the finite element method.

   Results for deformations and stresses in horizontal as well as in vertical direction can be obtained. To visualize the obtained values, a graph is created in which the different states of stresses or deformations are separated in terms of color.

In fact, the finite element method is a suitable tool to calculate the stress distribution during deformation processes. A drawback of this method is that paper is often considered as a homogenous material and this is not the case in reality. Another disadvantage is that arbitrary actions, such as the separation phase in the previous task, are very difficult to simulate by means of software.

In addition, no conclusion can be made regarding cutting quality or dust evolution during the cutting process and those are the aspects which we mainly want to study.

2.4.2 Devices for simulating cutting

It is known that machine suppliers for sheeters developed in-house cutting devices for test purposes. These devices are often used to test new knife materials / geometries or to investigate problems regarding cutting which are related to the substrate to be cut (dusting, abrasive materials ...). One idea was to use the technology of these machines but the suppliers keep the information confidential. Therefore, it is not possible to get the necessary information to copy such a machine.

Some systems developed for material testing offer the possibility to change / adapt the measuring head in order to record the material's behaviour during cutting.

In addition to that, purpose-made devices to simulate the shear cutting process have been introduced in several research works.

In the subsequent part, one device of the two above mentioned categories is introduced.

2.4.2.1 UST® - Universal Surface Tester

The Universal Surface Tester®, developed by ACCTRON [13], is used to investigate characteristics of many materials. By fixing different tools on the sensor, properties such as abrasion and the cutting resistance can be measured.

The test method uses the patented MISTAN®-process, a topography measurement where a defined surface area is scanned mechanically three times by a stylus. In a first step the topography of the present material surface is recorded by the stylus under minimal load. After that, the stylus scans again the material surface with a higher load. Finally, a further scan of the surface records the remaining deformation with the minimal load. By means of the obtained values, the elastic and plastic deformations of the material can be determined.

Concerning the determination of the cutting resistance of paper, the following sequence is carried out:

1) a special stylus in the shape of a scalpel scans the surface with minimal load,
2) the scalpel cuts the surface with a defined load,
3) the resulting cutting depth [µm], which is determined in a third scanning process, represents the cutting resistance of a paper.

Figure 2.4-2 shows the basic structure of the Universal Surface Tester®:

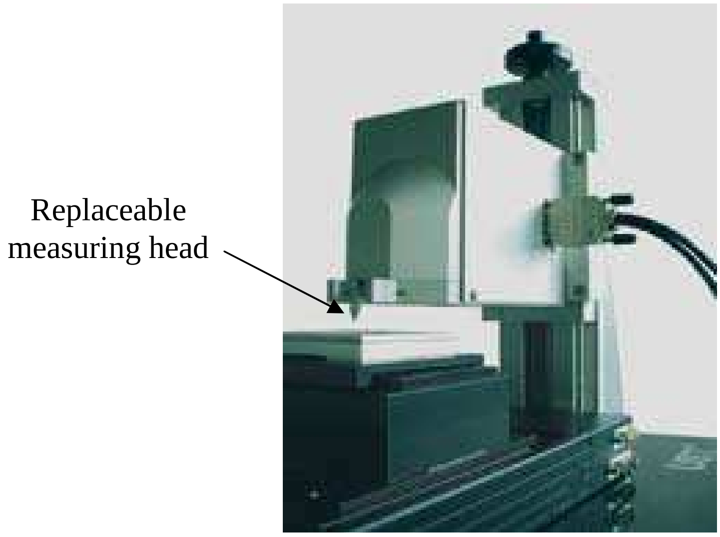


Figure 2.4-2: Universal Surface Tester® [13]

The use of the Universal Surface Tester® was one possibility for carrying out tests regarding the cutting behavior of papers. The forces needed to cut as well as the friction forces between the knife and the substrate can be measured.
Unfortunately, the cutting tool was still in development stage when I started with my thesis. Therefore, it was not possible to try out the functionality of the device. However, for further investigations regarding cutting, the UST is definitely an interesting option.

2.4.2.2 Shear testing apparatus

DOWNEY [14] constructed a module to determine the forces induced in shear cutting. The module was installed in a material testing machine (Instron 1026), to execute a guillotine cutting action. This material testing machine is able to record the required cutting load related to the covered distance of the crosshead. *Figure* 2.4-3 shows the mounting of the device. The bottom blade is fixed to an anvil, which is mounted to the holder of the Instron 1026. Next to the bottom blade there is a clamp to fix the paper strips to be cut. The upper blade is designed as a movable arm, which is linked via a cable to the crosshead. The moving of the crosshead results in a cutting action between top and bottom blades.
For the tests, different knife geometries and knife materials were used. Even a transparent knife, made of acrylic glass was constructed. Hence, the possibility to observe the paper during cutting is given.

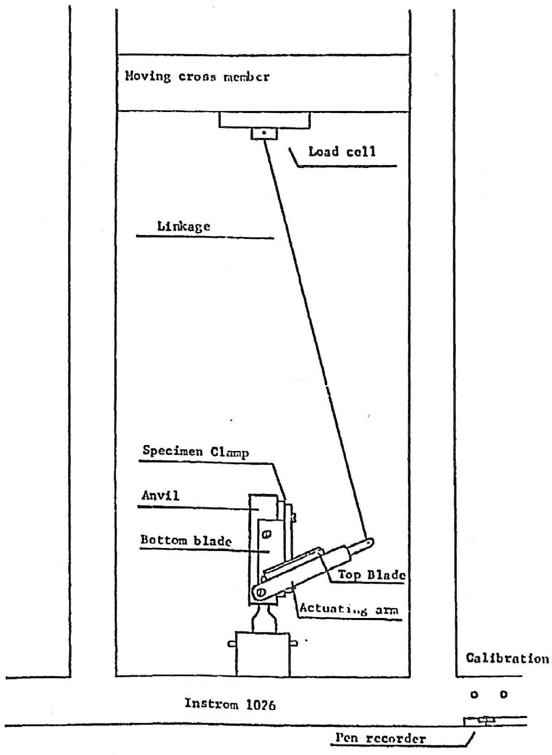


Figure 2.4-3: Instron 1026 with shear cutting module [14]

DOWNEY [14] mentions also some disadvantages of this system:

- the friction in between the bottom knife and the movable top knife influences the necessary cutting force,
- measurements are sensitive to the variations occurring during the adjustments,
- minor damages on the tip of the blade cause deviations in results.

Using a material testing machine would be an appropriate option, because it is the only type from the methods named above where shear cutting is performed.

Of course, measuring the cutting force is an interesting aspect to compare different papers. However, this parameter might not be sufficient to make conclusions about how papers behave during a cutting action. It is desired to determine the cutting quality of the cut samples and due to this, a method with similarities to the configuration at the sheeter is desired.

3 Development of a new method to simulate cutting

As discussed in chapter 2.4, no suitable laboratory cutting machine exists to investigate the behaviour of wood free coated papers during the cutting process. The basic idea from DOWNEY [14] is adopted: use a material testing machine with a compatible cutting device.
The first step was to choose an applicable device which is versatile, accurate and of course, available in Sappi Fine Paper Europe. Hence, the Zwick® material testing machine seemed to be the best solution, because this system allows installing different modules for determining parameters such as compression behaviour, strength properties or creasability[3] of papers. Modifying one of these modules in a way that a shear cutting action is executed was the approach to get a reliable testing apparatus at the end.

3.1 Characteristics and technical specifications of the Zwick® material testing machine

Information regarding the Zwick® material testing machine was collected from the operating instructions manual [15]. The Zwick® material testing machine (see *Figure* 3.1-1) which is located in SFPE, Gratkorn mill, is of the type TC-FR2.5TN.D09. The basic unit consists of the load frame and the control unit. The load frame includes a stationary bottom cross head and a moveable top cross head. Inside the apron, the electromechanic driving mechanism is located. To install an experimental mould, the cross heads are equipped with fixing parts. The load cell of the different modules is wired to the control unit. Based on the principle of a strain gauge[4], the measured load is converted into a voltage. The value of the voltage is proportional to the force applied. A software (testXpert®) offers a wide range of settings to perform a testing sequence as desired.

Figure 3.1-1: Zwick® material testing machine [16]

[3] State of the paper sample, after the sample was creased by a knife. A groove with a certain depth and width is applied to the sample.
[4] Testing bridge which consists of electrical resistors. A deformation of them results in a change of their values.

3.2 Modification and construction of the necessary parts

Decision was made to use the Zwick® material testing machine and the optional creasability module as a basic system. The creasability module consists of a stationary lower part which is linked via two guiding pins to a moveable upper component. When carrying out a measurement, the moveable upper component is moving from top to bottom.

During standard operation, a creasing knife is mounted into the movable upper part to perform a creasing action on the paper sample. The device creases the sheets by penetrating in a channel below the paper (see *Figure* 3.2-1).

An idea could be to use this creasing module to simulate a cutting action.

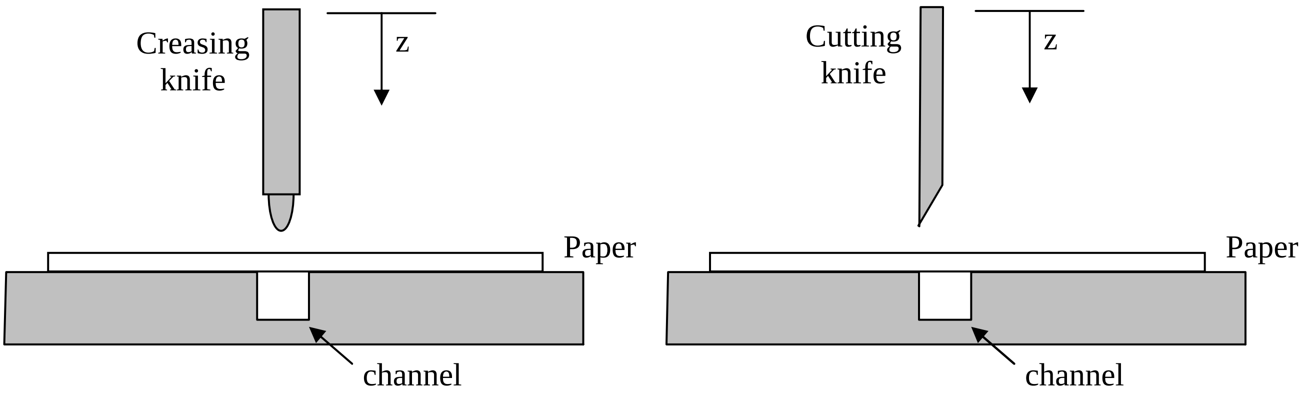


Figure 3.2-1: Mode of operation: creasing knife vs. cutting knife

3.2.1 Manufacturing the blade holder

To use the creasing device to execute a cutting action, a knife holder and the corresponding knife which can be fixed into the creasing device have to be manufactured. Because of the fact that the knife has to be sharpened from time to time, these parts were produced separately. It is intended to use the existing channel as a bottom knife. *Figure* 3.2-2 shows the basic composition of knife holder, knife and penetration channel. It is known from the sheeter, that insufficient knife holder stability for a slitting unit often reduces the cutting quality and also the machine stability. Thus, a stable knife holder for our system is of utmost importance. Therefore, the focus was set on using minimal tolerances when manufacturing the knife holder.

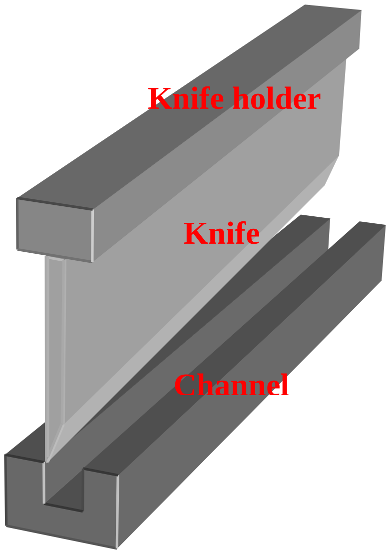


Figure 3.2-2: Basic concept of the cutting unit

Main part of the knife holder (see *Figure* 3.2-3) is the base plate where all other components are mounted (grey part). The piece for clamping the knife is laterally movable by sliding on two guiding pins. Three independent, adjustable screws are responsible for the stability of the system and for the alignment of the blade along the channel. The knife itself is fixed by two clamping screws (yellow screws) into the moveable part (blue part). A design drawing of the knife is available in *appendix A – Drawing 001 / 002.*

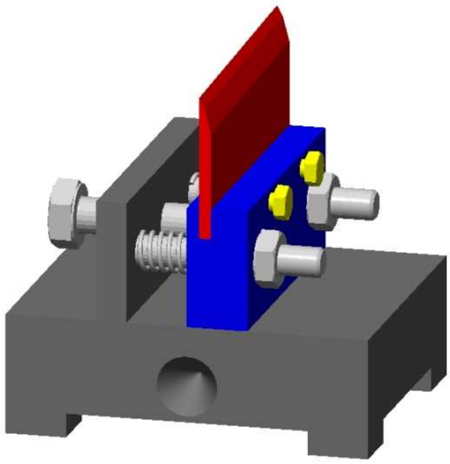


Figure 3.2-3: Knife holder

3.2.2 Manufacturing the blade

The intention was to produce a knife with sufficient hardness to perform several test series over a long period without the necessity of regrinding. Regrinding the knife would mean a manipulation of the tip of the blade, which downgrades the reproducibility of the measurement. To avoid a sharpening in between a measurement series, the knife was manufactured out of the same material as the rotating slitting knives in a sheeter. ASP23[5] is a usual material grade of the slitting knives used in Sappi Fine Paper Europe, Gratkorn mill.

[5] ASP23 is the term used for the material S790PM within Böhler Miller Messer und Sägen

The knife is subject to a primary grinding, to get the desired geometry. In a second phase, the tip of the blade is polished by a diamond grinding disc, to reach the desired smoothness.

Next to the material, the angles applied to the tip of the knife (see *Figure* 3.2-4) have a huge impact on the results. A too high bevel angle[6] (α) would increase the loading during a cutting action to a maximum, which leads to instabilities and in the worst case to damages of the system. On the other hand, blades with low bevel angles are endangered to break if irregularities occur while a cutting action is executed. The slitting units in SFPE, Gratkorn mill, run with blades using bevel angles between 15° and 60°. Bevel angles used for cross knives can reach to 85°. A compromise was made to avoid too high loading forces and to reduce the danger of unwanted blade damages. Therefore, a bevel angle of 27° was selected. Adjacent to the bevel angle, the secondary grind angle is located. The purpose of the secondary grind angle is to reduce the thickness of the blade. Therefore the friction action decreases when cutting several sheets simultaneously. The secondary grind angle is adjusted to 15°, which is a standard secondary angle for a 27° knife. A design drawing of the knife is available in *appendix A – Drawing 003*.

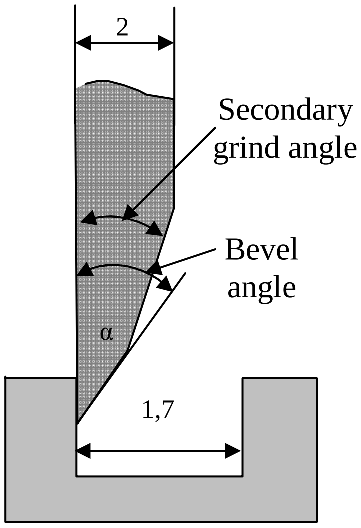


Figure 3.2-4: Tip angles of a blade

According to WISSELINK [17] the knife has to act like a pair of scissors to avoid that a punching action instead of a guillotining action is performed (see *Figure* 3.3-1). The cutting stroke has to move from side to side. Hence, the knife has to be set in an angle (γ) between 0,5° and 3° [17]. The helix angle, on which the cross knife is set on the rotating drum corresponds to 1,65° (see *Figure* 2.1-7). For this reason the decision was made to produce a knife with a cutting angle of 1,65° to keep similarities between the cutting device and the configuration at the sheeter.

3.3 Test conditions

Before performing the first tests, a lot of parameters, potentially influencing the results of the measurement, have to be defined. The testing conditions are based on the idea to keep similarities to the configuration at the sheeter and on the information found in some literature.

6 Outermost surface of the blade; treated surface when the knife is regrind

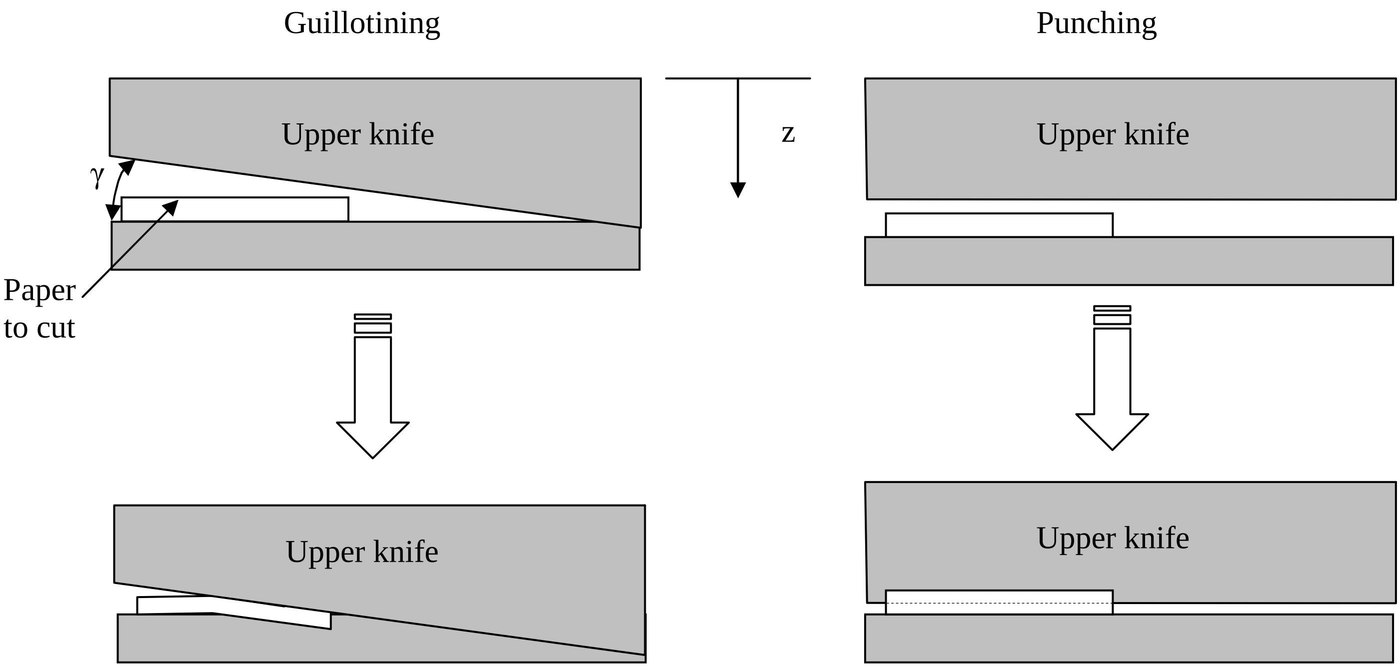


Figure 3.3-1: Guillotining vs. punching

3.3.1 Penetration speed of the knife

As mentioned above, it is intended to reproduce the settings from the sheeter as well as possible.

