Lappeenranta
University of Technology

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FEASIBILITY OF INDUSTRIAL IMPLEMENTATION OF LASER CUTTING INTO PAPER MAKING MACHINES

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Abstract

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Laser cutting implementation possibilities into paper making machine was studied as the main objective of the work. Laser cutting technology application was considered as a replacement tool for conventional cutting methods used in paper making machines for longitudinal cutting such as edge trimming at different paper making process and tambour roll slitting.

Laser cutting of paper was tested in 70's for the first time. Since then, laser cutting and processing has been applied for paper materials with different level of success in industry. Laser cutting can be employed for longitudinal cutting of paper web in machine direction. The most common conventional cutting methods include water jet cutting and rotating slitting blades applied in paper making machines. Cutting with CO_2 laser fulfils basic requirements for cutting quality, applicability to material and cutting speeds in all locations where longitudinal cutting is needed.

Literature review provided description of advantages, disadvantages and challenges of laser technology when it was applied for cutting of paper material with particular attention to cutting of moving paper web. Based on studied laser cutting capabilities and problem definition of conventional cutting technologies, preliminary selection of the most promising application area was carried out. Laser cutting (trimming) of paper web edges in wet end was estimated to be the most promising area where it can be implemented. This assumption was made on the basis of rate of web breaks occurrence. It was found that up to 64 % of total number of web breaks occurred in wet end, particularly in location of so called open draws where paper web was transferred unsupported by wire or felt. Distribution of web breaks in machine cross direction revealed that defects of paper web edge was the main reason of tearing initiation and consequent web break.

The assumption was made that laser cutting was capable of improvement of laser cut edge tensile strength due to high cutting quality and sealing effect of the edge after laser cutting. Studies of laser ablation of cellulose supported this claim.

Linear energy needed for cutting was calculated with regard to paper web properties in intended laser cutting location. Calculated linear cutting energy was verified with series of laser cutting. Practically obtained laser energy needed for cutting deviated from calculated values. This could

be explained by difference in heat transfer via radiation in laser cutting and different absorption characteristics of dry and moist paper material.

Laser cut samples (both dry and moist (dry matter content about 25-40%)) were tested for strength properties. It was shown that tensile strength and strain break of laser cut samples are similar to corresponding values of non-laser cut samples. Chosen method, however, did not address tensile strength of laser cut edge in particular. Thus, the assumption of improving strength properties with laser cutting was not fully proved.

Laser cutting effect on possible pollution of mill broke (recycling of trimmed edge) was carried out. Laser cut samples (both dry and moist) were tested on the content of dirt particles. The tests revealed that accumulation of dust particles on the surface of moist samples can take place. This has to be taken into account to prevent contamination of pulp suspension when trim waste is recycled. Material loss due to evaporation during laser cutting and amount of solid residues after cutting were evaluated. Edge trimming with laser would result in 0.25 kg/h of solid residues and 2.5 kg/h of lost material due to evaporation.

Schemes of laser cutting implementation and needed laser equipment were discussed. Generally, laser cutting system would require two laser sources (one laser source for each cutting zone), set of beam transfer and focusing optics and cutting heads. In order to increase reliability of system, it was suggested that each laser source would have double capacity. That would allow to perform cutting employing one laser source working at full capacity for both cutting zones. Laser technology is in required level at the moment and do not require additional development. Moreover, capacity of speed increase is high due to availability high power laser sources what can support the tendency of speed increase of paper making machines.

Laser cutting system would require special roll to maintain cutting. The scheme of such roll was proposed as well as roll integration into paper making machine. Laser cutting can be done in location of central roll in press section, before so-called open draw where many web breaks occur, where it has potential to improve runability of a paper making machine.

Economic performance of laser cutting was done as comparison of laser cutting system and water jet cutting working in the same conditions. It was revealed that laser cutting would still be about two times more expensive compared to water jet cutting. This is mainly due to high investment cost of laser equipment and poor energy efficiency of CO_2 lasers. Another factor is that laser cutting causes material loss due to evaporation whereas water jet cutting almost does not cause material loss.

Despite difficulties of laser cutting implementation in paper making machine, its implementation can be beneficial. The crucial role in that is possibility to improve cut edge strength properties and consequently reduce number of web breaks. Capacity of laser cutting to maintain cutting speeds which exceed current speeds of paper making machines what is another argument to consider laser cutting technology in design of new high speed paper making machines.

Keywords: laser cutting, CO_2 laser, paper, paper making machine, cutting, edge trimming

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Lappeenranta, August 2015 Alexander Stepanov

Symbols and abbreviations

A	area, m^2
a_1^*	value of redness before treatment by light
a_2^*	value of redness after treatment by light
b_1^*	value of yellowness before treatment by light
b_2^*	value of yellowness after treatment by light
C	heat capacity, J/K
C_p	specific heat of paper material, J/(kg K)
C_{p1}	specific heat capacity of paper material, J/ (kg K)
C_{p2}	specific heat capacity of water, J/ (kg K)
d	diameter of the focal spot, m
d_B	diameter of the incident beam, m
D_{lb}	diameter of laser beam, m
E_l	cutting energy per unit length, J/m
F	focal length of the lens, m
f	focal number
K	beam quality factor
L_2^*	value of lightness before treatment by light
L_1^*	value of lightness after treatment by light
M_e	mass of evaporated material due laser cutting, kg/h
M_{sr}	mass of solid residues, kg/h
m	mass, kg
P	laser power, W
Q	amount of heat, J
R	radius of laser beam, m
T_a	ambient temperature, K
T_d	degradation temperature, K
V_e	volume of laser cut material, kg/h
v	cutting speed, m/s
w_1	mass fracture of paper material, kg

w_2	mass fracture of water, kg
z_f	depth of focus, m
ρ	density of paper material, kg/m^3
δ	thickness of paper material, m
κ	thermal conductivity, J/(s K m)
λ	wavelength of the laser light, µm
η	absorption
ΔE	total color difference
ΔQ	change in amount of heat, J
ΔT_d	degradation temperature, K
ΔT	change in temperature, K