Regarding the cross cut, things are getting more complicated. At first an assumption has to be established to define the penetration speed in z-direction for cross cutting. *Figure* 3.3-2 shows a side view of a cross cutting action of three sheets cut simultaneously.

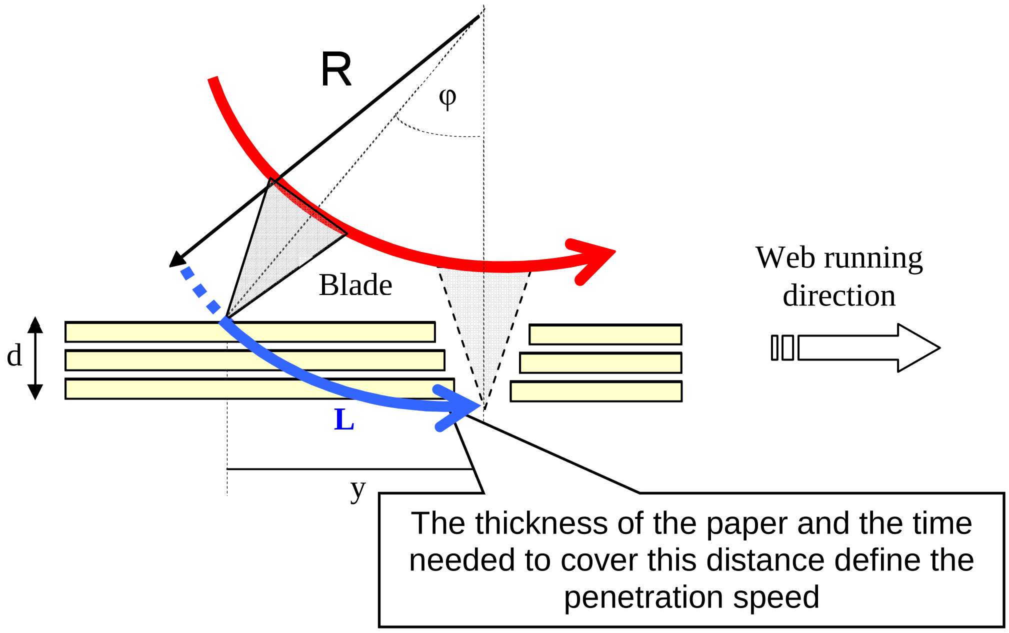


Figure 3.3-2: Cutting velocity in cross direction

The red line indicates the rotating drum cylinder, the blue line (L) the length which is covered by the tip of the blade. In the case of using a synchronous cutter, the circumferential speed of the tip of the blade is equal to the path speed, in the moment of cutting. During the knife penetration into the layers, the movement of the paper corresponds to the distance y. The penetration in z-direction can be defined by the paper thickness (d) divided by the time needed to cover the distance y.

The distance y is just the chord length of the circle sector L:

$$y = \sqrt{2 \times d \times R - d^2}$$

By using the path speed (v_p), the time needed for cutting (t_c) can be determined:

$$t_c = \frac{y}{v_p}$$

According to the assumption outlined above, the penetration speed v_z can be expressed:

$$v_{z=} \frac{d}{t_c}$$

An average machine speed of a sheeter is about 150 m/min and the rotating drum cylinder has a radius of 0,2m. Typical thickness of the substrate when cutting three sheets simultaneously is 0,3 mm. For this practical approach the penetration speed represents 4,1 m/min.

The cutting speed of a slitting unit can be determined in a similar way. As outlined in chapter 2.1.1, the bottom knife should run with a certain over speed compared to the web speed and to the top knife. If we assume that the machine is running on optimized mechanical settings, the top knife velocity on its outermost point is equal to the path speed. By replacing the cross knife with a rotating circular knife in *Figure* 3.3-2 it becomes visible that the penetration process is still the same in case of cross cutting and slitting.
The outermost point of a rotating slitting knife is comparable with the tip of a rotating cross knife. When using a circular knife with a diameter of 0,2 m and the parameters from the speed

calculation for the cross knife, the penetration speed for the slitting knife amounts to 5,8 m/min.

The penetration speed in z-direction of the Zwick® material testing machine is variable from 1 mm/min to 800 mm/min. To reconstruct the high cutting speeds at the sheeter, a penetration speed of 800 mm/min was chosen at the Zwick. With the calculated penetration speed for the cross cut of 4,1 m/min and 5,8 m/min for the long cut, the following ratios can be defined:

$$\frac{v_{cross\ cut}}{v_{Zwick}} \approx \frac{5}{1}$$

$$\frac{v_{long\ cut}}{v_{Zwick}} \approx \frac{7}{1}$$

3.3.2 Width of the channel

The penetration channels which belong to the creasability device are used as a bottom knife. The width of the channel is variable from 0,9 to 1,7 mm and the result of the measurement is influenced by this width.

By taking a channel with a small width, the bending of the paper, when the knife touches the surface until the cutting starts, is limited. A drawback of this configuration is that the edges of the cut paper move between the knife and the sidewall of the channel. This kind of jamming would falsify the measurement.

On the other hand, when using a broader channel, the paper is bending into the channel to a larger extent. The bending of the paper happens during the compression phase of the substrate before the real cutting action starts. This bending of the paper can cause a decrease in cutting quality of the sample piece to the right of the knife, but the force needed to perform the cut is not influenced by jamming the paper (see *Figure* 3.3-3).

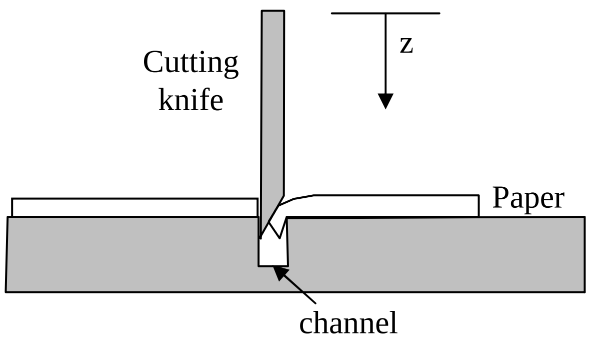


Figure 3.3-3: Jamming of the paper when using a narrow channel

Primarily it is desired to have an accurate measurement system, for this reason the selected width of the channel is 1,7 mm. The decrease in cutting quality, of the sample piece to the right side of the knife, is accepted. This is due the fact that the cutting quality of this part of the sample is not subject to a further investigation. The importance of the cutting quality of the cut sample is outlined in the chapters 4.2 and 4.3.

3.3.3 Distance between top and bottom knife

WISSELINK [17] proposes to keep a certain distance between top and bottom knife (see *Figure* 3.3-4). A gap of 1 % to 25 % of the substrate thickness is suggested. To keep a constant setting, we assume that a common thickness for coated papers is around 90 µm. It is intended to perform a multi layer cut[7] if a measurement series is elaborated. This means for cutting three sheets together, that every gap width from 2,7 µm to 67,5 µm is possible. Initially we decided to keep a gap of 30 µm between the blades.

By dint of a feeler gauge, the favoured clearance was adjusted.

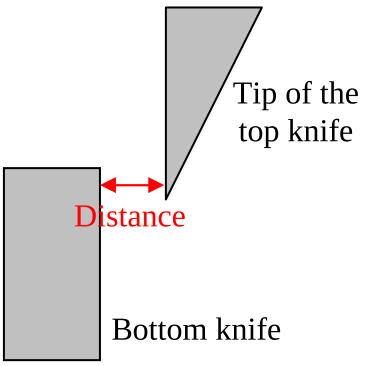


Figure 3.3-4: Distance between top and bottom knife

The first trials with this configuration did not bring the desired results. Even though the loading forces needed to cut samples of similar type were constant, the cutting quality observed was definitely not good enough. Due to the clearance between top and bottom knives, the friction between both blades, which is typical of a shearing action, is missing. It leads to a tearing of the paper and therefore, an investigation of the cutting edge of the cut samples is impossible.

Thus, the knives have to be in contact when the cutting action is performed. To ensure that the cutting is carried out in an exact manner, the contact force between the blades has to be constant over the full length. Therefore, the idea to use strain gauges was coming up to assure a perfect blade alignment.

[7] cut a certain number of sheets at the same time

3.3.3.1 Principle action of strain gauges

The basic function of strain gauges was outlined by GRIMM et al. [18]. Strain gauges are used to determine the static or dynamic stresses which act on a component. The strain gauges are fixed on the component by gluing. The effectiveness of a strain gauge is based on changing its electrical resistance if the gauge is compressed or elongated. This change in size is caused by elongation or compression of the component respectively of the strain gauge.

The elongation (ε) of a gauge in µm/m is defined as the change of its length relating to its initial length:

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

The change of the electrical resistance (ΔR) based on its initial value (R) is explained by the formula:

$$\frac{\Delta R}{R} = k \times \varepsilon$$

The factor k specifies the variation of the electrical resistance caused by elongation. By reforming the equation above, the elongation (ε) is determined by:

$$\varepsilon = \frac{\Delta R}{R \times k}$$

Several methods to connect the strain gauges to an electric circuit for determining a deformation of a component exist. For this application the full bridge circuit is implemented. With a full bridge circuit, two of the gauges are elongated and two of them are compressed.

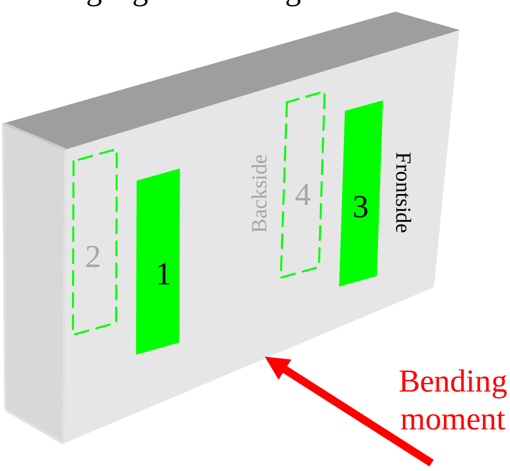


Figure 3.3-5: Arrangement of the strain gauges in a full bridge circuit

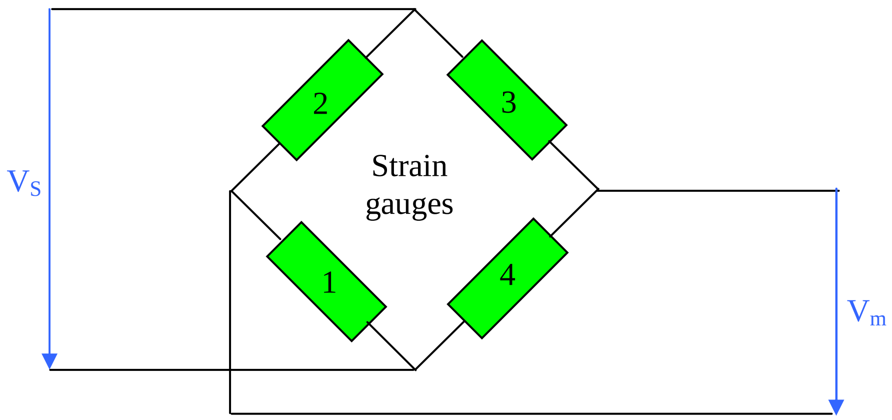


Figure 3.3-6: Connection of the strain gauges in a full bridge circuit - Redrawn according to [18]

The supplying voltage (V_s) energizes the full bridge circuit. In the passive state a full bridge circuit (see *Figure* 3.3-6) is compensated and the measurement voltage (V_m) represents zero. A bending of the component (see *Figure* 3.3-5), where the full bridge circuit is applied, causes a stretching of gauge no. 1 and no. 3 and a compression of gauge no. 2 and no. 4. Due to this, the full bridge circuit leaves its passive state and a measurement voltage according to the following equation can be recorded.

$$V_{m=}V_s \times k \times \varepsilon$$

3.3.3.2 Knife adjustment

The adjustment of the top knife along the bottom knife is carried out by an external institute. The necessary equipment to analyze the measurement voltage of the full circuit bridge is not available in Sappi Fine Paper Europe.

The equipment used to adjust the top knife is listed in the following:

- Measurement amplifier: The measurement amplifier MGCplus from the supplier *Hottinger Baldwin Messtechnik GmbH* is used to analyse the test signal.
- Software: Software of the type Beam 3.15a18 communicates with the measurement amplifier for recording the test signal.
- Strain gauge: The implemented strain gauges are of the type 3/350DY11 supplied by the *Hottinger Baldwin Messtechnik GmbH*. The nominal resistance of the strain gauge amounts to 350 Ω and the gauge factor represents 2,05.

By "pressing" the upper knife against the sidewall of the channel, the upper knife is subjected to a marginal bending action. As discussed in chapter 3.3.3.1, the application of strain gauges onto the top knife enables the determination of the resulting bending action. The implementation of two full bridge circuits, one on the left side and one of the right side of the blade, ensures that the loading force on both sides are equal. The first step in the adjustment procedure is that the knife penetrates completely into the channel. By turning the adjustment screws of the knife holder, the parallel alignment of the blade along the channel is set. The aim is to reach same values of elongation on left side and right sides of the blade. When the knife is set parallel to the channel, the adjustment curve (see *Figure* 3.3-8) can be recorded:

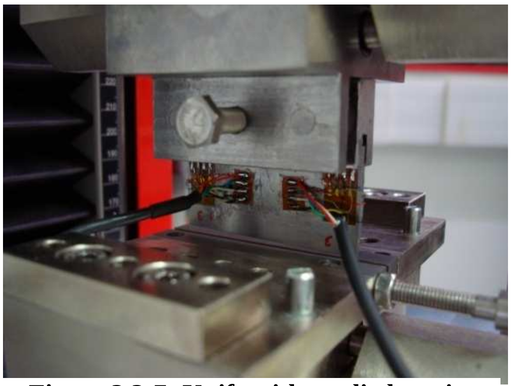


Figure 3.3-7: Knife with applied strain gauges

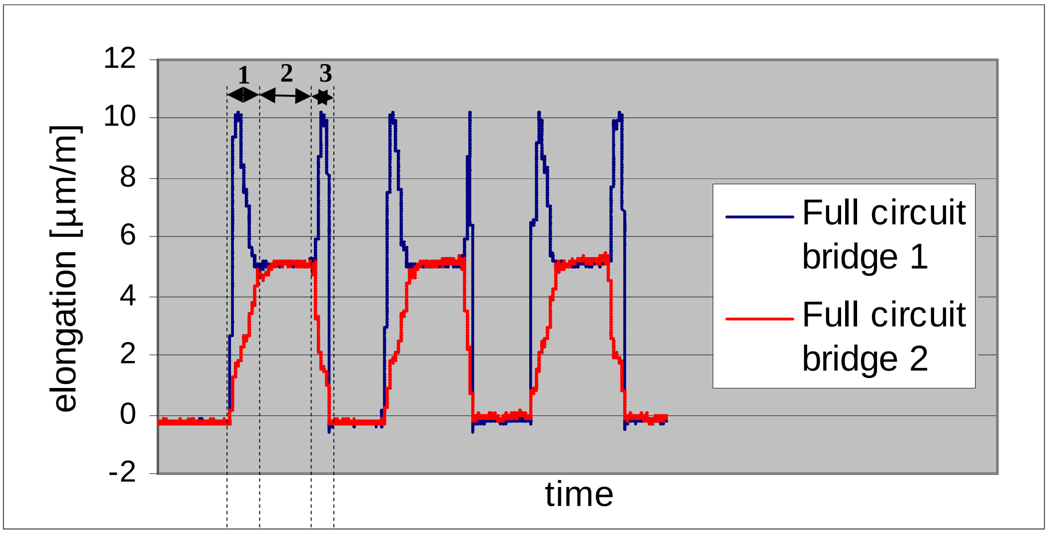


Figure 3.3-8: Adjustment curve

Figure 3.3-8 presents the curve for adjusting the upper blade along the lower blade:

1. The blade starts to penetrate into the channel. Because of the inclination of the upper blade (see *Figure* 3.3-1), one side of the blade penetrates at first, only the full bridge circuit 1 is strained. The reason for the high peak is that the complete loading acts on the foremost tip.

   The ongoing penetration induces also the full bridge circuit 2.
2. After completed penetration, the loading is evenly distributed between both bridges.
3. The blade is moving upwards and the reverse action to step 1 is carried out.

To ensure that the contact force between the blades remains constant, this procedure is executed three times.

3.3.3.3 Calcul of the contact force for the bending conditions

The aim is to calculate the loading force (F), which acts between the blades on the basis of the measured value of the bending.