BCTMP	bleached chemi-thermo-mechanical pulp
CD	cross machine direction
CTMP	chemi-thermo-mechanical pulp
CW	continues wave
FTIR	Fourier transform infrared spectroscopy
HC	hydrocarbons
IR	infrared radiation
LWC	lightweight coated
Ref	reference
SEM	scanning electron microscopy
SC	supercalandered
SGW	stone groundwood pulp
TEA	tensile energy adsorption
TMP	thermo-mechanical pulp
TSI	tensile strength index
UV	ultraviolet radiation

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1 Introduction

Laser cutting of paper materials was demonstrated in the middle of 70’s for the first time. However, the cost of laser equipment was for a long time too expensive compared to conventional methods of cutting of paper and board such as mechanical cutting with blade tool and water jet cutting. Laser cutting of wood-fiber based materials became more popular during 90´s because of lower cost level of laser equipment. One of the first successful application of laser technology to paper based material was perforation of cigarette filter paper. Nowadays, with reducing the cost of equipment and developing of laser technology, laser cutting of paper has become more accepted and more efficient (Piili, 2009).

Use of laser technology in paper making industry can provide several advantages over conventional cutting methods. Paper making industry usually needs high-capacity machines that creates the need for high-speed cutting. Cutting operations in paper making machine are mainly done by mechanical blade and water jet cutting methods what to certain extend restricts the increase of speed. Laser cutting has higher capacity in increasing the cutting speed. Laser cutting is also a non-contact method, as there is no contact with cutting tool and no wear which ensures constant cutting quality. Besides that, laser cutting can provide better quality of cut edge what is especially important in case of edge trimming in forming section of a paper making machine. Problem of dust, which occurs when paper material is cut with blade slitters or other blade tools, can also be eliminated (Malmberg et al., 2006 (a)). Cutting needs which are applied in paper making machines have been defined:

- edge trimming of web in the end of forming section (about 150 – 200 mm cut width),
- edge trimming can be also applied before sizing,
- edge trimming before calender,
- edge trimming of paper web in reel,
- cutting of paper web in cross direction
- cutting (slitting) of web to customer size
- cutting of paper web in sheets (final product)

Based on that, the most promising areas where laser cutting can be applied can be defined. They are edge trimming in wet end, edge trimming in dry end and slitting of web to customer width.

Research on implementation of laser cutting in a paper making machine can be interesting, on the one hand, for paper making industry as it can be a potential cutting tool which can solve problems associated with conventional cutting technologies. The clear tendency of increasing speeds, improving runability and economic performance of paper making machines requires new technological solutions, what can be laser cutting in this case. On the other hand, laser manufacturers are interested in such high volume markets, which paper making industry definitely is, where dozens of lasers can be utilized.

1.1 Aims and scope of the thesis

The doctoral thesis aims to investigate possibility of implementation of laser cutting in paper making machine and give implications on practical implementation of laser cutting system into paper making machine providing discussion of associated challenges. Another aim was to estimate the effect of laser cutting on paper material cut edge properties, particularly tensile properties.

More precisely, laser cutting method was aimed to be applied for longitudinal cutting of moving paper web. Three potential application areas, where longitudinal cutting of paper web is required, were investigated on whether it was possible and reasonable to replace conventional cutting systems with laser cutting system. These three considered areas were wet end, dry end and rewinder of a paper making machine. Implications on the most beneficial location of laser cutting were given principally and technologically, describing particular locations where laser cutting was required as process and where this process could be maintained with existing laser equipment.

Another aim was to investigate possible improvement of strength properties of laser cut edge of paper material after laser cutting. Strength properties of laser cut paper material edges were tested with methods accepted in paper making industry. The reason to take this approach was in the fact that runability of a paper making machine depends on quality of paper web edges after trimming. Improvement of edge tensile strength of paper web edge can result in lower number of breaks and consequently higher production and lower losses of resources and work time.

Calculation method for determination linear cutting energy required for efficient laser cutting was used. The aim of linear cutting energy calculations was to provide reliable method for determination of precise laser cutting parameters as it can be essential in paper making industry in case of change of paper grade in paper making machine.

Economic performance evaluation of the laser cutting system performance was carried out in order to obtain information on costs associated with laser cutting implementation. Laser cutting was compared to conventional cutting methods from point of view of economic performance.

This research provides a view on opportunities to utilize laser cutting systems in paper making industry and implicates some possible practical ways of laser cutting implementation. Cutting needs in paper making industry were restricted by cutting utilized in a paper making machine. Thus, cutting of paper material in converting, printing, packaging, etc. industries are out of the scope of this research. Paper making machine was generalized to most commonly used scheme. Variety of paper making machine types and constructions were not considered, as each paper machine type require individual verification of laser cutting possibilities of implementation.

2 PAPER MATERIAL

2.1 Structure of paper material

Papers are commonly described as materials with smooth and flat surface that have an even structure. However, microscopic view reveals that paper materials structure is far from homogeneous. In fact, paper is complex structure that consists of network formed by fibers originated from wood or similar to wood sources. Moreover, filler particles (usually kaolin, calcium carbonate or other mineral components), various papermaking chemicals and residual raw material components, like lignin, are present in a paper material structure. Pores filled with air occupy free space between fibres. Some paper materials, especially printing papers, are coated with one or several thin layers of mineral pigments (usually kaolin, calcium carbonate, other minerals or mixture of these pigments).depending on the end-use purpose in order to obtain desired properties of final product or to reduce the raw material costs by substituting high quality chemical pulp by cheap mechanical pulp or recycled pulp in the middle layer of the paperboard. Therefore, various paper materials can be regarded as very heterogeneous composite products where the wood or wood-like fibres are the main constituents of the network (Piili, 2009).

The main constituent of the paper network, the wood fibres, have much longer length than their width. Therefore, a paper sheet is typically thin and at a macroscopic scale the fibre network in paper reminds of a flat 2D network. However, when the pores between fibres are taken into consideration, fibre network can be understood as a 3D network in a microscopic scale, where the network structure is filled with pores and air voids, as shown in Figure 1 (Niskanen, 1998; Piili, 2009).

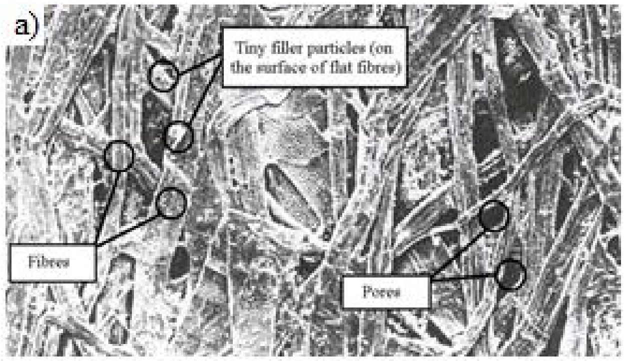


Figure 1. Typical fibre 3D network: top side of paper material (Piili, 2009).

This special structure of paper materials, i.e. 3D fibre network, has a strong effect on the optical properties of paper materials and consequently also on the interactions between laser beam and paper material (Niskanen, 1998).

2.1.1 Cellulose structure

The elemental composition of cellulose consists of 44-45 % of carbon, 6.0-6.5 % of hydrogen and 48.5-50 % of oxygen. The empirical formula of cellulose is $C_6H_{10}O_5$. The chain-like macromolecular structure of the cellulose molecule has been generally accepted (Figure 2) (Krassig, 1993).

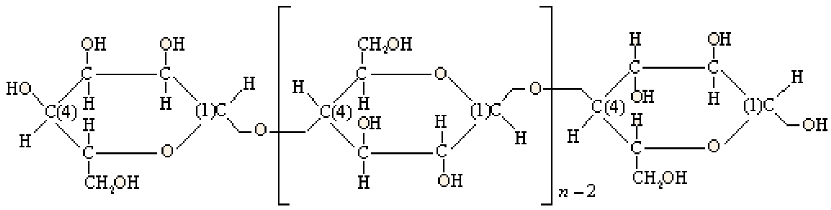


Figure 2. Structure of the cellulose molecule (Krassig, 1993).

The structure of cellulose can be described as a long chain polymer molecule consisted of repetitive glycoside residues. The glucose base units are linked together by one, 4-β-glucosidic bonds formed between the carbon atoms C (1) and C (4) of bordering glucose units. The β-glucosidic link requires that the plane of the pyranose ring of each second glucose unit along the molecular chain is turned around the C1 - C4 axis by 180° with respect to the glucose units lying in between. This means that cellulose is actually one, 4-β-polyacetal of cellobiose with a repeating length of 1.3 nm (Krassig, 1993).

At the both ends of cellulose molecule, the terminal hydroxyl groups are present. These two hydroxyl groups are different in their nature. The C1 hydroxyl group, shown on the Figure 2 at left side of molecule, is an aldehyde hydrate group with reducing activity. They originate from the formation of the pyranose ring through an intermolecular hemiacetal reaction. The C (4) hydroxyl group on the right side of the cellulose molecule is an alcoholic hydroxyl and consequently non-reducing (Krassig, 1993).

2.1.2 Hemicelluloses

Hemicelluloses are low-molecular polysaccharides, which are contained in plant cell walls as well as cellulose and lignin. Most of hemicelluloses differ from cellulose better solubility in alkaline solutions and their ability to hydrolyse in water. Hemicelluloses in plants are the backbone of the construction material. The content of hemicelluloses in wood and others wood-based materials is 13-43 % (Sharkov and Kuibina, 1972). Although hemicellulose is usually considered as structural polysaccharides, it includes a few other plant polymers such as the arabinogalactans, among them (Timell, 1967).

2.1.3 Lignin

Lignin is a natural, amorphous, three-dimensional, polyphenolic polymer, which is built up of phenyl propane units. Most of the lignin is concentrated in the middle lamella (the space between the cells). The biological role of lignin is to participate in forming cell walls in living plants along with the cellulose and hemicelluloses. It serves the purpose to bind fibers together. The remaining part is located throughout the secondary cell wall. Here lignin interpenetrates and encrusts the cellulose fibers and the hemicellulose (Timell, 1967; Papp et al., 2004).

2.1.4 Paper material/Fibres

Basically, natural fibers have a hollow cross section structure. Never-dried fibers are almost completely uncollapsed (Figure 3) (Page, 1967).

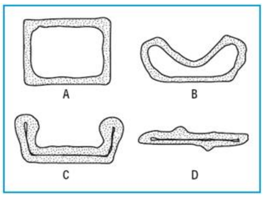


Figure 3. Different degrees of fiber collapse: (A) original fiber, (B) partially collapsed fiber, and (C, D) completely collapsed fiber (Jayme amd Hunger, 1961).