For the configuration presented in *Figure* 3.3-9, the operands have to be defined:

- Effective length l = 20mm
- Material thickness h = 2 mm
- Width of the knife b = 50 mm

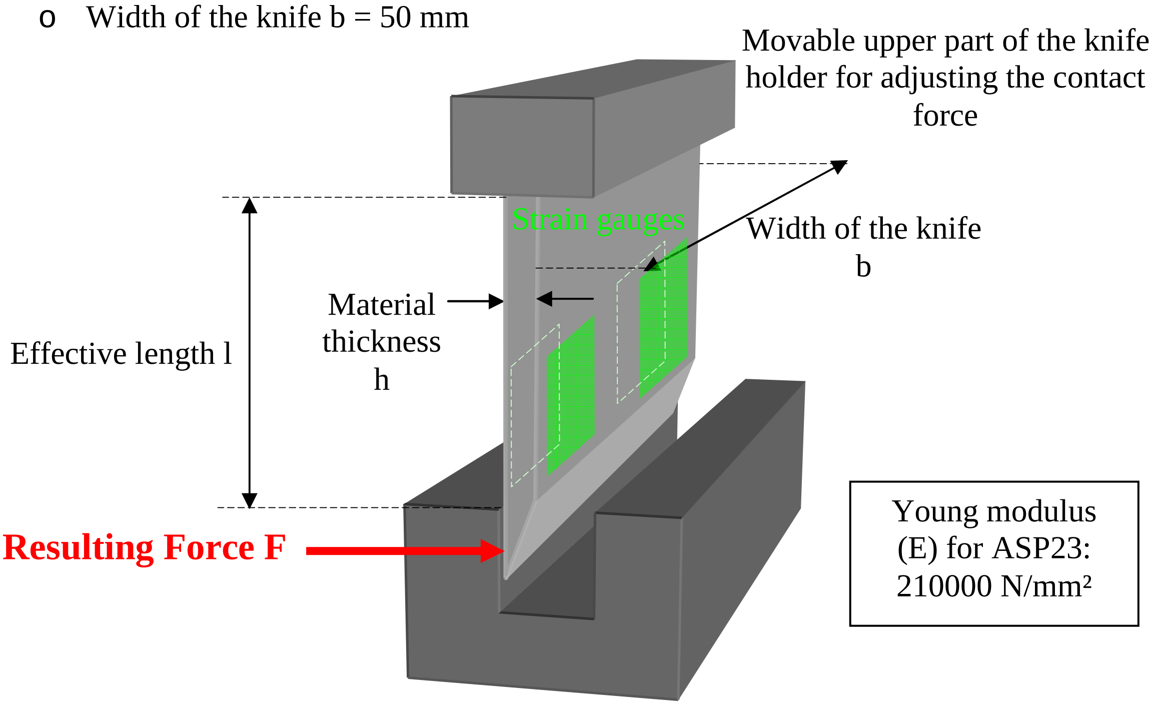


Figure 3.3-9: Arrangement to calculate the contact force

The basic formulas used to explain the mechanical approach are listed in the following:

The bending stress (σ_b) is calculated on the basis of the obtained elongation (5 µm/m) when the loading is evenly distributed between both full bridge circuits (see *Figure* 3.3-8):

$$\sigma_b = E \times \varepsilon = 210000 \frac{N}{mm^2} \times 5 \times 10^{-6} = 1{,}05 \frac{N}{mm^2}$$

Moment of inertia (I_b):

$$I_b = b \times \frac{h^3}{12} = 50mm \times \frac{2^3 mm^3}{12} = 33{,}33mm^4$$

Bending moment (M_b):

$$M_b = \frac{\sigma_b \times I_b \times 2}{h} = \frac{1{,}05\,\frac{N}{mm^2} \times 33{,}33mm^4 \times 2}{2mm} = 35Nmm$$

Force (F):

$$F = \frac{M_b}{l} = \frac{35Nmm}{20mm} = 1{,}75N$$

The resulting contact force between the tip of the upper blade and the top edge of the lower blade amounts to 1,75 N.

3.3.4 Initial position of the upper knife

For the first tests the bottommost knife point in the initial position was adjusted 1,5 mm above the upper edge of the channel (see *Figure* 3.3-10). Primary trials pointed out the limitation for this configuration. For every measurement the tip of the blade has to pass the upper edge of the channel. By cutting a substrate with a higher thickness, the alignment of the blade during the downward movement can be changed marginally. It can result that the tip of the blade hit on the surface of the channel which lead to damages of the knife.

Because of that, an initial knife position has to be adjusted at which the lowest part of the knife is already penetrated when the cutting action starts. Due to the frictions between the blades, the upper knife is “guided” by the bottom knife and the danger of damages is limited.

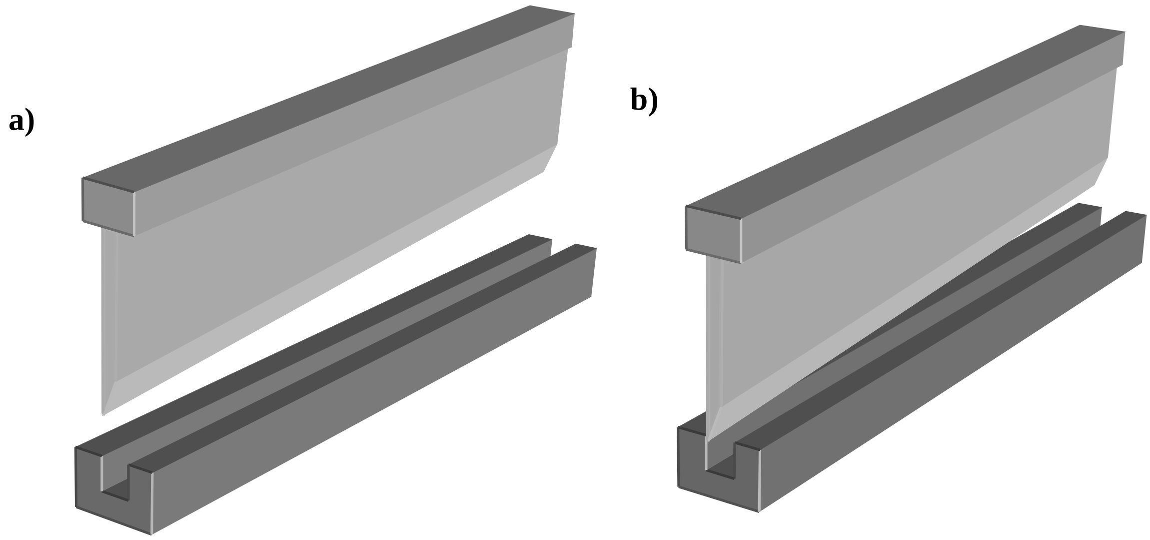


Figure 3.3-10: Initial position of the knife
a) primary
b) current

For the current initial position the bottommost point of the blade penetrates 0,5 mm into the channel (see *Figure* 3.3-10).

3.3.5 Sample preparation

In the beginning it was intended to use a sample size of 90 x 45 mm, to fully use the available area for cutting the sample. As discussed in chapter 3.3.4 it is not possible to set an initial knife position where the tip of the blade is not penetrated partly in the channel. Thus, the sample size has to be adapted according to the current initial knife position. The length of 90 mm remains constant while the width has to be decreased to 20 mm (see *Figure* 3.3-11). The samples to cut have to be prepared in a way to perform a cutting action in machine direction as well as in cross direction. As already discussed in chapter 2.1, long cutting means a separation of the paper parallel to the main fibre direction and cross cutting a separation of the paper perpendicular to the main fibre direction (see *Figure* 3.3-12).

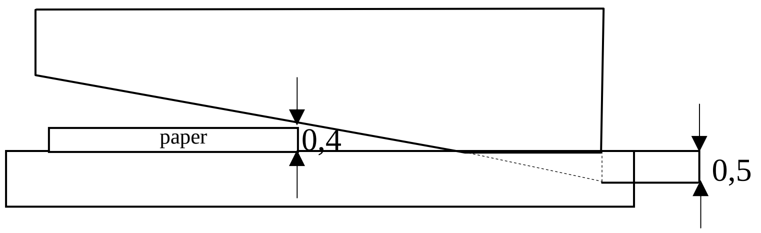


Figure 3.3-11: Reduced sample size

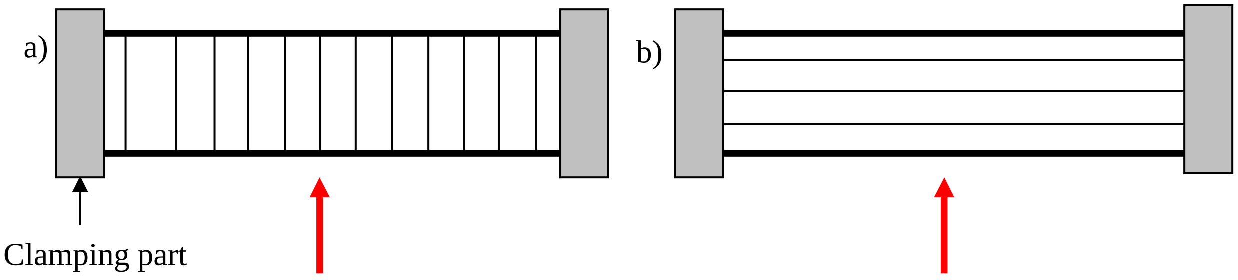


Figure 3.3-12: a) Cutting action in machine direction; b) Cutting action cross direction

The sample is put tautly in the fixture and is clamped on both sides.

3.4 Implementation of the test Method

After installing the knife properly and specifying the basic settings, first measurements were carried out.

3.4.1 First results

The aim of the first trials was to see a general trend in a typical force / path diagram which results from a cutting of three sheets of a standardized paper (IGT 404.009.025 Ka APCO 2005). The basis weight of this paper is 145 g/m², so for three sheets cut simultaneously the overall basis weight of the substrate to cut is 435 g/m².

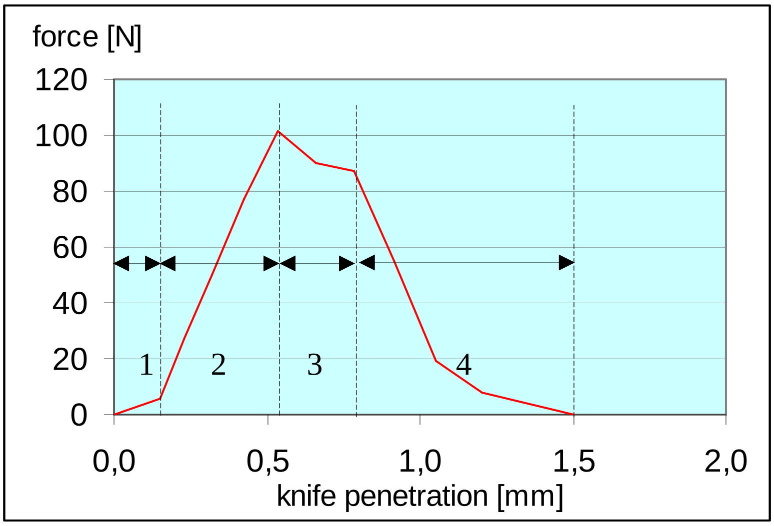


Figure 3.4-1: Shape of a force / path diagram

Based on the results shown in *Figure* 3.4-1 the processes during a cutting action can be explained. By considering the curve, several phases become visible:

1. Due to the short distance between the knife and the paper surface, the knife touches the surface of the paper immediately and the cutting force starts to increase.
2. The second phase is a combination of compressing the paper layers up to their minimum void volumes and the bending of the paper layers into the channel because of the knife load. The maximum peak represents the force which is necessary to cut the sheets. At this point the real cutting action starts.
3. After the compression phase, the force reaches a constant state while cutting the paper stack with a uniform thickness.
4. If the cut is almost completed, the knife passes out of the paper stack. Therefore, the force decreases with decreasing thickness of the remaining substrate.

3.4.2 Methods to analyze the results

To allow a clear statement about the processes during the cutting action the results are analyzed using several methods. By means of MATLAB®, a software tool was designed to determine the most important parameters of the recorded force / path diagram. Besides that, the cutting quality of the cut samples is investigated with a microscope.

3.4.2.1 MATLAB analysis tool

The corresponding software to the Zwick® material testing machine offers the possibilty to export the recorded data for a further analysis. The data are read into a Matlab programm, where an algorithm calculates the results:

a) Maximum force [N] needed to perform the cutting action (see *Figure* 3.4-2): Variations in force are expected when cutting substrates with different compositions regarding raw materials. In addition, differences are expected when cutting the paper in different directions (long vs. cross cut).

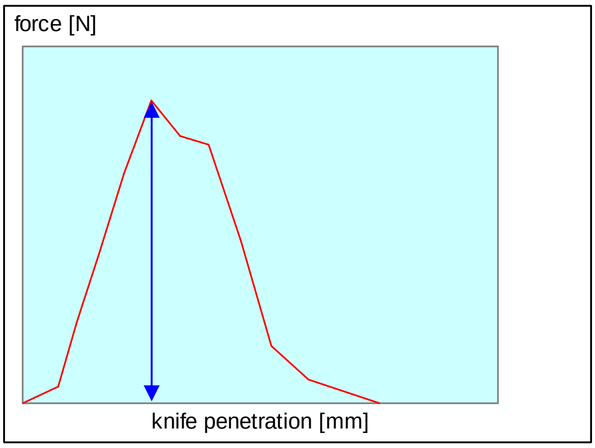


Figure 3.4-2: Maximum force

b) Specific Work [mJ] (see *Figure* 3.4-3): The specific work needed to cut a substrate is defined as the area below the curve. The mathematical approach for the specific work is the integral of the curve with the limitations s1 and s2:

$$W = \int_{s1}^{s2} F(s)ds$$

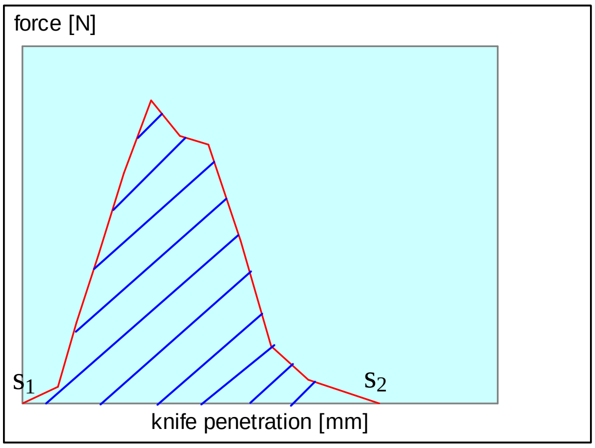


Figure 3.4-3: Specific work (energy)

c) Slope of the tangent during the compression phase [N/mm] (see *Figure* 3.4-4): The slope of the curve, before the real cutting action starts, is an important parameter to determine the resistance of the paper against knife penetration. To avoid that the bending of the paper, caused by the width of the channel, influences the result, the calculation starts when a maximum force of 25 N is achieved.

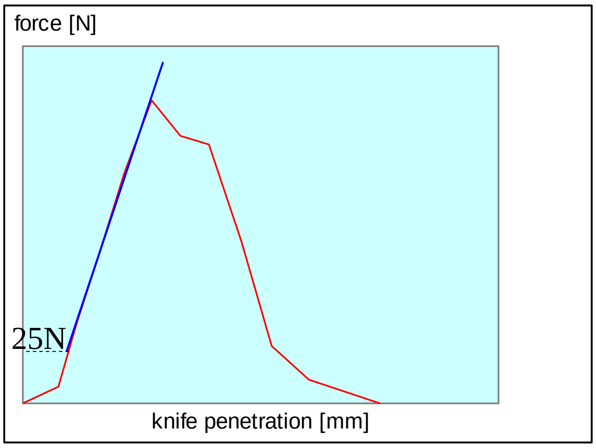


Figure 3.4-4: Slope of the tangent during the compression phase

3.4.2.2 Quality of the cut sample

The parameters mentioned above are important to compare several papers cut by the Zwick® material testing machine. An additional aspect to study is the relationship between the cutting quality at the sheeter and the resulting edge quality obtained with the Zwick®.

For the first trials different paper samples were cut at the Zwick®, to investigate the cutting quality by means of a microscope. These tests delivered good results for the raggedness of the edges for all samples without appreciable differences. It was not possible to obtain the same raggedness at the Zwick® than at the sheeter (see *Table* 3.4-1). The same phenomenon was obtained regarding the fibre pull issue. An explanation for this phenomenon is that the cutting process at the Zwick® is more stable compared to the cutting process at the sheeter. At the Zwick® the substrate to cut is static and fixed on both sides by clamping parts. An additional aspect is the perfect knife quality at the Zwick® which in fact also increases the cutting quality.

However, variations in the number of cracks were noticed between the samples cut at the Zwick®. Therefore, the number of cracks is used as a parameter to draw comparisons between the cutting quality from the sheeter with the cutting quality from the Zwick®.

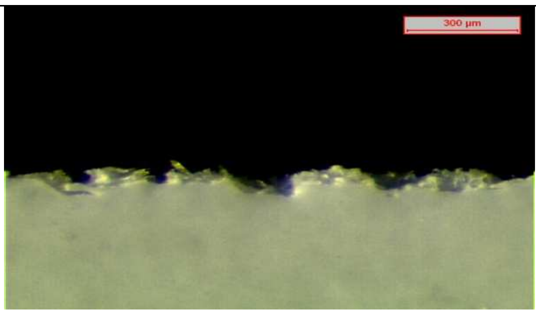
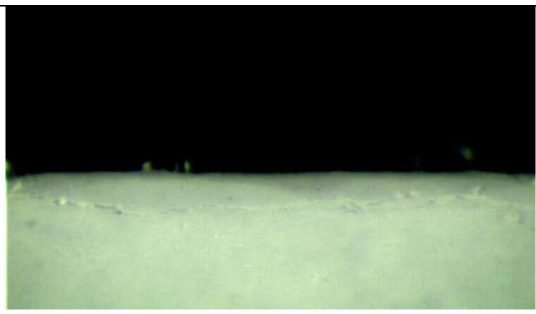
Cutting edge obtained at the sheeter	Cutting edge obtained at the Zwick®
	

Table 3.4-1: Comparison of the obtained cutting qualities of both systems

3.4.3 Reproducibility

The term reproducibility stands for the accordance of single measurements, when all the parameters which influence the measurement are kept constant.

To check the reliability of the system, a measurement series was performed to ensure that the single measurements do not differ too much from each other when cutting the same paper. For this reason a standardized paper (APCO II / II) with a basis weight of 145 g/m² is used to execute a statistical analysis regarding the maximum force needed, the specific work and the slope of the tangent during the compression phase. The test series, which consists of ten measurements, is subject to an analysis regarding its standard deviation and coefficient variation.

Paper is subjected to a higher elongation in cross direction than in machine direction. This fact influences also the behavior of the paper during cutting. During a cutting action in the machine direction (long cut), the paper is separated parallel to the main fibre direction, in contrast a cross cutting action happens perpendicular to the main fibre direction. To avoid that the stretchability of the paper in cross direction leads to an increased variation in cutting force, specific work and slope, the paper is just cut in cross direction for this application.