Hollow structure of the wood fibers is collapsed in paper/cardboard making process. During drying both the fiber cross section and the fiber cell wall respectively collapse and contract. Thus, the cell walls also contribute in light scattering and act as optical boundaries (Jayme amd Hunger, 1961).

The effects of laser treatment on cellulosic material (in terms of behaviour under laser treatment) can be studied also from materials such as cotton that has the chemical structure close to that of paper material. Study done by Chow et al. studied surface morphology of cotton fibres after interaction with CO_2 laser beam. It was revealed that surface was severely influenced by laser beam what resulted in pores, cracks and fragments. Observations were made on the fibre surface using scanning electron microscopy (SEM) technology. Using the results of Fourier transform infrared spectroscopy – Attenuated total reflectance (FTIR-ATR) analysis, it can be said that laser irradiation induced thermal degradation. Amount of oxidation products, such as carbonyl and carboxyl groups, was higher in areas treated with laser beam. This was also further supported by X-ray photoelectron spectroscopy (XPS) analysis which revealed changes in the elemental composition and content of carbon and oxygen after irradiation with laser beam. This clearly indicated that the chemical composition of the surface of the laser-treated cotton fabric was modified (Chow et al., 2011).

2.1.5 Paper products and their classifications

Generally paper products can be classified into two major groups: mechanical pulp dominating grades and chemical pulp dominating groups. Thus the classification is maid according to the origin of raw material (Paulapuro, 2000).

Mechanical pulp dominating paper grades generally can contain 25 – 100 % mechanical pulp, but usually more than 50 %, and chemical pulp is added in order to increase strength properties and improve runability. Minerals are used as fillers and/or as coating. Mechanical pulp dominating paper grades comprise various newsprint grades, supercalandered (SC) papers and coated mechanical paper grades (Paulapuro, 2000).

Chemical pulp dominating grades are uncoated or coated fine paper grades with maximum mechanical fiber content of 10 %. Generally, these paper grades contain only traces or no mechanical pulp and 5 – 25 % fillers (Paulapuro, 2000).

2.2 Degradation of paper

When paper material is exposed to external influence, degradation of paper material can occur. Degradation of paper material results in decrease of paper strength propertied, lower degree of polymerisation or complete failure of paper material structure. Several degradation mechanisms of cellulose have been studied by Fellers et al. According to this study, the degradation and ageing mechanisms have been subdivided into several categories (Fellers et al., 1989)

1. Hydrolysis. It causes reducing of degree of polymerization and formation of reducing free end-groups.
2. Oxidation. As a result of oxidation the degree of polymerization is reduced. It also causes formation of carboxyl groups (aldehydes and ketones).
3. Cross-linking between the cellulose chains and semi-acetal bonds.
4. Microbiological breakdown.
5. Mechano-chemical breakdown. In this case, chain-cleavage and mechano-chemical oxidation leads to reduction of the degree of polymerization.
6. Photochemical degradation.

2.2.1 Thermal decomposition

Heat transfer in paper material goes through conduction, convection and radiation. The behaviour of the paper material under influence of heat can be divided into five stages before the temperature level reaches 500 ◦C when complete degradation should occur. These stages are shown in Figure 4. The heating rate applied was 20 ◦C per minute. Critical points (cp) which separating these stages were obtained (Chen et al., 2012).

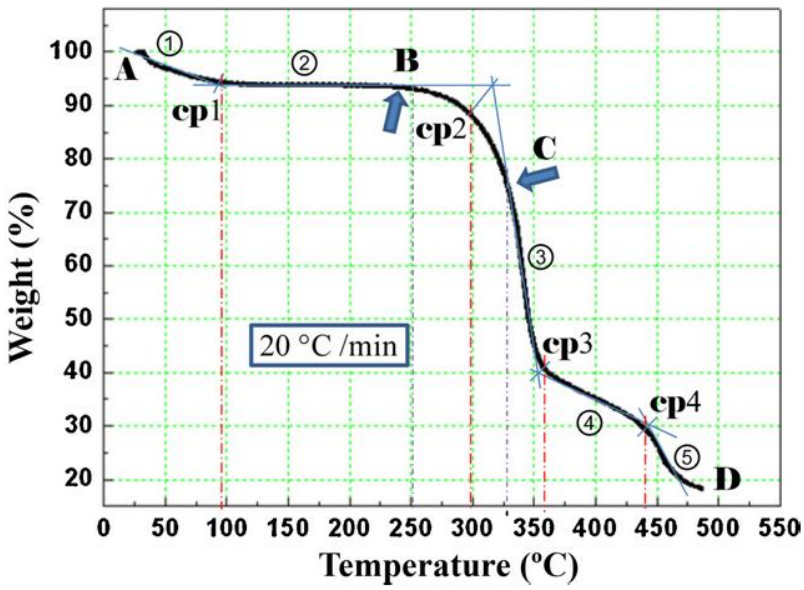


Figure 4. Degradation stages of paper material (Chen et al., 2012).

As it can be noticed from Figure 4, critical points correspond to approximately 100, 300, 360, and 440 °C. The first stage is attributed to weight loss of paper material which is caused by evaporation. The rate of weight loss significantly increases in the second stage. Third stage of cellulose decomposition resulted in severe weight loss with the fastest rate. The declined rate of weight loss was observed in the following fourth and fifth stages (Chen et al., 2012).

Cellulose and other paper ingredients breaks down into short chains at high temperatures when exposed to air and/or oxygen. This is because of the presence of oxygen and other active ingredients. They are also susceptible to oxidation reactions, including main-chain depolymerisation and side-chain removal. During pyrolysis in air or in an atmosphere with presence of oxygen, substances that are difficult to break down will burn again at high temperatures. Moreover, presence of flammable volatile products (alkenes and cycloalkanes) of pyrolysis in air has been notice (Chen et al., 2014).

2.2.2 Products of thermal decomposition

The major component of cellulose thermal degradation in temperature range of 155 and 380, products are water vapour and CO_2 gas. Furans and carbonyl derivatives were found as the second major degradation products in gaseous form. At the same time, alcohols, acids, aromatic and aliphatic hydrocarbons can be considered as minor products. Table 1 shows major steps and gaseous decomposition products of cellulose pyrolysis when cellulose was exposed to steadily elevating temperature from 155ºC to 900ºC (Chen at al., 2014, Klass, 1998; Soares et al., 1995).

Table 1. Gaseous decomposition products of cellulose (HCs - hydrocarbons) (Klass, 1998).

Decomposition process	**Temperature, ºC**	**H_2, mol %**	**CO, mol %**	**CO_2, mol %**	**HCs, mol %**
Elimination of water	155-200	0	30.5	68.0	2.0
Evolution of carbon oxides	200-280	0.2	30.5	66.5	3.3
Start of hydrocarbon evolution	280-380	5.5	20.5	35.5	36.6
Evolution of hydrocarbons	380-500	7.5	12.3	31.5	48.7
Dissociation	500-700	48.7	24.5	12.2	20.4
Evolution of hydrogen	700-900	80.7	9.6	0.4	8.7

2.2.3 Solid and high boiling products of paper decomposition

Table 2 shows the amount of solid residue, high boiling products and gases produced due to thermal decomposition of cellulose. Thermal decomposition was observed at different temperatures. Results were obtained for cellulose decomposition under vacuum. Cellulose was in powder form, sheets (Whatman paper) and Kraft paper (Soares et al., 1995).

Table 2. Products of thermal decomposition of cellulose (Soares et al., 1995).

T, ºC	**Solid residue,%**	**High boiling products, %**	**Gases, %**
Cellulose powder			
250	69	22	9
275	32	47	21
325	14	53	33
420	4	58	38
Whatman paper			
250	80	13	7
275	51	40	9
325	27	57	16
420	6	59	35
Kraft paper			
250	83	2	15
275	64	8	28
325	35	32	33
420	12	47	41

As it can be observed from Table 2, powder cellulose produced higher volume of furanic compounds. Methyl furans and furancarboxyaldehyde were also in high volume in case of powder cellulose. Kraft paper showed low volume of furan, methyl furans and furancarboxyaldehyde (Soares et al., 1995).

High boiling products were produced at different temperatures of cellulose decomposition. Evolution of high boiling products in powder cellulose and Whatman paper occured at temperatures around 275 ºC. Kraft paper produces high boiling products at temperatures above 275 ºC (Soares et al., 1995).

Decomposition of cellulose with the access of oxygen was also studied. The presence of oxygen resulted in higher amount of solid residues in case of Kraft paper but in case of powder cellulose and Whatman paper this effect was lower. Lignin was also found to be able to increase the content of solid residues (Soares et al., 1995).

2.2.4 Potential of dust air explosive mixture formation

Hybrid mixture of dust and air are potentially explosive in the presence of ignition source. Explosions in industrial processes, where dust and flammable gases or vapours are present, occurs frequently. However, explosions of dust mixtures with air are not frequent compared to gas and/or vapour–air mixtures. This is due to flammable gases that are more likely to form ignitable mixtures as a result of diffusion. Nevertheless, dust have to be dispersed and settled. In this case, it is more unlikely to combine correct dispersion of dust and ignition source of sufficient power. All these conditions have to happen during explosive regime of considered mixture. It can be concluded that explosion dust is mainly dependent on the dispersion in the air (Serafin et al., 2013). Non-flammable mixture can be obtained due to the high H_2O_{vap} content at high temperature. It was noticed that the mixtures of dust and air were not flammable, when water vapour in the mixture composition was higher than 55 % (Cheikharavat et al., 2015).

Amyott and Eckhoff reports wood and paper production (dusts from sawing, cutting, grinding, etc.) as industry with a risk of dust/air explosion (Amyott and Eckhoff, 2010).

2.2.5 Heat induced color change

Color change of paper materials during and/or after laser treatment has been noticed, especially in case of such materials as newsprint grades, copy paper and to lesser extend cardboard. These materials may contain different types of high-yield pulps with considerable content of lignin, such as stone groundwood pulp (SGW), thermo-mechanical (TMP) or chemi-thermo-mechanical pulps (CTMP), and impurities. The trend in paper making industry is to further increase the content of high-yield pulp in order to reduce the cost of paper products. Hence, coloration of paper material is one of the most essential problem which has to be solved to enable implementation of lasers into processing of paper materials production (Stepanov, 2011).

Examples of heat-induced colour change due to thermal influence are shown in Figure 5.

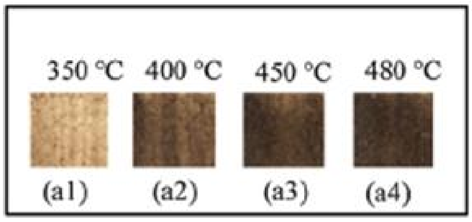


Figure 5. Colour change of paper material at different temperatures (Chen et al., 2012).

Figure 5 represents the colour change when paper was exposed to heat influence at the range from 350 to 480 ºC. Figure 4 (a1) shows that when temperature of heat-induction exceeded 350 °C, it resulted in paper material yellowing. The critical temperature is 430 ◦C, when severe colour change occur (which is also corresponds to the temperature of fourth stage of cellulose degradation). It was also found that colour change did not indicate deterioration of strength properties (Chen et al., 2012).