For a visual assessment the curves of the single measurement are put on top of each other (see *Figure* 3.4-5):

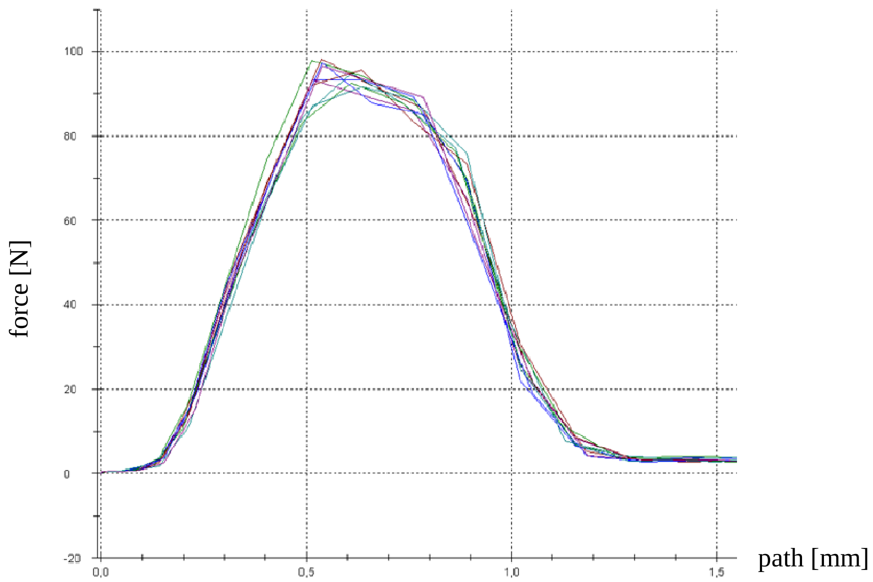


Figure 3.4-5: Reproducibility of the system

An investigation of the visual assessment of the curves in more detail indicates an important fact. Curves with a higher peak at the end of the compression phase show a continuous decrease when the knife passes out of the paper stack. On the other hand, curves with a lower maximum force show a break in the off-peak part of the curve (see *Figure* 3.4-6):

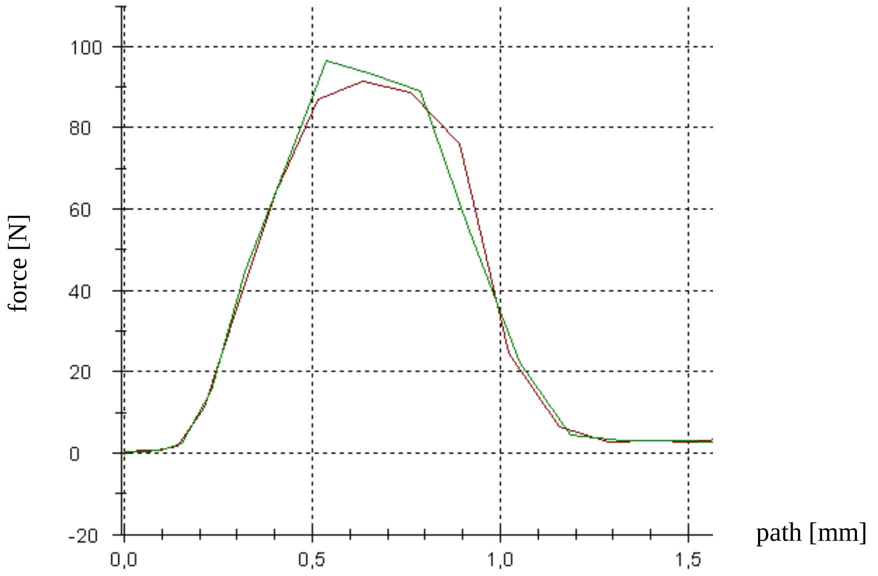


Figure 3.4-6: Different shape of the curves in terms of reproducibility

An explanation for this phenomenon is that the load cell of the Zwick® transmits a different amount of value pairs (x, y) for each curve.

In addition, there is an adjustable parameter at the Zwick®, the averaging time which defines the resolution of the curve. The single measurements within this time interval are added up and the average is calculated. The possible settings for the averaging time are in the range of 2 to 500 ms. To ensure an optimal resolution the averaging time is set to 2 ms. The red frame in *Figure* 3.4-7 presents the averaging time and the single measurements are indicated by blue bars. The frame is shifted continuously along the x-axis, for every position of the frame the average is calculated.

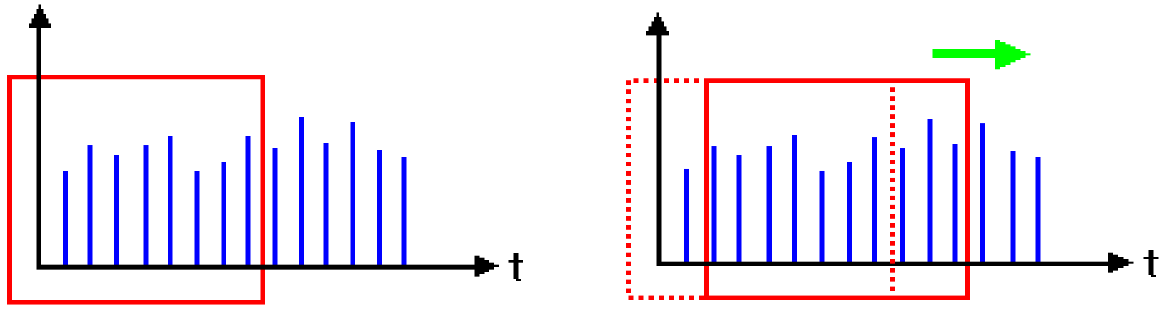


Figure 3.4-7: Averaging time

Due to the combination of the facts that the number of value pairs (x,y) is varying and that the time interval for the averaging time is still constant the curves can appear in different shapes, although the substrates to cut have identical properties.

The results of the measurements are listed in *Table* 3.4-2:

Crosscut			
measurement	Fmax [N]	spec, work [mJ]	gain [N/mm]
1	98,351	504,3372	316,1667
2	96,5346	488,502	323,5201
3	97,9337	516,1504	309,1876
4	93,3326	498,5422	319,8197
5	94,7233	495,7715	273,5356
6	93,3224	494,0423	319,0816
7	95,7058	509,5702	302,4847
8	92,6341	492,3048	284,6752
9	97,3458	483,5345	296,7407
10	91,5431	484,2127	284,3802
µ	95,14	496,70	302,96
s	2,39	10,69	17,53
cv	2,51	2,15	5,78

Table 3.4-2: Reproducibility

The statistical analysis regarding standard deviation and coefficient variation shows good results for the cutting force and the specific work. Greater deviations can be observed for the slope of the tangent during the compression phase. The deviation is caused by the same phenomenon as mentioned above. An eventual break in the curve in the compression phase has a greater influence on the slope of the curve than on the maximum force and the specific work.

3.4.4 Influencing paper parameters when cutting with the Zwick®

Next to the test conditions, the paper parameters play a major role regarding cutting. As already mentioned in the last topics, the direction of cutting (long cut vs. cross cut) has a significant influence on the results. Therefore, a test series has been carried out to show the effect of the fibre orientation on cutting.

The impact of the overall basis weight on cutting is also discussed in the following part.

3.4.4.1 Cutting direction

To investigate the impact of the fibre orientation on cutting, samples of the APCO II / II paper are prepared in a way, that cutting actions are performed in different directions to the main fibre orientation. Identically to the *30° method*[8], the angle of the samples increases in 30° steps starting from the main fibre direction (see *Figure* 3.4-8).

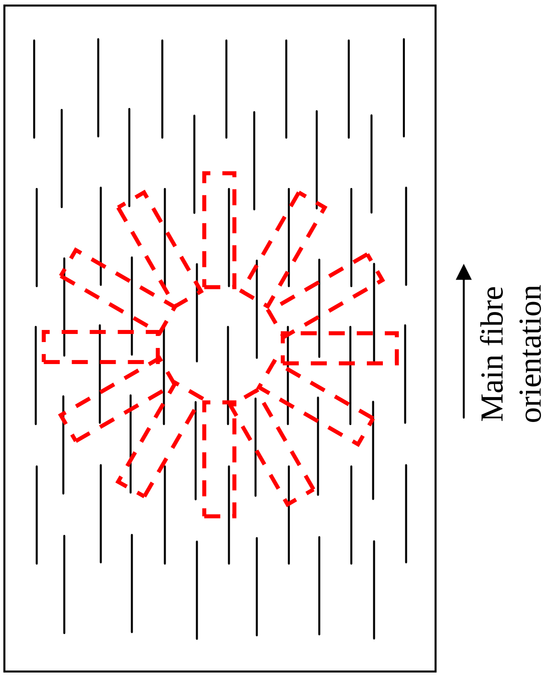


Figure 3.4-8: Sample preparation for determining the impact of the fibre orientation on cutting

Figure 3.4-9 represents the results obtained regarding the cutting force:

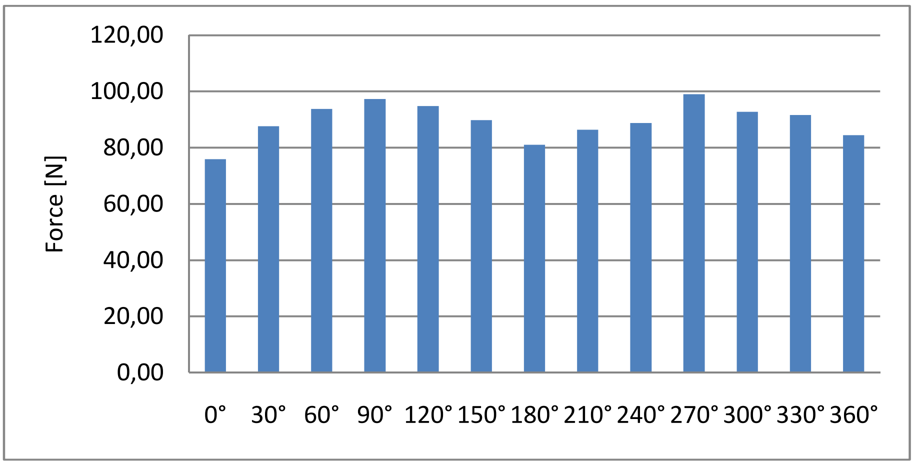


Figure 3.4-9: Force progression when cutting in different directions

The angles 0°, 180° and 360° represent a long cut whereas 90° and 270° are cross cuts. It becomes obvious that cross cutting requires higher cutting forces than long cutting. In cross cutting, every fibre which is coming in contact with the tip of the blade, is cut. Whilst at long cutting the knife penetrates primarily in between the fibres. Additionally, the fibres are

[8] Mechanical method to determine the mean fibre orientation by using a tensile testing device

bending away if the contact surface between the blade and the fibre is not big enough. Therefore the fibre network is torn apart instead of being cut.

The increased force when cutting in cross direction also affects the amount of specific work required (see *Figure* 3.4-10). The width of the curve in the force / path diagram is still the same for the long and the cross cut. The only difference is the rate of the force required, which has an impact on the size of the area below the curve.

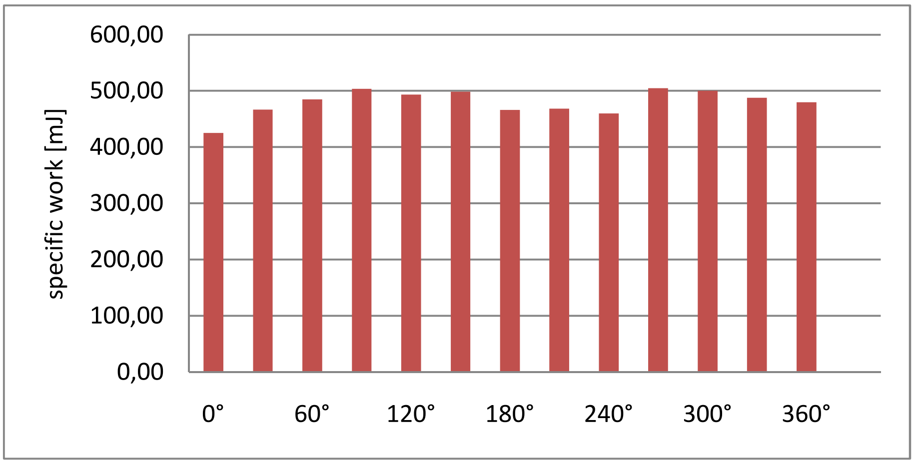


Figure 3.4-10: Progression of the specific work

As already seen in chapter 3.4.3, the results for the slope in the compression phase are not well defined. Similar observations can be made when cutting in different directions. The slope of the tangent follows only partly the orientation of the fibres (see *Figure* 3.4-11).

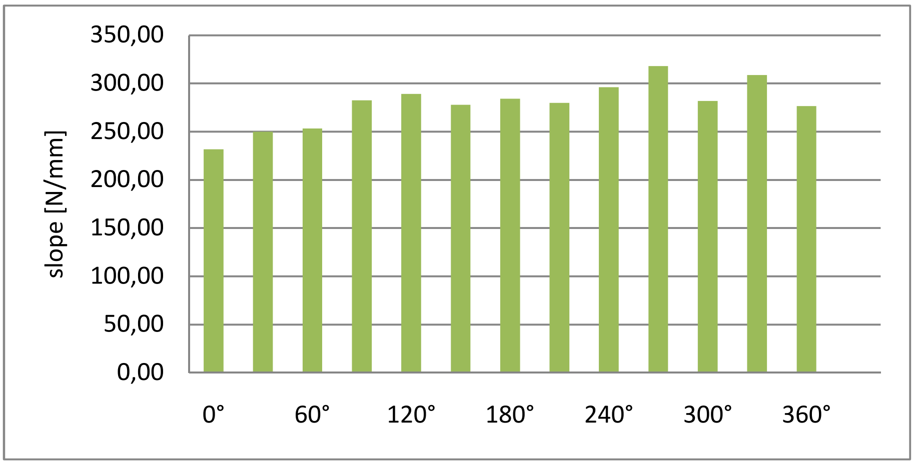


Figure 3.4-11: Slope of the curve when cutting in different directions

3.4.4.2 Basis weight

To determine the influence of the basis weight on the parameters maximum force, specific work and slope of the tangent during the compression phase, APCO II / II paper is cut by putting a different amount of layers on top of each other. By cutting a single layer, two and three layers at the same time, different basis weights are simulated. The investigation regarding the basis weight is carried out for long and for cross cutting. The maximum force, specific work and the slope of the tangent in the compression phase are discussed in the following part.

For this investigation, the slope of the tangent in the compression phase has to be discussed first. The reason for this is that the results for the maximum force and the specific work can be derived from the observations made with the slope (see *Figure* 3.4-12).

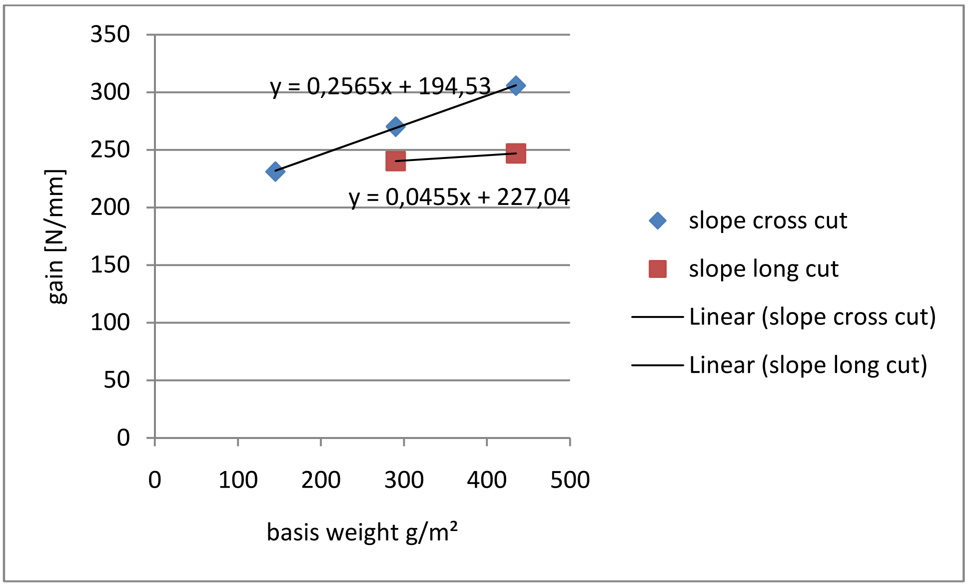


Figure 3.4-12: Slope of the tangent of the compression phase for long and cross cutting for different basis weights

The slope is calculated at a force > 25N. The maximum force for the long cut at 145 g/m² is 24,89 N. Therefore, it is not possible to calculate a gain for this measurement.

Both lines are tending upwards when increasing the basis weights. By considering the equations for the linear regression for both lines more in detail, a difference in the slopes is present. The incline for the cross cut is much more distinctive than the incline for the long cut. The run of the lines is explained by the difference in the expansion behavior in machine direction and cross direction.

The distinctive elongation behavior of paper in cross direction enables the knife to penetrate much easier into the paper when cutting in long direction. Indeed, the resistance for knife penetration into the paper raises when increasing the basis weight for both directions, but the increase is greater when cutting in cross direction.

Figure 3.4-13 shows the result for the cutting force needed.

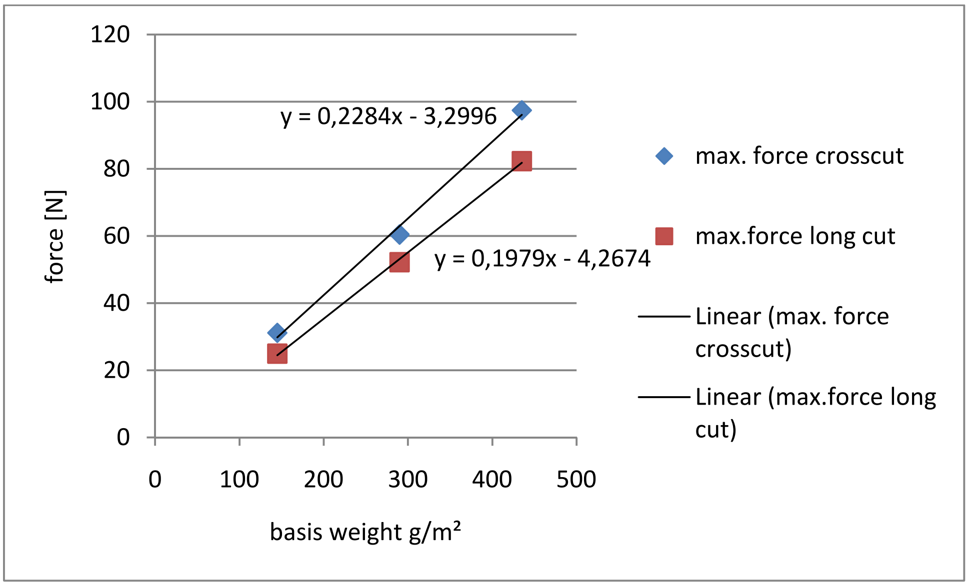


Figure 3.4-13: Force progression for long and cross cutting for different basis weights

Force increase and basis weight increase show a linear correlation. If the basis weight is doubled also the force is doubled.

Similar to the observations made with the slope of the tangent during the compression phase, the slopes of the lines are different, even if the difference is not present in that large extent.

As outlined above, the impact on the resistance against knife penetration, when increasing the basis weight, is higher for cross cutting. Thus, the maximum force required increases to a larger extent for cross cutting than for long cutting.

The same is true for the specific work which is necessary to perform the cutting action. For the sake of completeness, the evolution of the specific work, when increasing the basis weight is shown in *Figure* 3.4-14.