Kaminska et al. (Kaminska et al., 2003) investigated the effect of interaction of laser beam and paper material in laser cleaning of artificially soiled samples. UV and near-IR laser wavelengths of 266, 355, 532 and 1064 nm were used in this study. Three samples of different content were used: mixture of wood pulp and pure cotton cellulose (40% and 60%), mixture of wood pulp and pure cotton cellulose (40% and 60%) with addition of gelatin glue and mixture of wood pulp and pure cotton cellulose (40% and 60%) with addition of gelatin glue and artificially soiled surface (charcoal powder). The 10 days accelerated aging was applied. The behaviour of the parameters such as lightness, green-red and yellow-blue changes in paper, whiteness and yellowness were investigated (Kaminska et al., 2003).

It was found that lightness of the first and second samples decreased whereas in case of the third sample lightness increased. The whiteness of the samples decreased for the first and second samples and increased for the third sample. All samples showed negligible changes of parameter a*(red-green changes) except the second sample irradiated with wavelength of 1064 nm where significant changes were observed. The behaviour of parameter b* varied depending on laser wavelength. The general tendency of yellowing was growth for all samples (Kaminska et al., 2003).

Colour change of paper materials under the influence of irradiation can be described using CIE L*a*b* method. This method allows to determine the lightness ($L*$), redness ($a*$) and yellowness (b*). The total colour difference (ΔE) can be calculated as Equation (1) shows (Muller et al., 2003)

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

where ΔE - the total color difference

L_2^* - value of lightness after treatment by light

L_1^* - value of lightness before treatment by light

a_2^* - value of redness after treatment by light

a_1^* - value of redness after treatment by light

b_2^* - value of yellowness after treatment by light

b_1^* - value of yellowness before treatment by light.

$L*$ value represents the grey value, which is in the range from 0 (black) to 100 (white). The positive values of ($a*_2 - a*_1$) describe a red shift when negative values of this unit describe a green shift. Similarly, the positive values of ($b*_2 - b*_1$) describe a yellow shift and negative values of ($b*_2 - b*_1$) describe the blue shift (Muller et al., 2003).

2.3 Linear cutting energy calculation

Heat transfer properties of paper material are relevant considering laser cutting of paper material. Heat transfer can be accomplished by conduction, convection or radiation. Laser cutting of paper material, energy needed for paper material degradation is transferred via radiation. It has to be note also that heat conductivity in the direction of paper material thickness are more important than in plane direction. In plane thermal conductivity is often neglected (Niskanen, 2008).

2.3.1 Thermal conductivity

Property of a material that represents its ability to conduct heat is referred as thermal conductivity. When one unit of area is observed and heat flow is going through it, it is noticed that heat flow rate is proportional to area and thermal gradient as Equation (2) shows (Green and Perry, 2008)

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \kappa A \frac{\mathrm{d}T}{\mathrm{d}z} \tag{2}$$

where $\frac{\mathrm{d}Q}{\mathrm{d}t}$ heat flow rate, J/s

κ thermal conductivity, J/(s K m)

A area, m^2

$\frac{\mathrm{d}T}{\mathrm{d}z}$ thermal gradient (= temperature difference per unit length), K/m.

Thermal conductivity can be calculated as Equation (3) shows.

$$\kappa = \frac{\frac{\mathrm{d}Q}{\mathrm{d}t}}{A \frac{\mathrm{d}T}{\mathrm{d}z}} \tag{3}$$

Thermal conductivity of paper material vary depending on grade and raw materials. Thermal conductivity value of paper 0.064 W/(K m) (Avallone et al., 1996) can be generally applied. However, thermal conductivity of newsprint is 0.456 W/(K m) (Kawamizu et al., 2009), fine paper grades (copy paper belongs to fine paper grades) is 0.456 W/(K m) (Kawamizu et al., 2009). Thermal conductivity of pure cellulose is 0.057 W/(K m) (Brandrup et al., 2005).

2.3.2 Heat capacity and specific heat capacity

Heat capacity *C* represents the amount of heat energy which is needed to be supplied to material to change its temperature by 1 Kelvin. It can be calculated as Equation (4) shows (Green and Perry, 2008).

$$C = \frac{Q}{\Delta T} \tag{4}$$

where C heat capacity, J/K

Q amount of heat, J

ΔT change in temperature, K.

For practical applications, specific heat capacity C_p is used. Specific heat capacity describes how much heat energy is needed to be supplied to material of a unit of mass to rise its temperature by one Kelvin. Thus, specific heat capacity shows the ability of paper material to store thermal energy. Specific heat capacity can be calculated as Equation (5) shows (Green and Perry, 2008, Niskanen, 2008).

$$C_p = \frac{\Delta Q}{\Delta T \; m} \tag{5}$$

where C_p specific heat capacity, J/(K kg)

ΔQ change in amount of heat, J

ΔT change in temperature, K

m mass, kg.