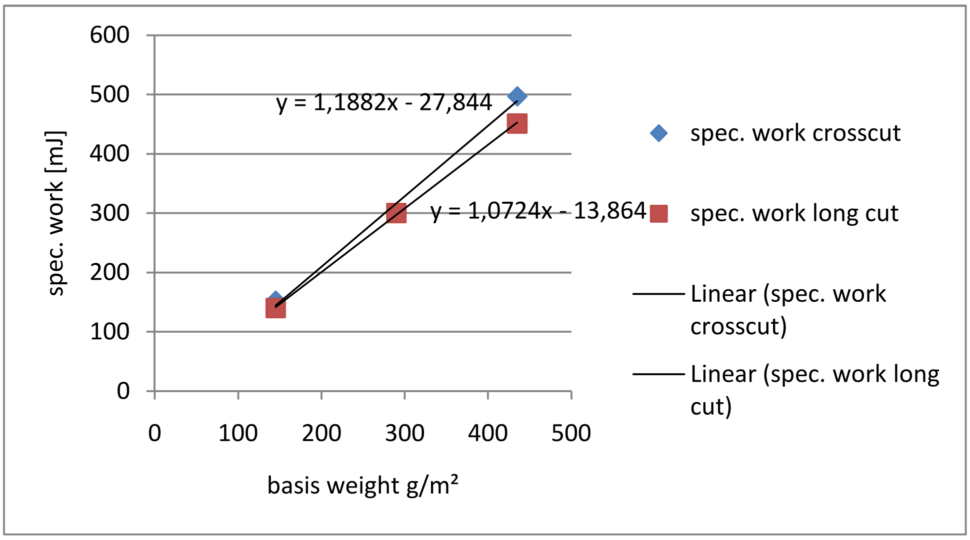


Figure 3.4-14: Progression of the specific work for long and cross cutting for different basis weights

Conclusion regarding the influencing paper parameters:

In chapter 3.4.4.1 it was shown that the fibre orientation has a huge impact on the cutting parameters.

When cutting a single sheet in several directions the development of the force follows the orientation of the fibres. A cut perpendicular to the main fibre direction requires the highest force because the fibres cannot bend away from the tip of the blade. Therefore, it is obvious that the amount of single fibres to cut is one factor which determines the force required.

On the other hand the fibre orientation correlates linearly with the elongation behavior of the papers. A distinctive elongation behavior of papers enables the knife to penetrate easier into the fibre matrix. At cross cutting, the knife has to penetrate at right angles to the main fibre direction. Hence, the elongation in machine direction which is normally lower compared to cross direction becomes important. This results in a greater exertion of force.

In chapter 3.4.4.2 it is shown that an increase of the basis weight (in combination with the fibre orientation) influences the cutting parameters to a great extent. Next to the higher amount of fibres to cut, the rubbing between the knife and the paper increases due to the bigger cross section surface of the cutting edge increases.

4 Comparison of the cutting quality at the sheeter and at the Zwick®

In this chapter the relationship between the cutting quality at the sheeter and the cutting quality achieved with the Zwick® cutting device is studied. As mentioned in chapter 3.4.2.2 only a comparison of the cracks in the coating layer is possible. In a previous work within Sappi Fine Paper Europe, the negative impact of the cracks in the coating layer around the cutting edge was proven. The observations made during a print trial are outlined in the following chapter.

4.1 Impact of the cracks in the coating layer on the offset printing process

The importance of the cracks in the coating layer became already visible in chapter 2.3, where the quality of the printed samples is presented. Coating particles are generated during the cutting process, some of them are released and lie on the paper surface and some will stay partly linked to the paper (cracks). Sappi Fine Paper Europe has run commercial printing tests with several pallets presenting different cutting quality to validate this theory. In *Figure* 4.1-1 the printing quality and the number of cracks have been plotted.

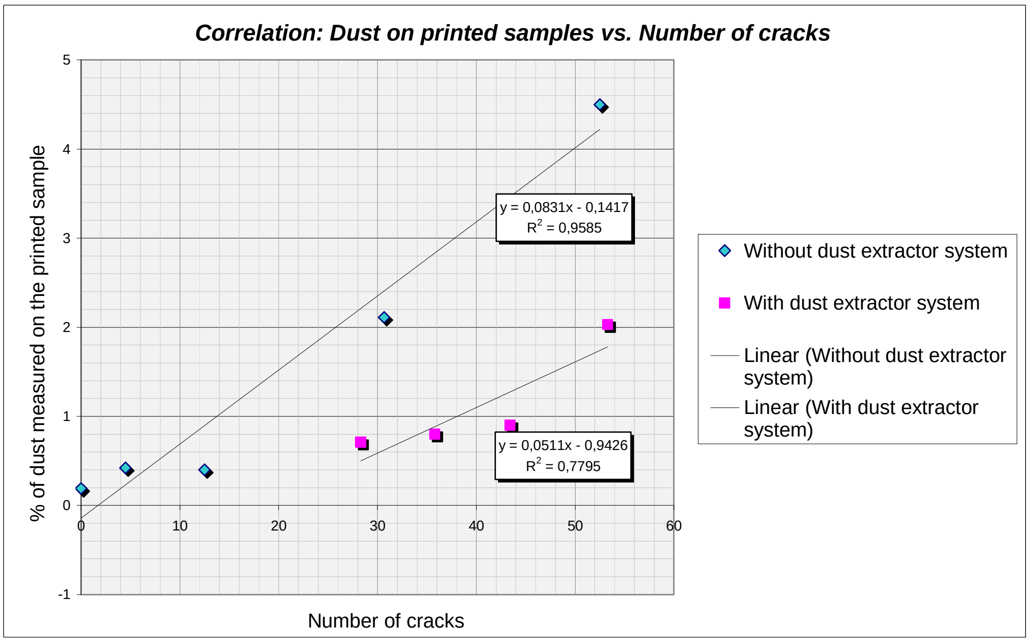


Figure 4.1-1: Correlation between the number of cracks and the printing quality

The efficiency of the dust extractor system on the sheet cutter also becomes visible. During the cutting process, a lot of dust is removed from the substrate and settle down on the paper surface again. The dust can either be removed by a dust extractor system or remain on the paper surface. Remaining dust particles on the paper will disturb, in addition to the cracks, the printing process.

During cutting at the sheeter, many parameters influence the creation of cracks in the coating layer. Of course, the paper properties play a major role regarding cutting quality, but the machine parameters and the quality of the knives are important factors, too. A poor knife quality leads to irregularities during the cut, which leads to a mechanical destruction of the cutting edge.
A perfect knife quality limits the mechanical destruction of the cutting edge. In this case the cracks are mainly created by the folding action which is acting on the cutting edge during a cut. WILDBERGER [19] states that the magnitude of the compression stress is larger on the internal side as on the external side of the fold. Due to this fact, a link between the cracks of both systems which are mainly created by folding is investigated.

4.2 Relationship between long cutting at the sheeter and long cutting at the Zwick®

The configuration of the slitting unit at the sheeter is similar to the construction of the cutting unit of the Zwick®. By means of *Figure* 4.2-1, the comparison between both mechanisms is explained in more detail.

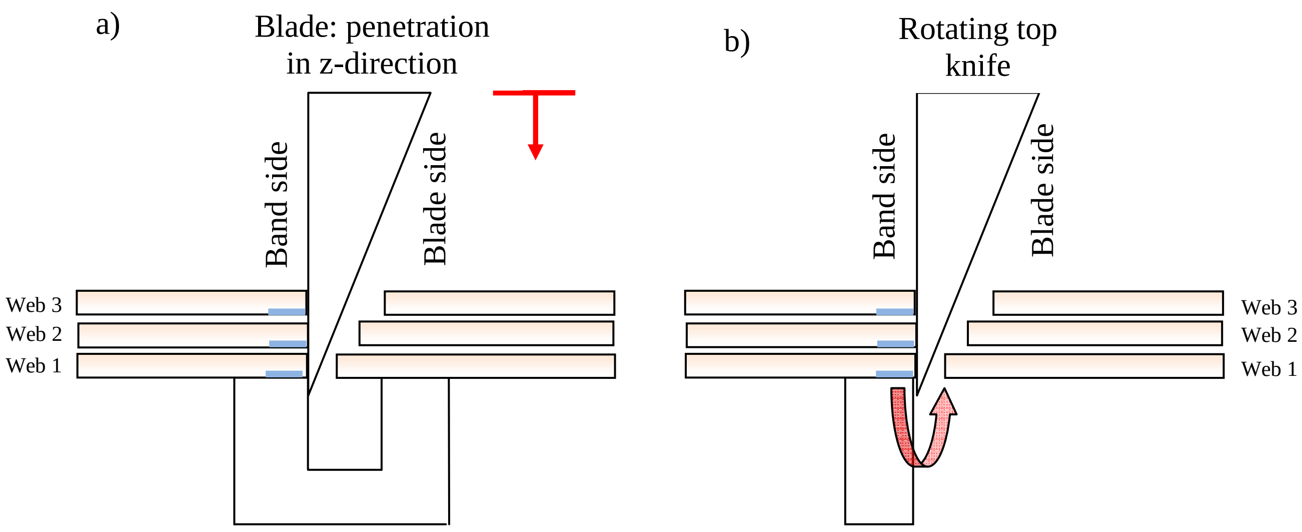


Figure 4.2-1: Long cut - Comparison between the cutting mechanisms - a) configuration at the Zwick® - b) configuration at the slitting unit

Cutting in parallel to the main fibre orientation in case a) is achieved by the downward movement of the blade. Due to the cutting angle along the tip of the blade, the web is not cut in one moment. The progressive penetration of the knife into the paper, caused by the cutting angle, simulates the running web in a slitting unit.

On the blade side the sheets are free to deflect and no folding action is performed. This is true for both systems, for the sheeter and for the Zwick®. For this reason the blade side is not taken into account for a comparison of the two different cutting mechanisms.

In both cases, the web is slightly folded on the band side during the cut and the internal fold is marked by blue bars. Sheet number 3 is exposed to the highest folding action and presents the highest amount of cracks at the inner fold. Sheet number 2 is folded to a smaller extent. Therefore, it presents a better cutting quality than sheet number 3. Sheet number 1 is not folded anymore and shows no irregularities in terms of cracking. For the relationship between the number of cracks created by the slitting unit and the number of cracks caused by the Zwick®, the results for the internal fold are compared.

4.3 Relationship between cross cutting at the sheeter and cross cutting at the Zwick®

Although the similarities between the configuration at the cross cutter and the cutting unit at the Zwick® are not obvious at first view, there is still an approach to compare them.

Because of the fact that the bevel angle for cross cutting knives amounts to 85°, the cross knife provides a surface where the paper is supported during the cut. The same configuration, where one side of the paper is supported by the top edge of the channel, is given at the Zwick®. Due to the helix angle at the cross knife and the cutting angle at the Zwick®, the cutting stroke is moving from side to side.

The basic concept to match the sheeter with the Zwick® and the comparable edges of the paper are presented in *Figure* 4.3-1.

In contrast to the slitting unit where a maximum of three sheets is cut simultaneously (twin slitting system), the cross knife at the sheeter has to cut up to seven sheets in one moment. For the comparison between both systems, the three top layers at the sheeter (Web 6, Web 5 and Web 4) are not taken into consideration.

Regarding the cutting quality, the same aspects become important for the cross cut than for the long cut. The trailing edge is not considered because there is no supporting area to perform a folding action. The sheets are free to deflect and no folding is obtained.

The leading edge is supported during the cut in both systems, therefore, cracks are only created at the inner fold of the sheets. For a comparison of both mechanisms the numbers of cracks at the inner fold of the leading edges are compared.

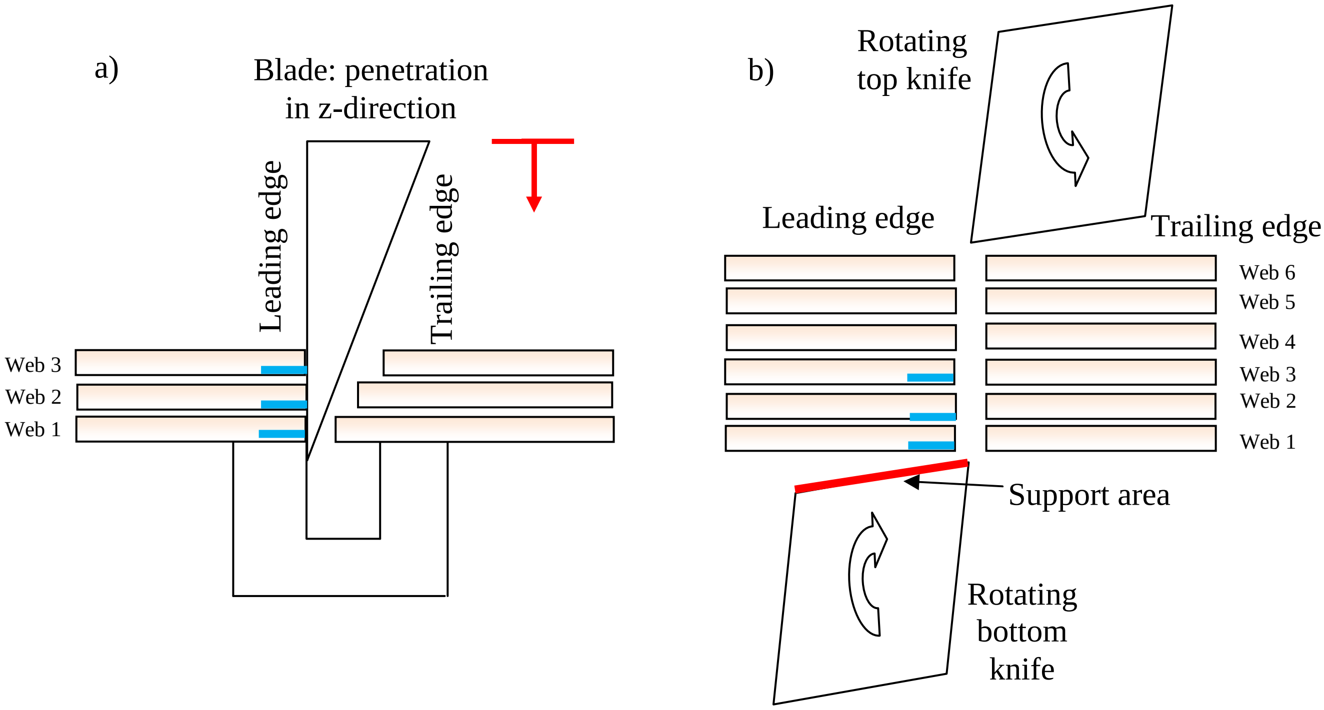


Figure 4.3-1: Cross cut - Comparison between the cutting mechanisms - a) configuration at the Zwick® - b) configuration at the cross cutter

4.4 Correlation of the number of cracks between the sheeter and the Zwick®

To check whether there is a correlation between the cracks created at the sheeter and the cracks generated at the Zwick®, four different papers with a basis weight of 130 / 135 g/m² were cut at the sheeter. The number of cracks per 5 cm was investigated, for both, the long cut and the cross cut. To cover the range of papers produced within SFPE, two different gloss grades and two different matt grades were used for this test. Paper A and paper B represent the gloss grades, paper C and paper D the matt grades.

At the sheeter, based on the test method developed within Sappi, the number of cracks per 5 cm was investigated on the long cut and the cross cut. To avoid the influence from the knife wearing, the papers were cut within one day.

At the Zwick®, the same papers were cut, also in both directions. Because of the reduced sample size for the Zwick®, only an area of 20 mm for the crack analysis is available. As observed in *Table* 4.4-1, more cracks are developed per unit area on the Zwick®:

(cracks/ 2 cm)*2,5 = cracks/ 5 cm.

In *Table* 4.4-1 the results are presented for the cracks created at the sheeter and the cracks generated when cutting with the Zwick®.

		Zwick®				Sheeter			
		Cracks Long cut/2cm		Cracks Crosscut/2cm		Cracks Long cut/5cm		Cracks Crosscut/5cm	
Paper	sheet	Band	Blade	Leading edge	Trailing edge	Band	Blade	Leading edge	Trailing edge
Paper A (gloss)	3	45	33	31	25	65	11	30	57
	2	28	64	14	57	34	22	5	6
	1	0	60	0	41	2	17	0	0
Paper B (gloss)	3	48	28	26	17	70	21	47	55
	2	24	61	18	61	42	13	10	10
	1	0	52	0	36	0	28	0	0
Paper C (matt)	3	37	37	29	9	106	9	20	70
	2	21	85	11	45	39	24	3	14
	1	0	58	0	33	0	63	0	0
Paper D (matt)	3	45	38	23	15	74	12	23	23
	2	25	87	13	39	55	19	5	8
	1	0	56	0	41	0	77	0	0

Table 4.4-1: Results of the crack analysis for the sheeter and for the Zwick®

The interdependence of the columns which are presented in the same color is shown in *Figure* 4.4-1.

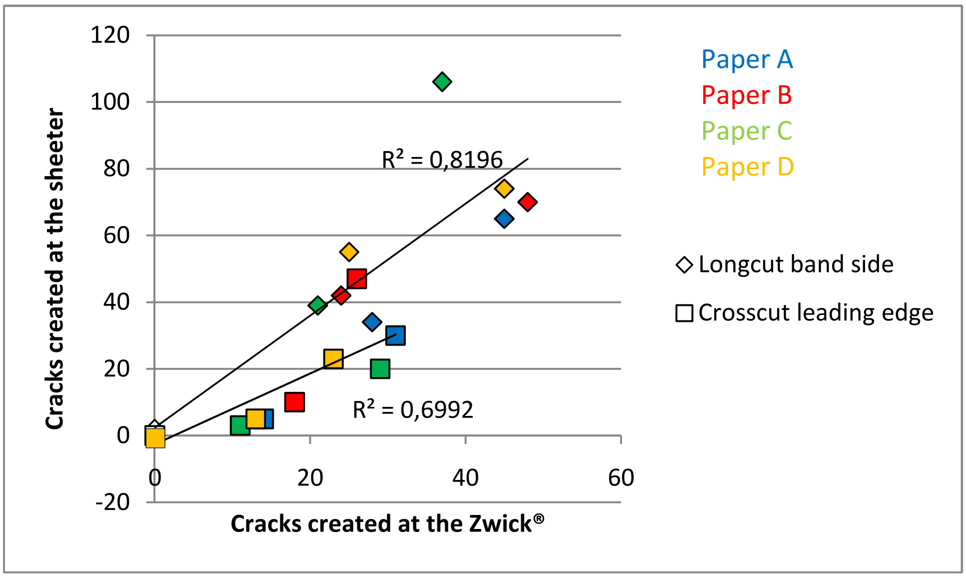


Figure 4.4-1: Correlation between the number of cracks generated at the sheeter and the number of cracks generated by the Zwick®

The resulting R^2 (0,8196) for the comparison between the long cuts of both systems presents a relatively significant correlation. It can be observed that the amount of cracks is highly dependent of the position of the sheet during the cutting process.

The difference in cutting quality can be explained by the fact that sheet number 3 is the first one to be cut. This is true for both systems, for the sheeter and for the Zwick® (for the cross cut as well as for the long cut). Therefore, sheet number 3 is subjected to the highest folding action. Thus, this layer presents the highest amount of cracks in the coating layer. The folding action decreases, with decreasing distance to the bottom knife. Thus, the inner fold of layer number 1 is not subjected to a folding anymore and presents a better quality.

Similar observations can be made regarding the cross cut. The grouping of the cutting quality obtained with the different sheets can also be observed for the cross cut, but only to a smaller extent.

The results of this correlation prove that the cutting mechanisms (sheeter and Zwick®) are comparable for the long cut and for the cross cut. A bad cutting quality for the external web is obtained at the sheeter as well as at the Zwick®. Sheet number 2 present an average quality for both cases. Sheet number 1 presents no irregularities, again, for both systems.

For the papers used, no conclusion can be drawn that a paper which is critical to at the sheeter is also critical to cut at the Zwick®. The paper set which was used for this test was produced within one mill and therefore the paper properties may not present the necessary differences to reach significant difference in cutting quality. To prove that papers with a good cutting quality at the sheeter present a good cutting quality at the Zwick®, a test with completely different papers in terms of cutting quality has to be carried out. To organize a test in such a dimension is very time and cost intensive, because for each paper at least six reels have to be ordered to be able to cut it at the sheeter. Therefore, it was decided that such a test should not be carried out during this thesis work. So the question regarding the correlation of cracks created on the sheet cutters to cracks created when cutting with the Zwick® device still remains open.

5 Analysis of papers produced within Sappi Fine Paper Europe

In this chapter an analysis regarding the cracks in the coating layer which are created during a cutting action at the Zwick® is carried out.

The Zwick® is also ready to use for a statistical analysis to study the impact on the force which is required to perform a cutting action. The idea is to find out which mechanical paper properties are influencing the cutting force. Several mechanical paper properties were measured in the lab to see whether they correlate with the cutting force. The measured data were put in a data base for a further analysis.

To check also the stability of the measurement over time, 44 papers were cut with the Zwick®.

5.1 Papers used for the analysis

In total, 44 different papers were collected from several mills within Sappi Fine Paper Europe. The basis weight of the papers is varying between 115 and 150 g/m². Approximately 15 papers per basis weight are measured. Because of the different manufacturing process of matt and gloss papers and their different behavior during the cutting process, the data base is split in two parts for the analysis.

Every paper was cut with the Zwick® to determine the number of cracks with the microscope. To present the results, an average of the cracks measured on sheets 3, 2 and 1 is calculated.

Additionally, the maximum force which is necessary to perform the cutting actions is recorded.

The specific work is not taken into account for this investigation, because a clear correlation between the results of the force needed and the specific work is noticed. In Figure 5.1-1 the results for the force and the specific work of the paper set to investigate, are plotted.

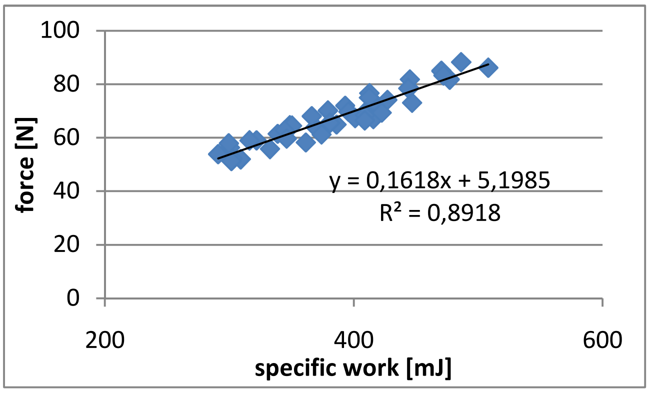


Figure 5.1-1: Correlation between the cutting force and the specific work

Regarding the slope of the tangent in the compression phase, it is decided, to leave it out for this analysis. The reason for this action is the high variation of the results for the slope obtained during the reproducibility test. Due to this variation, no reliable interpretation of possible correlations between the slope and the paper properties is acceptable.

5.2 Mechanical paper properties

To complete the data bank, the mechanical properties of these papers were measured. The aim is, to find out the parameters which are mainly responsible for the results of the obtained cutting forces. Therefore, the following paper parameters are determined:

- the tear resistance in machine and in cross direction (ISO 1974:1990: Determination of tearing resistance - Elmendorf method),
- the thickness (ISO 534 / EN 20.534: Determination of thickness, density and specific volume),
- the breaking force in machine and in cross direction (ISO 1924-2: Paper and board – Determination of tensile properties – Constant rate of elongation method),
- the elongation in machine and in cross direction (ISO 1924-2: Paper and board – Determination of tensile properties – Constant rate of elongation method),
- the Young modulus in machine and in cross direction (ISO 1924-2: Paper and board – Determination of tensile properties – Constant rate of elongation method) and
- the stiffness in machine and cross direction (ISO 5628: Determination of bending stiffness by static methods – general principles)

The obtained values for the mechanical paper properties are available in the *appendix B* (gloss papers) and *appendix C* (matt papers).

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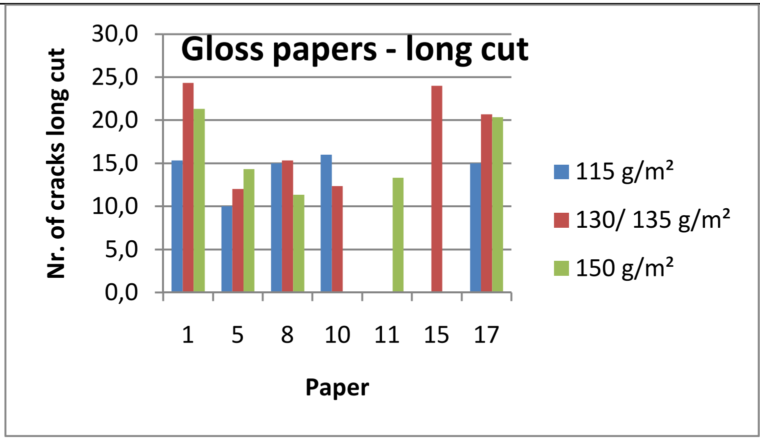
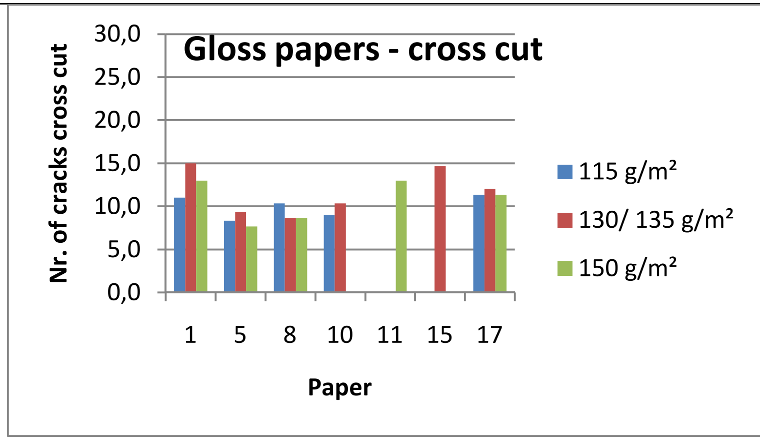
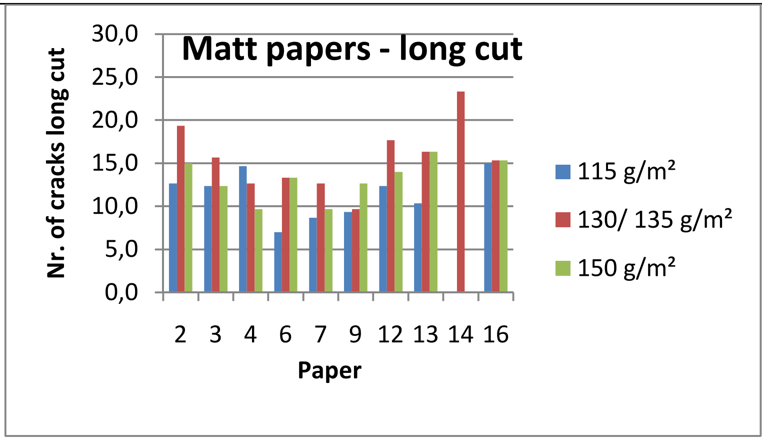
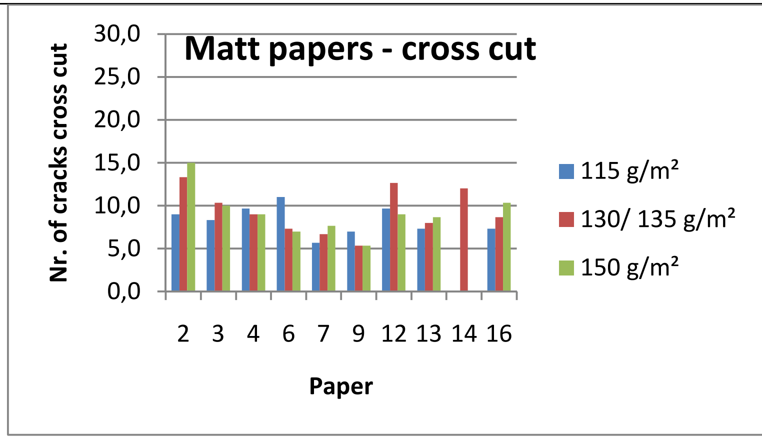
5.3 Analysis of the cracks in the coating layer

The following graphs present the cracks in the coating obtained for the gloss and the matt papers. The papers were cut in long direction and in cross direction to find out the influence of the fibre orientation on the cracks.

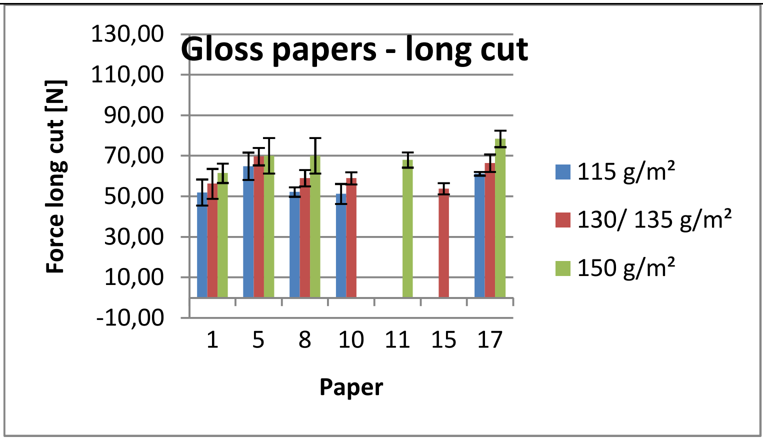
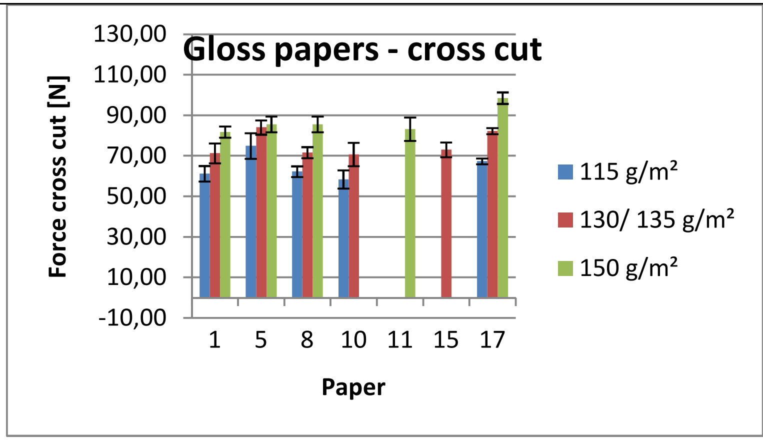
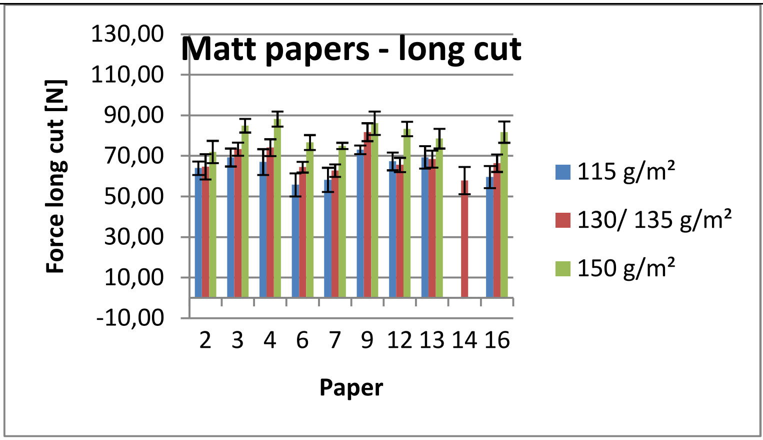
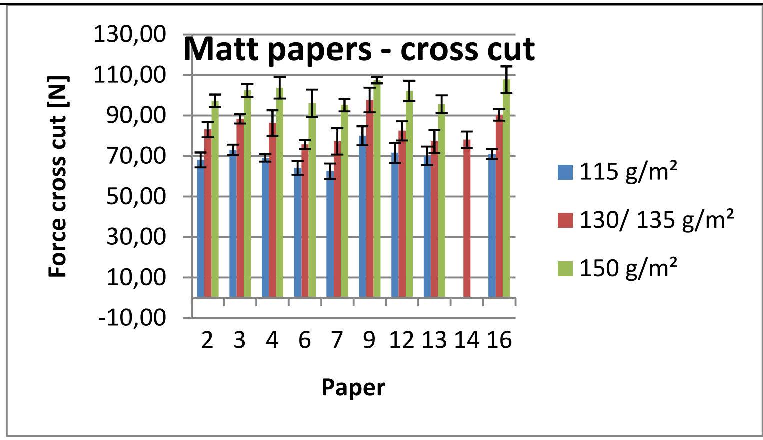
<table>
<tr><th></th><th>Long cut</th><th>Cross cut</th></tr>
<tr><td>Gloss papers</td><td>
</td><td>
</td></tr>
<tr><td>Matt papers</td><td>
</td><td>
</td></tr>
</table>

According to the obtained results the following conclusions can be drawn:

1. More cracks are obtained for the long cut than for the cross cut. This applies for the gloss and for the matt papers. A theory to explain this phenomenon is the higher stiffness of the paper in machine direction. The stiffness in machine direction is effective when cutting in cross direction. Due to the higher stiffness the paper is bending to a lower extent for cross cutting than for long cutting. A high resistance of the paper against bending means less folding of the cutting edges. Therefore the number of cracks obtained for the cross cut is lower compared to the long cut.
2. The papers 1 and 15 from the gloss grades and the papers 2 and 14 for the matt papers are triple coated papers. Especially these papers present an increased amount of cracks. It seems that a higher ratio of coat weight to base paper weight decreases the cutting quality, although an application of coating increases the stiffness of a paper.
3. In general, slightly better results are achieved for the matt papers. This observation can be explained by two theories:
    - Because of the calendaring, the paper bulk is reduced. A loss in volume and a loss in volume means a reduced resistance against bending. As discussed under 1) a reduced bending stiffness leads to an increased number of cracks.
    - Due to calendering the flexibility of the coating layer is reduced. Therefore the coating becomes more brittle and the results are worsened. An uncalendered paper, with a flexible coating layer, is less susceptible for cracking. The ratio of elastic deformations to plastic deformations due to folding is higher for matt papers than for gloss papers.

5.4 Analysis regarding the necessary cutting force

The following graphs present the maximum forces necessary to perform a cut:

<table>
<tr><th></th><th>Long cut</th><th>Cross cut</th></tr>
<tr><td>Gloss papers</td><td>
</td><td>
</td></tr>
<tr><td>Matt papers</td><td>
</td><td>
</td></tr>
</table>

According to the obtained results the following conclusions can be drawn:

1. The results obtained regarding the necessary cutting force confirm the importance of the fibre orientation. The cutting force is always higher for the cross cut than for the long cut. In cross cutting, the fibres are cut perpendicular to the main fibre direction which means that every fibre that contacts the tip of the blade is cut. Whereas for long cutting the knife penetrates mainly in between the fibres. A too small angle between the fibre and blade causes that the fibre is bending away instead of it is being cut.

   The impact of the stiffness becomes also important. When cutting in cross direction the stiffness in machine direction is effective. The paper does not bend too much into the channel when the paper is compressed by the knife in the beginning of the cut. Therefore, the resistance against knife penetration is higher which leads to a higher force maximum.

2. In general, higher forces are obtained for the matt papers than for the gloss papers. This is an indication that the importance of the thickness outweighs the influence of the basis weight. The amount of material to cut for a calendered paper and for an uncalendered paper, with the same basis weight, is still the same. The difference is the higher thickness / higher deformation for the matt grades which leads to a higher friction action between the blade and the paper.

   The decrease in stiffness due to calendering is also an important aspect. The impact of the stiffness is outlined in 1.

3. It is noticeable that cutting forces of the different papers from one paper machine follow the same trends for every basis weight. In other words, a paper with a higher cutting force in the 115 g/m² range, presents also a higher cutting force in the 130 / 135 g/m² range and in the 150 g/m² range.

   If we assume that the papers from one paper machine have a similar architecture, the difference observed in the cutting force might come from the raw material used.

   A second aspect is the similar fibre orientation within paper grades which are produced on the same paper machine. In chapter 3.4.4.1 it has been proven that the cutting force is highly dependent on the fibre orientation.

5.5 Statistical analysis for the cutting force

In the beginning it was intended to carry out a multiple linear regression to analyze the influence of the mechanical paper properties on the cutting force. Due to the fact that the data base has to be split up to treat the gloss and the matt papers separately, the amount of the predictor variables is too high compared to the observations made with the different papers.

Therefore it was decided to construct a correlation matrix, to analyze the noticed correlations. To allow a correlation independent from the influence of the basis weight, for some measurements the indices were calculated. The values of the Elmendorf measurements are converted to the tear index and from the tensile test results the tensile index is calculated.

The correlation matrix uses the Pearson correlation coefficient (r) to show the interdependence of two parameters. That means, for calculating the linear connection (r^2) between the parameters, the values presented in the matrix have to be squared.

To interpret the correlation matrix, a color code has been set up in which the green color represents a good correlation and red colored cell means that there is no correlation between the parameters. In this case, correlations greater ± 0,3 are discussed in the conclusion. A second requirement is that the correlation has to be true for the gloss and for the matt grades. The abbreviations used in the matrix stands for:

- MD – machine direction,
- CD – cross direction,
- LC – long cut,
- CC- cross cut.