Some measured specific heat capacity values of materials relevant to paper making process:

paper is 1500 J/(K kg) (Pages et al., 2005),

newsprint is 2893 J/(K kg) (Kawamizu et al., 2009)

fine paper is 2893 J/(K kg) (Kawamizu et al., 2009)

cellulose is 1266 J/(K kg) (Brandrup et al., 2005)

clay (kaolin) is 940 J/(K kg) (Avallone et al., 1996)

$CaCO_3$ is 900 J/(K kg) (Avallone et al., 1996)

water is 4181 J/(K kg) (Niskanen, 2008)

Specific heat capacity of moist paper can be calculated using model for determination of specific heat capacity of mixture. Specific heat capacity can be calculated as arithmetic mole or weight fraction average of the pure component values, according to Equation (6) (Teja, 1983):

$$C_{mp} = w_1 C_{p1} + w_2 C_{p2} \tag{6}$$

where w_1 mass fracture of paper material, kg

C_{p1}	specific heat capacity of paper material, J/(K kg)
w_2	mass fracture of water, kg
C_{p2}	specific heat capacity of water, J/(K kg)

2.3.3 Heat input

Heat input describes the amount of heat that is transported into top surface of work piece to attain good quality laser cutting. Heat input can be expressed as heat input per cut length (J/m) or heat input per mass of evaporated paper material (J/g). Heat input in relation to cut length can be calculated as Equation (7) shows (Lukkari, 1998; Malmberg et al., 2006 (a)).

$$Q = \eta \frac{P}{v} \tag{7}$$

where Q heat input, J/m

P laser power, W

v cutting speed, m/s

η absorption

This value describes how much energy (in joules) is needed to cut one meter of material. It has to be noted that material thickness and cut kerf width is not included in this value (Malmberg et al., 2006 (a)).

2.3.4 Energy needed for cutting

Heat input cannot be directly used to measure energy needed for laser cutting of paper material. Following calculation model was suggested by Pages et al., (Pages et al., 2005) for linear cutting energy needed to perform cutting of paper material (Equation (8)):

$$E_1 = \frac{P}{v} = \frac{\rho \, \pi \, R \, \delta \, C_P \, \Delta T_d}{2} \tag{8}$$

where E_l cutting energy per unit length, J/m

P laser power, W

v cutting speed, m/s

ρ density of paper material, kg/m^3

R radius of laser beam, m

δ thickness of paper material, m

C_p specific heat of paper material, J/kg K

ΔT_d (= T_d - T_a, T_d = degradation temperature, T_a = ambient temperature), K.

For paper materials C_p = 1500 J/(kg K) can be used, for fine paper grades C_p is 2893 J/(K kg) (Kawamizu et al., 2009).

Paper material is supposed to degrade at temperature T_d. It is assumed that profile of the used laser beam is uniform with radius R what results in uniform deposition of heat over paper material thickness δ. Heat transfer between paper and environment as well as heat transfer into material is assumed to be negligible (Pages et al., 2005).

Disadvantage of this model is that it does not take into account absorption characteristics and thermal diffusion of the heat during laser cutting (Pages et al., 2005). Pages et al. (Pages et al., 2005) concluded that the simple model described in Equation (8) must be greatly improved in order to provide more precise calculation results. Interaction phenomena that occur during laser beam treatment of paper material such as optical penetration, absorption, transmittance and scattering and thermal diffusion during laser cutting had to be taken into account (Pages et al., 2005).

2.4 Laser processing of cellulosic materials

2.4.1 Interaction of light and paper material

Laser cutting process can be considered as a thermochemical decomposition process. However, decomposition process takes place when laser radiation is absorbed by the paper material, i.e. the paper material is in interaction with the laser beam. Since laser introduces the energy as light the interactions between the paper material and the laser beam are also optical (Piili, 2009).

Paper material consists of several different optical boundaries: surface, pores with different size and shape, mineral pigments with size of few micrometers and fibers. Light can transmit, reflect, scatter, refract, diffract, absorb, etc., when it interacts with paper material or components of it (Piili, 2009; Gustavsson, 1995; Pauler, 2002).

From microscopic point of view, it can be said that, when light meets paper material, a complicated interaction of 3D network of fibers and light takes place. Figure 6 illustrates this complexity of the interaction between light and paper (Pauler, 2002).

When light interacts with paper material, it reflects horizontally, vertically and back from the fiber and pigment surfaces. Different routes for light rays when they hit paper and print surface are presented in Figure 6. In case A, first-surface reflection occurs from non-printed surface. B represents a light beam that is absorbed in the ink layer. A first-surface reflection can also occur from the surface of the ink layer (C). D case represents a diffuse reflection. E describes a situation, where a light beam enters the paper from a non-printed point and as a result of a diffuse reflection is absorbed into the ink layer. The cases F-I represent situations that can take place when ink layer is not absorbing light rays completely (Gustavsson, 1995, Niskanen, 2008).

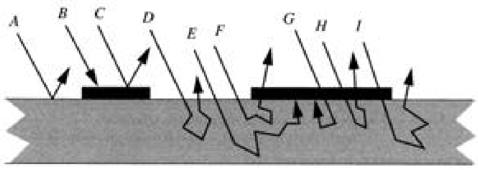


Figure 6. Different entering and exiting routes for light rays as they hit paper and print surface (Niskanen, 2008).

To describe reflection, refraction and diffraction, light scattering is used as one concept. When considering paper materials, light scattering is dependent on (Pauler, 2002; Lindholm and Kettunen, 1983)

- the number of optical boundaries to reflect the light,
- refractive index of the material to which the light is exposed and
- amount, size, shape, and distribution of particles that have the same size as wavelength of light (especially particle size in the range of 0.25 – 1 µm).

2.4.2 Cellulose absorption of laser beam

Figure 7 represents the light transmittance and absorbance properties of cellulose molecule (Anon., 1996). Absorption characteristics of material allow to evaluate the amount of laser energy to be absorbed by material. Thus, suitability of laser emitting certain wavelength for processing of considered material can be evaluated.