Correlation matrices for the gloss and for the matt papers:

	ForceLC	ForceCC	Basis Weight [g/m^2]	Tearing Index MD [mN*m^2/g]	Tearing Index CD [mN*m^2/g]	thickness [mm]	Tensile Index MD [Nm/g]	Tensile Index CD [Nm/g]	Elongation MD [%]	Elongation CD [%]	Emodulus MD [Gpa]	Emodulus CD [Gpa]
ForceLC	1	0,937	0,667	0,660	0,794	0,857	-0,318	-0,034	0,363	0,167	-0,534	-0,524
ForceCC	0,937	1	0,817	0,519	0,703	0,903	-0,448	-0,190	0,182	-0,051	-0,332	-0,300
Basis Weight [g/m^2]	0,667	0,817	1	0,227	0,391	0,920	-0,744	-0,191	0,180	-0,126	-0,252	-0,013
Tearing Index MD [mN*m^2/g]	0,660	0,519	0,227	1	0,801	0,496	0,035	0,500	0,543	0,490	-0,691	-0,675
Tearing Index CD [mN*m^2/g]	0,794	0,703	0,391	0,801	1	0,659	0,014	-0,024	0,289	0,228	-0,517	-0,706
thickness [mm]	0,857	0,903	0,920	0,496	0,659	1	-0,580	-0,093	0,336	0,074	-0,489	-0,317
Tensile Index MD [Nm/g]	-0,318	-0,448	-0,744	0,035	0,014	-0,580	1	0,113	-0,420	-0,125	0,349	-0,070
Tensile Index CD [Nm/g]	-0,034	-0,190	-0,191	0,500	-0,024	-0,093	0,113	1	0,422	0,432	-0,412	-0,080
Elongation MD [%]	0,363	0,182	0,180	0,543	0,289	0,336	-0,420	0,422	1	0,853	-0,916	-0,639
Elongation CD [%]	0,167	-0,051	-0,126	0,490	0,228	0,074	-0,125	0,432	0,853	1	-0,852	-0,714
Emodulus MD [Gpa]	-0,534	-0,332	-0,252	-0,691	-0,517	-0,489	0,349	-0,412	-0,916	-0,852	1	0,745
Emodulus CD [Gpa]	-0,524	-0,300	-0,013	-0,675	-0,706	-0,317	-0,070	-0,080	-0,639	-0,714	0,745	1

Table 5.5-1: Correlation matrix for the gloss papers

	ForceLC	ForceCC	Basis Weight [g/m^2]	Tearing Index MD [mN*m^2/g]	Tearing Index CD [mN*m^2/g]	thickness [mm]	Tensile Index MD [Nm/g]	Tensile Index CD [Nm/g]	Elongation MD [%]	Elongation CD [%]	Emodulus MD [Gpa]	Emodulus CD [Gpa]
ForceLC	1	0,879	0,716	0,444	0,412	0,784	-0,534	-0,110	-0,086	-0,066	-0,456	-0,203
ForceCC	0,879	1	0,910	0,327	0,540	0,938	-0,331	-0,341	-0,053	-0,233	-0,307	-0,203
Basis Weight [g/m^2]	0,716	0,910	1	0,086	0,350	0,944	-0,360	-0,373	0,073	-0,212	-0,284	-0,172
Tearing Index MD [mN*m^2/g]	0,444	0,327	0,086	1	0,784	0,347	0,091	0,338	0,364	0,510	-0,482	-0,458
Tearing Index CD [mN*m^2/g]	0,412	0,540	0,350	0,784	1	0,553	0,355	0,022	0,304	0,235	-0,243	-0,461
thickness [mm]	0,784	0,938	0,944	0,347	0,553	1	-0,270	-0,248	0,209	-0,068	-0,455	-0,349
Tensile Index MD [Nm/g]	-0,534	-0,331	-0,360	0,091	0,355	-0,270	1	0,244	0,283	0,031	0,378	-0,034
Tensile Index CD [Nm/g]	-0,110	-0,341	-0,373	0,338	0,022	-0,248	0,244	1	0,428	0,381	-0,189	0,076
Elongation MD [%]	-0,086	-0,053	0,073	0,364	0,304	0,209	0,283	0,428	1	0,706	-0,603	-0,601
Elongation CD [%]	-0,066	-0,233	-0,212	0,510	0,235	-0,068	0,031	0,381	0,706	1	-0,514	-0,580
Emodulus MD [Gpa]	-0,456	-0,307	-0,284	-0,482	-0,243	-0,455	0,378	-0,189	-0,603	-0,514	1	0,753
Emodulus CD [Gpa]	-0,203	-0,203	-0,172	-0,458	-0,461	-0,349	-0,034	0,076	-0,601	-0,580	0,753	1

Table 5.5-2: Correlation matrix for the matt papers

Regarding the force which is necessary to perform a cut the following conclusions can be drawn:

- The importance of thickness and basis weight become visible again. These parameters were already discussed in chapter 5.4.
- A correlation between the *tearing index* and the maximum force needed is noticeable. A better correlation is obtained for the gloss papers than for the matt papers. The reason behind this could be that there is a difference in the number of measurements for the gloss and for the matt papers. The number of measured points for the gloss papers is only half of the measured points for the matt papers.

  For a comparison between the maximum force for the long cut and the tear index, the tear index in machine direction is used. The reason for taking this action is that for long cutting and tearing in machine direction, the paper is separated along the fibre direction. For the cross cut the tearing in cross direction is used to show up similarities. A theory to explain this correlation is that the paper is torn in front of the cut point. Due to the certain thickness of the tip of the blade (especially when using higher bevel angles) the external sheets of the stack cannot resist the stresses which are induced by the knife and the paper is torn before the knife arrives at the cut point.
- The slightly negative correlation between the cutting force for the cross cut and the tensile index in machine direction is explained by the theory that the tensile index is partly determined by the fibre orientation and the kind of fibres used. The influence of the fibre orientation is discussed in chapter 3.4.4.1. The influence of the fibre material used is explained by the theory that softwood fibres present a lower hardness compared to the hardwood fibres. A harder fibre leads to an increased cutting resistance. On the other hand, papers which consist of softwood fibres usually present higher strength properties (the production process of the pulp – sulfate or sulfite - is not considered). From this it follows that papers with a higher tensile index require lower cutting forces. No correlation between the cutting force for the long cut and the tensile index in cross direction is observable. This is due the fact that the knife penetrates mainly in between the fibres when cutting in long direction. The influence of the fibre hardness does not become important in this case.

  Another aspect is that the amount of fibres per unit area of a sheet is much higher when using hardwood fibres instead of softwood fibres. Again, papers made with softwood fibres usually present higher strength properties. But due to the less amount of fibres to cut, the required cutting force is lower.

- According to the obtained results the elongation does not influence the cutting force. This is a contradiction to the constructed theory in chapter 3.4.4.1 that a distinctive elongation behavior of papers eases the knife to penetrate into the fibre matrix.
- The E-modulus is a sign of the elasticity of a material. When performing a cutting test with the Zwick® device, the material is compressed in a first step. During this compression phase the force increases in a linear way. An elastic material (small E-modulus) will be able to deform to a greater extent than a non elastic material (high E-modulus). Therefore, an elastic material requires a higher forces to be cut.

5.6 Stability of the system over time

First trials with Zwick® showed the necessity of a perfect blade alignment. Small deviations in the blade alignment caused high deviations in the cutting force needed. To check the stability of the system over time, paper 1, which was the first paper to test in the test series, was cut again at the end of the series. The aim is to see whether there is a deviation in the cross cutting forces in the beginning of the test series and at the end of the test series. Five measurements in the beginning and five measurements at the end of the test series were carried out:

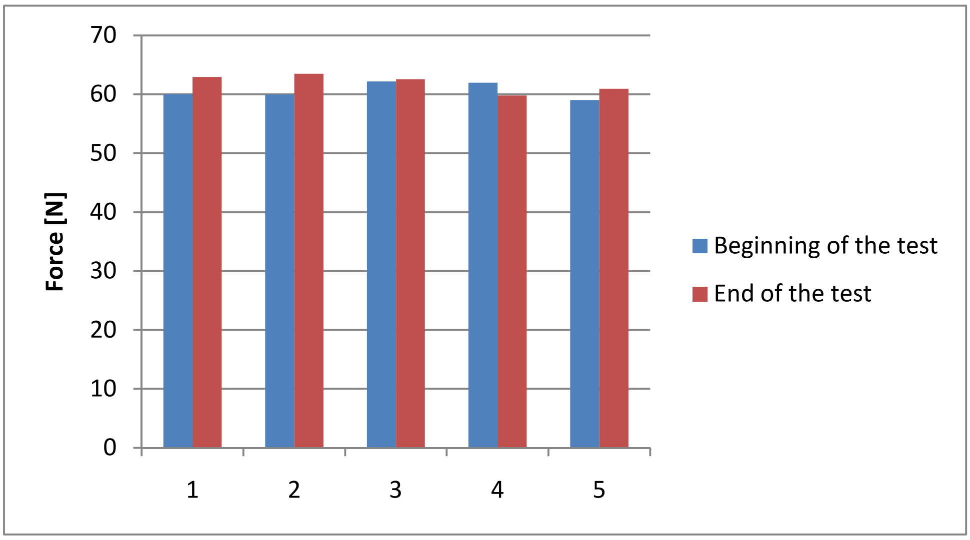


Figure 5.6-1: Evolution of the stability of the system over time

The results in *Figure* 5.6-1 prove that there is no big deviation in the cutting forces for both cases. Slightly higher results regarding the force are obtained for the cutting forces at the end of the test series. This could be due the fact that the blade is already worn to a small extent.

Conclusion of this chapter:

The investigations done in this chapter present reasonable results. It has been proved that the Zwick® is a reliable device to simulate the cutting process in the lab and helps to understand the influences of the paper properties on the cutting parameters (cutting quality and cutting force).

The stability of the measurement over time is also given. The system allowed to perform the complete measurement series without irregularities in terms of instabilities of the knifeholder or blade damages.

6 Outlook

The developed cutting device in the laboratory scale offers a wide range of studies in the future. An investigation regarding the raw materials used for wood free coated papers is possible now:

- The influence of the base paper architecture (stiffness, fibre orientation) is discussed in the thesis. Further research regarding this aspect might be necessary to utilize the properties of different paper parameters to improve the cutting quality.
- On one hand, there is the difference in the available fibres which has to be studied. The impact of hardwood and softwood on the cutting quality is one important aspect which has to be pointed out.
- In the composition of the coating layer it is of utmost importance that the coating is robust against rupturing. The impact of different pigments on the cutting could be determined by means of the new method (if the changes induce are high enough to influence significantly the measurement).

A research work, which includes the aspects mentioned above, is presently carried out within Sappi Fine Paper Europe. At the end, it is intended to find out what can be done to facilitate the cutting process (better cutting quality, higher productivity …).

So far, the developed cutting device is available in the laboratory. To further optimize this device and improve similarities with the sheeter, the following modifications could be made in the future:

- One possibility to improve the functioning of the device is, to install a bottom knife instead of the penetration channel. The sharper bottom knife should intensify the similarities to the sheeter.
- The adjustment of the knife with the strain gauges is a time intensive procedure. For this operation the support of an external institute is necessary. Simplifying this procedure would make the system more user-friendly.

We know that it is possible with the Zwick® device to create cracks in the coating layer which are caused by folding. Therefore, a test is proposed to check whether a paper with a bad cutting quality on the sheeter also presents a bad cutting quality at the Zwick®. To carry out such a test, papers with large differences in terms of cutting quality must be used to be sure to obtain reliable results at the end.

7 Appendix

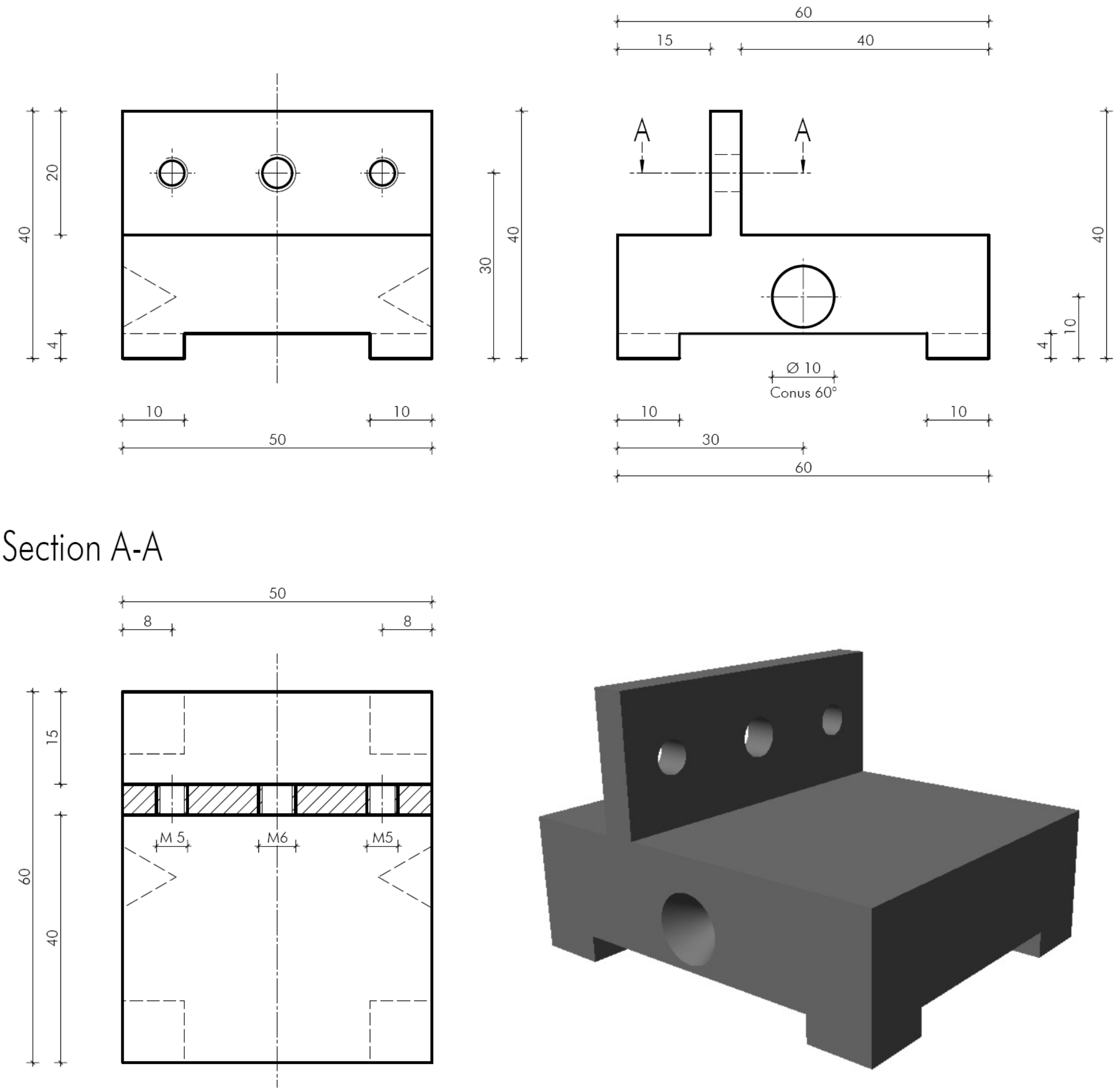
Appendix A:

Drawing 001 – Base plate

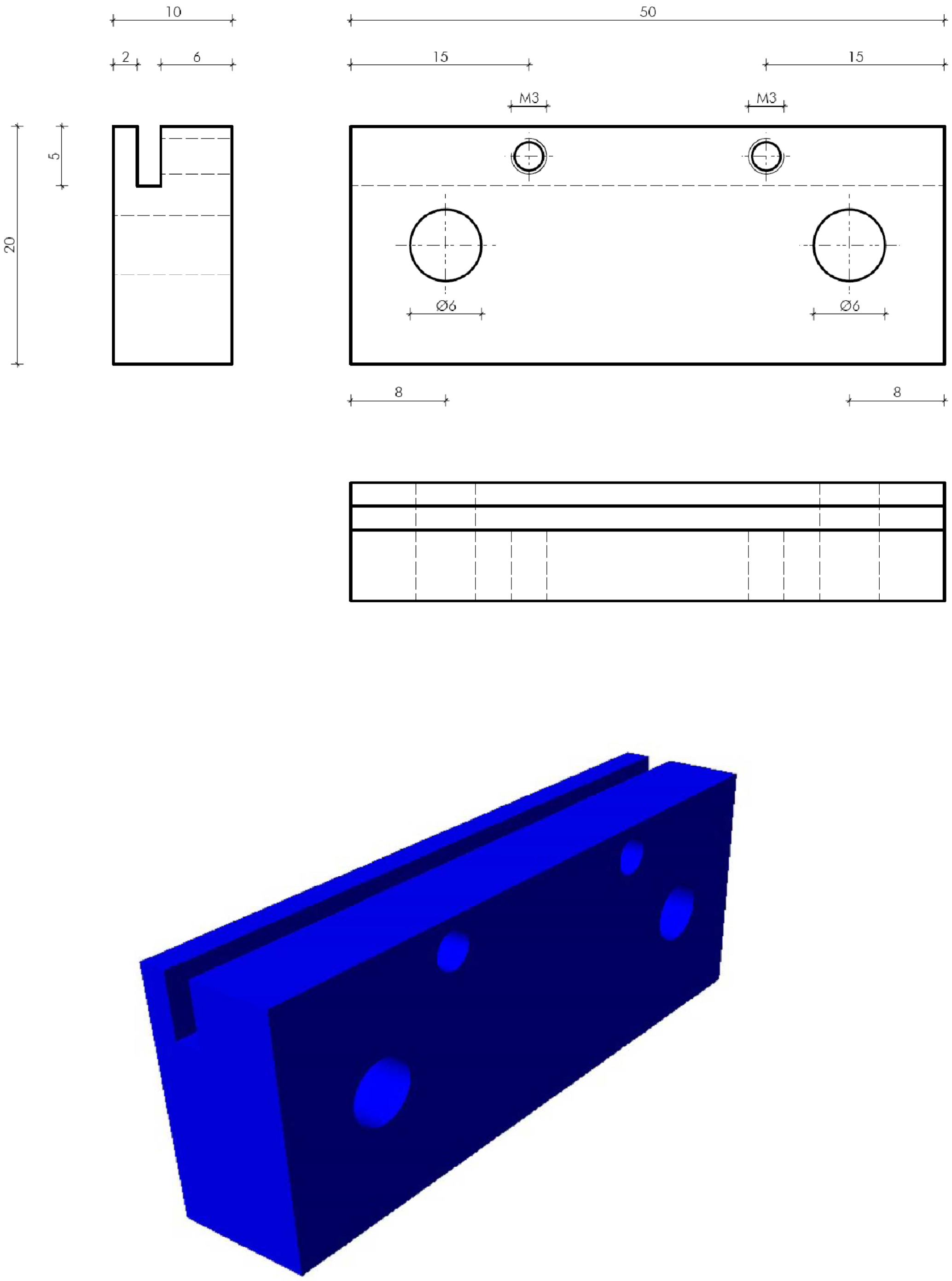
Drawing 002 – Moveable part

Drawing 003 – Knife

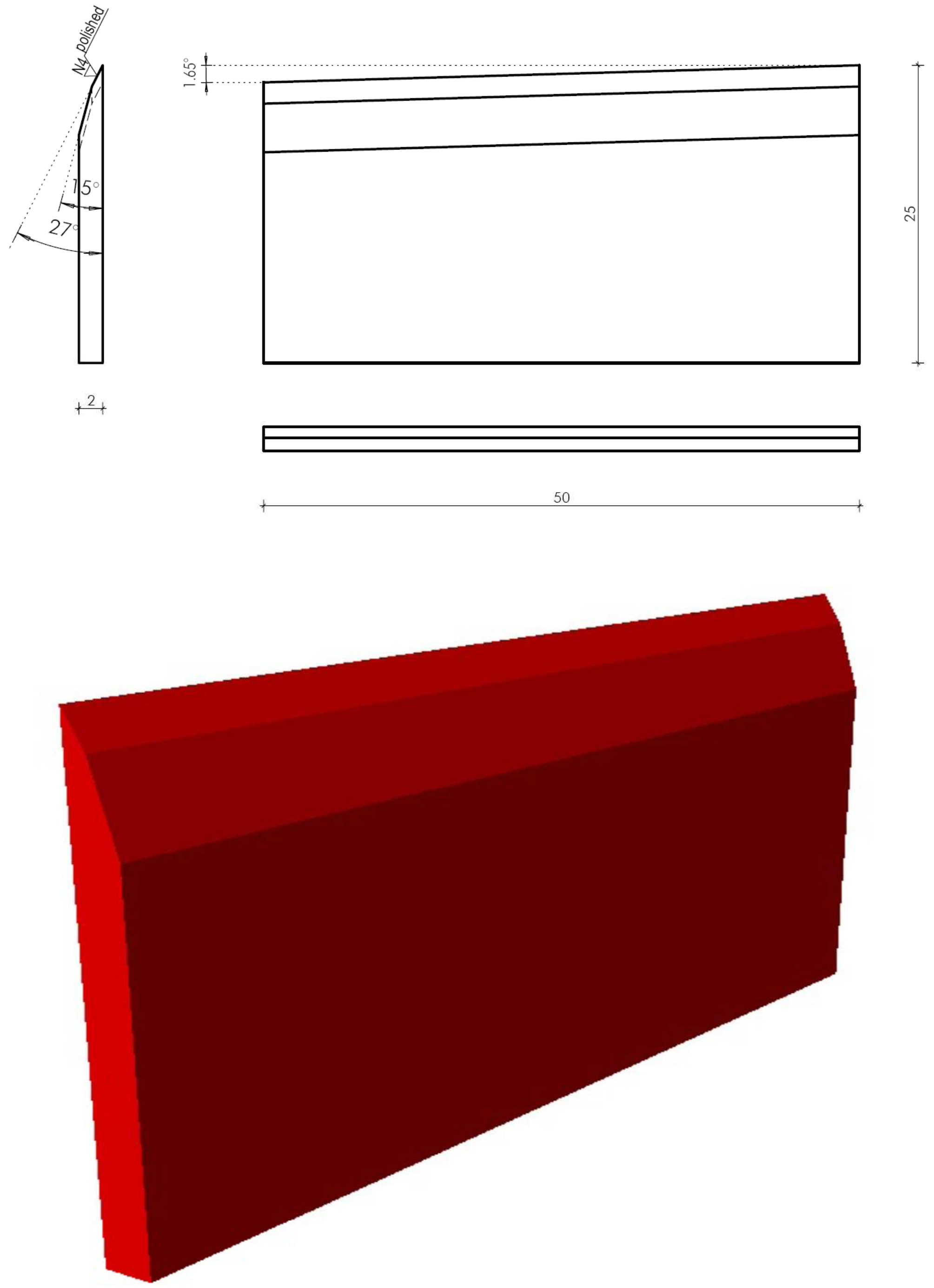
Drawing 004 – Assembly drawing



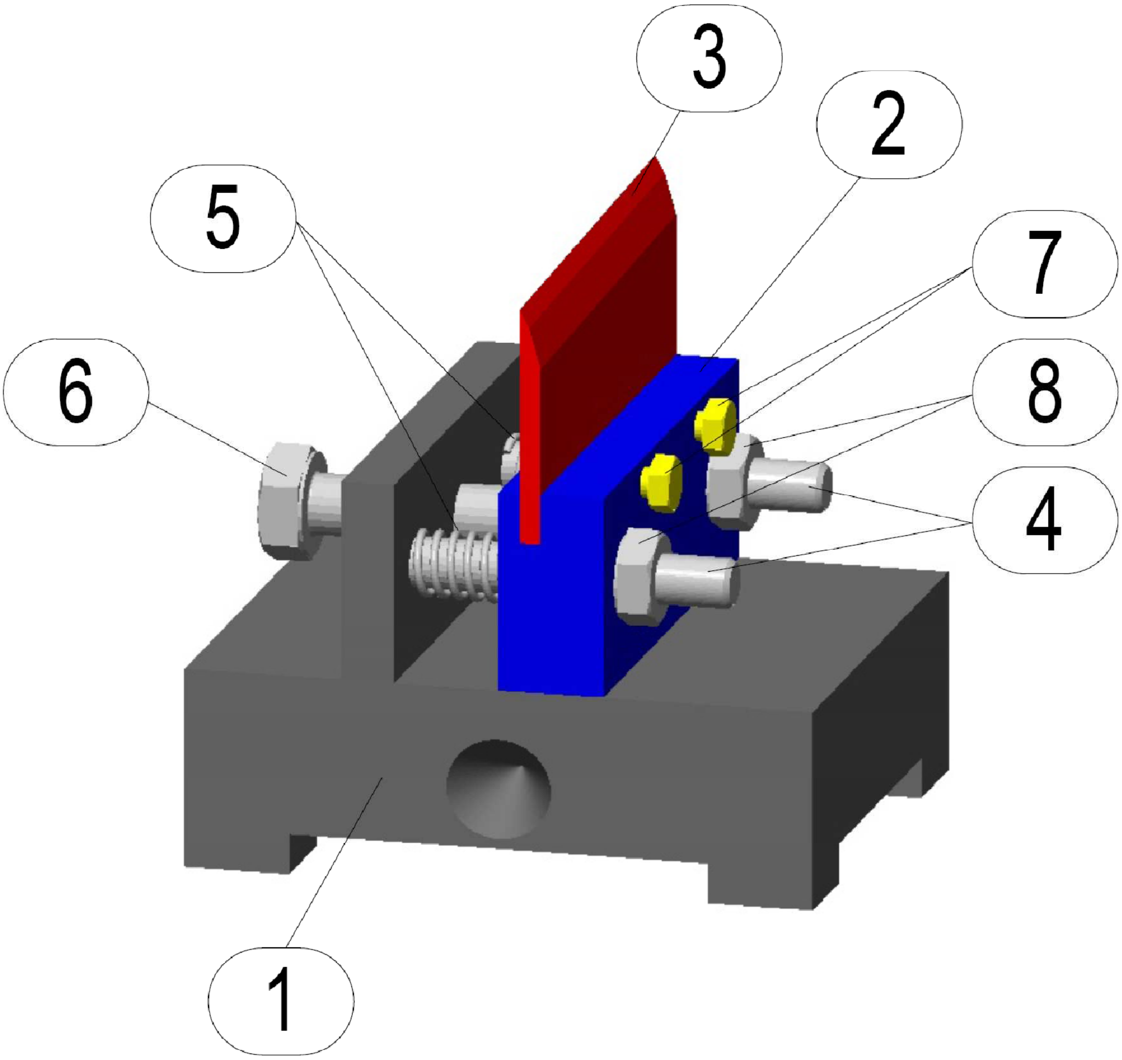
OBJECT			
Knife holder			
Part			
Base plate			
NAME	SCALE	DRAWING-NR.	DATE
Mario Penaso	1:1	001	05.04.2011



OBJECT **Knife holder**			
Part **Moveable part**			
NAME Mario Penaso	SCALE 1:0,5	DRAWING-NR. 002	DATE 05.04.2011



OBJECT Knife holder			
Part Knife			
NAME Mario Penaso	SCALE 1:0,5	DRAWING-NR. 003	DATE 26.04.2011



2	Bolt nut ISO 4032, 24017 - M6 - 6	8	
2	Screw ISO 4017, 24017 - M3 x 10 - 5.6	7	
1	Screw ISO 4017, 24017 - M6 x 30 - 5.6	6	
2	Spring DIN 2098 - 1 x 8 x 20	5	
2	Bolt M5 / M6	4	
1	Knife	3	
1	Moveable part	2	
1	Base plate	1	
Amount	Part	Part Nr.	Remarks

OBJECT

Knife holder

Assembly drawing

NAME	SCALE	DRAWING-NR.	DATE
Mario Penaso	-	004	05.04.2011

Appendix B:

NR	CracksLCBand	CracksCCBand	ForceLC [N]	ForceCC [N]	Basis Weight [g/m²]	Elmendorf MD [mN]	Tearing Index MD [mN*m²/g]	Elmendorf CD [mN]	Tearing Index CD [mN*m²/g]
1a	15,3	11	51,96	61,22	115	355	3,09	488	4,24
1b	24,3	15	56,27	71,32	135	408	3,02	563	4,17
1c	31,3	13	61,45	81,81	150	551	3,67	729	4,86
5a	10	8,3	64,92	74,98	115	511	4,44	556	4,83
5b	12	9,3	69,69	84,05	130	512,5	3,94	632	4,86
5c	14,3	7,7	70,11	85,56	150	638	4,25	788	5,25
8a	15	10,3	52,2	62,25	115	462	4,02	534	4,64
8b	15,3	8,7	59,03	71,65	135	514	3,81	596	4,41
8c	11,3	8,7	70,11	85,56	150	618	4,12	748	4,99
10a	16	9	51,3	58,41	115	440	3,83	509	4,43
10b	12,3	10,3	58,98	70,71	135	490	3,63	565	4,19
11c	13,3	13	68,01	83,22	150	559	3,73	659,5	4,40
15b	24	14,7	53,85	73,01	130	412	3,17	532	4,09
17a	15	11,3	61,22	67,35	115	405	3,52	548	4,77
17b	20,7	12	66,46	82,3	135	537	3,98	668	4,95
17c	20,3	11,3	78,48	98,55	150	653,5	4,36	810,5	5,40

Table 5.6-1: Results for the gloss papers

NR	thickness [mm]	Breaking Force MD [N]	Tensile Index MD [Nm/g]	Breaking Force CD [N]	Tensile Index CD [Nm/g]	Elongation MD [%]	Elongation CD [%]	Emodulus MD [Gpa]	Emodulus CD [Gpa]	Stiffness MD [mN]	Stiffness CD [mN]
1a	0,0804	84,29	48,86	25,1	14,55	1,37	4,73	11,19	4,45	44,12	29,7
1b	0,0924	90,22	44,55	34,74	17,16	1,28	3,17	11,42	5,82	74,88	57,98
1c	0,105	97,58	43,37	35,46	15,76	1,32	4,36	10,23	4,55	101,83	71,23
5a	0,0881	88,3	51,19	38,95	22,58	1,53	4,92	9,38	3,89	55,03	31,55
5b	0,0988	89,53	45,91	39,46	20,24	1,54	5,22	9,2	3,8	78,93	47,77
5c	0,1165	104,63	46,50	45,29	20,13	1,57	4,36	8,8	4,16	126,08	74,77
8a	0,0857	79,92	46,33	37,07	21,49	1,77	6,35	8,31	3,95	50,58	31,87
8b	0,095	86,24	42,59	41,92	20,70	2,02	5,7	8,69	4,08	70,87	45,68
8c	0,11	88,53	39,35	42,64	18,95	1,9	5,19	7,42	3,69	97,02	64,87
10a	0,0833	79,5	46,09	36,58	21,21	1,73	5,98	8,58	3,77	48,72	29,98
10b	0,0965	86,23	42,58	44,64	22,04	1,83	5,84	7,96	5,49	70,63	45,97
11c	0,1106	90,63	40,28	42,83	19,04	1,89	6,22	7,57	3,78	103,2	63,95
15b	0,0885	85,4	43,79	31,11	15,95	1,18	2,94	12,24	6,47	72,22	53,22
17a	0,0896	80,39	46,60	28,61	16,59	1,71	5,65	8,3	3,36	50,88	34,82
17b	0,105	91,94	45,40	32,73	16,16	1,8	5,55	7,88	3,03	82,33	52,27
17c	0,1141	95,23	42,32	36,03	16,01	1,86	5,68	7,67	3,13	110,48	69,68

Table 5.6-2: Results for the gloss papers

Appendix C:

Paper NR	CracksLCBand	CracksCCBand	ForceLC [N]	ForceCC [N]	Basis Weight [g/m²]	Elmendorf MD [mN]	Tearing Index MD [mN*m²/g]	Elmendorf CD [mN]	Tearing Index CD [mN*m²/g]
2a	12,7	9	63,98	68,14	115	492,5	4,28	498	4,33
2b	19,3	13,3	64,67	83,09	135	497	3,68	646,5	4,79
2c	15	15	71,98	97,28	150	552	3,68	741	4,94
3a	12,3	8,3	69,26	73,12	115	499	4,34	583	5,07
3b	15,7	10,3	73,38	88,38	135	527	3,90	624	4,62
3c	12,3	10	84,95	102,38	150	667,5	4,45	777	5,18
4a	14,7	9,7	67	69,19	115	478	4,16	498	4,33
4b	12,7	9	74,11	86,32	135	524	3,88	566	4,19
4c	9,7	9	88,23	103,72	150	621	4,14	700	4,67
6a	7	11	55,79	64,21	115	459	3,99	520	4,52
6b	13,3	7,3	64,48	75,69	135	534	3,96	642	4,76
6c	13,3	7	76,65	96,06	150	610	4,07	763	5,09
7a	8,7	5,7	58,22	62,57	115	464	4,03	523	4,55
7b	12,7	6,7	62,78	77,27	135	551	4,08	614,5	4,55
7c	9,7	7,7	74,96	95,2	150	642	4,28	755,5	5,04
9a	9,3	7	73,07	80,05	115	511	4,44	601	5,23
9b	9,7	5,3	81,75	97,74	135	662	4,90	793	5,87
9c	12,7	5,3	86,15	107,5	150	699,5	4,66	829	5,53
12a	12,3	9,7	67,35	71,58	115	433	3,77	473	4,11
12b	17,7	12,7	65,58	82,49	130	446	3,43	497	3,82
12c	14	9	83,29	102,18	150	583	3,89	706,5	4,71
13a	10,3	7,3	69,34	70,13	115	431	3,75	487	4,23
13b	16,3	8	68,42	77,3	135	474	3,51	547	4,05
13c	16,3	8,7	78,52	95,69	150	542	3,61	656,5	4,38
14b	23,3	12	57,89	78,11	130	417	3,21	579	4,45
16a	15	7,3	59,63	70,99	115	453	3,94	543	4,72
16b	15,3	8,7	66,46	90,32	135	615	4,56	823	6,10
16c	15,3	10,3	81,81	107,78	150	665,5	4,44	828	5,52

Table 5.6-3: Results for the matt papers

NR	thickness [mm]	Breaking Force MD [N]	Tensile Index MD [Nm/g]	Breaking Force CD [N]	Tensile Index CD [Nm/g]	Elongation MD [%]	Elongation CD [%]	Emodulus MD [Gpa]	Emodulus CD [Gpa]	Stiffness MD [mN]	Stiffness CD [mN]
2a	0,0929	66,03	38,28	34,46	19,98	1,36	5,56	8,85	4,85	64,82	51,62
2b	0,1101	90,5	44,69	34,73	17,15	1,17	2,71	9,6	4,55	108,68	76,47
2c	0,1194	91,18	40,52	31,82	14,14	1,35	5	8,47	3,48	130	90,23
3a	0,0944	73,49	42,60	30,3	17,57	1,76	7,28	7,88	3,68	59,95	38,12
3b	0,1074	77,25	38,15	38,55	19,04	1,59	5,46	7,72	4,24	94,12	67,52
3c	0,1245	84,76	37,67	41,16	18,29	1,55	5,27	6,97	3,54	129,72	89,12
4a	0,0945	59,45	34,46	29,83	17,29	1,43	7,42	6,48	3,18	48,95	31
4b	0,1121	67,23	33,20	33,27	16,43	1,38	5,21	6,72	4,24	80,95	55,87
4c	0,1301	79,01	35,12	42,75	19,00	1,62	4,76	5,89	3,52	120,13	80,5
6a	0,0961	72,1	41,80	35,77	20,74	2,04	6,87	6,69	3,18	53,5	33,67
6b	0,1116	83,53	41,25	39,68	19,60	2,21	6,81	7	3,59	91,43	62,63
6c	0,128	89,82	39,92	41,59	18,48	2	6,44	6,57	3,29	133,52	85,47
7a	0,0965	69,46	40,27	29,45	17,07	1,88	8,8	7,61	3,14	58,97	38,93
7b	0,1117	84,57	41,76	37,73	18,63	1,95	6,26	7,01	3,61	97,73	62,77
7c	0,1285	91,02	40,45	40,78	18,12	2,19	7,5	6,63	3,43	128,77	84,12
9a	0,1034	72,3	41,91	34,7	20,12	1,49	5,35	7,44	3,82	69,92	48,08
9b	0,121	79,66	39,34	36,67	18,11	1,48	6,11	7,05	3,53	120,1	72,1
9c	0,1306	82,57	36,70	34,53	15,35	1,43	6,38	7,2	3,35	165,7	108,22
12a	0,0917	68,97	39,98	30,49	17,68	1,26	5,12	8,46	3,92	61,2	41,73
12b	0,1036	74,18	38,04	26,68	13,68	1,26	3,37	8,29	4,14	91,98	66,77
12c	0,121	76,35	33,93	34,52	15,34	1,38	4,75	7,57	4,05	140,98	106,3
13a	0,0956	71,88	41,67	33,8	19,59	1,59	6,23	7,5	3,6	50	33,5
13b	0,1066	67,67	33,42	29,76	14,70	1,47	5,15	7,04	3,52	73,17	50,28
13c	0,1231	75,83	33,70	33,31	14,80	1,41	4,83	6,83	3,36	114,43	78,53
14b	0,1005	83,08	42,61	30,07	15,42	1,13	3,46	10,34	5,03	91,32	70,62
16a	0,0981	76,59	44,40	27,96	16,21	1,68	4,76	7,2	3,33	60,78	38,35
16b	0,1175	91,11	44,99	31,15	15,38	1,79	6	7,1	2,71	102,72	61,47
16c	0,133	88,75	39,44	34,78	15,46	1,89	5,84	6,28	2,73	145,27	88,88

Table 5.6-4: Results for the matt papers

8 Figure list

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