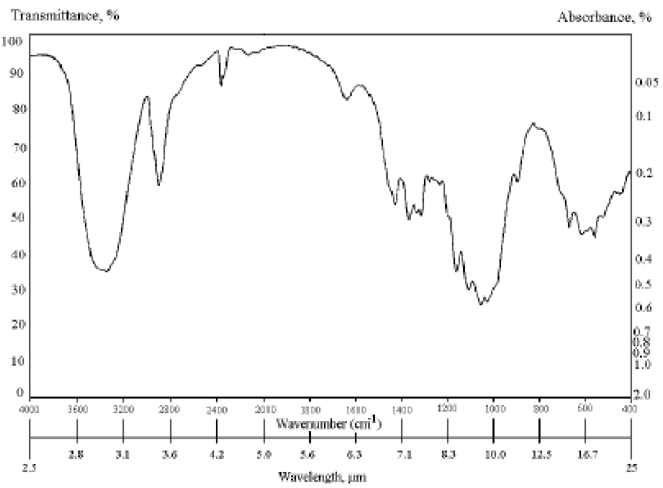


Figure 7. Light transmittance and absorbance of cellulose molecule as function of wavenumber (Anon., 1996).

Maximum values of absorption of cellulose can be found from Figure 7 at following wavelength ranges (Anon., 1996):

- wavelength range of 2.86-2.94 µm (wavenumber range of 3400-3500 1/cm),
- wavelength range of 8.30-10.00 µm (wavenumber range of 1000-1200 1/cm)
- wavelength range, which is larger than 14.29 µm (smaller wavenumbers than 700 1/cm)

Figure 8 shows infrared spectra of cellulose in various temperatures (Soares et al., 1995). Main absorption peaks of pure cellulose at room temperature are following wavelengths as it can be seen from Figure 8 (Jain et al., 1982):

- 3.0 µm (wavenumber 3347 1/cm) OH, hydrogen bonded
- 3.4 µm (wavenumber 2901 1/cm) CH group
- 6.1 µm (wavenumber 1637 1/cm) OH, absorbed water
- 7.0 µm (wavenumber 1428 1/cm) CH_2
- 7.3 µm (wavenumber 1377 1/cm) CH, bending
- 7.6 µm (wavenumber 1320 1/cm) C-OH, bending
- 8.6 µm (wavenumber 1167 1/cm) Glucopyranose ring
- 8.8-10 µm (wavenumber 1130-1000 1/cm) OH
- 11.2 µm (wavenumber 894 1/cm) CH

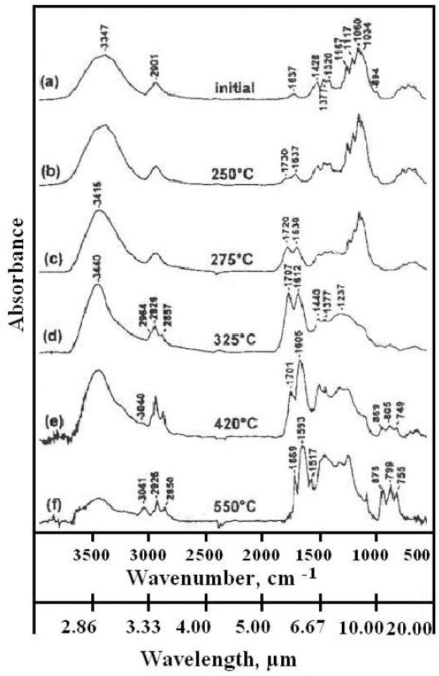


Figure 8. FTIR of cellulose in different temperatures (Soares et al., 1995).

As it can be seen from Figure 8, infrared spectra solid residue at temperature of 250 ºC is similar to cellulose at initial temperature. At the same time, weight loss of about 31 % have been reported for the temperature of 250 ºC. A band of wavelength 5.78 µm (wavenumber 1730 1/cm) in infrared spectra is due to appearance of carbonyl functionalities.

From Figure 8 it can be also seen that the intensity of absorption peaks of glucosidic structure (wavelength range of 8.3-11.1 µm) decrease with heating and glucosidic structure complete degradation was observed at 325ºC (14 % of solid residue remains). At the same time, there is an increase in intensity of absorption peak of double bond (wavelength range of 6.11-6.20 µm; wavenumber range of 1637-1612 1/cm) and carbonyl (wavelength range of 5.78-5.86 µm; wavenumber range of 1730-1707 1/cm).

It can also be concluded from Figure 8 that aliphatic structure (wavelength range of 3.33-3.57 µm; wavenumber range of 3000-2800 1/cm and wavelength 6.94 µm; wavenumber 1440 1/cm) appeared, when cellulose was heated to temperature of 325ºC. A cross linked unsaturated aliphatic-carbonylic structure was formed and that was seen precursor of char. A new wavelength 6.59 µm; wavenumber 1517 1/cm (which corresponded to aromatic semicircle stretching) was observed at temperature 550ºC what was related to carbonisation and formation of char stable at these temperatures (Jain et al., 1982; Soares et al., 1995).

2.5 Laser cutting mechanism and equipment

The main laser types include CO_2, Nd:YAG, diode, fiber and disk lasers. CO_2 lasers are often used for processing of wood and wood-based materials (Piili, 2009). Application of Nd:YAG and diode lasers to processing of paper materials was shown in few studies (Kolar et al., 2000; Pages et al., 2005). Fiber and disk lasers emit laser radiation with around 1 µm wavelength. However, documented application of either lasers type for cutting of paper or paper based materials was not find.

2.5.1 Principle of laser cutting of paper material

The laser cutting process of paper, as with most wood-based materials, is a thermochemical decomposition process. The principle of laser cutting process applied to paper material is shown in Figure 9 (Piili, 2009).

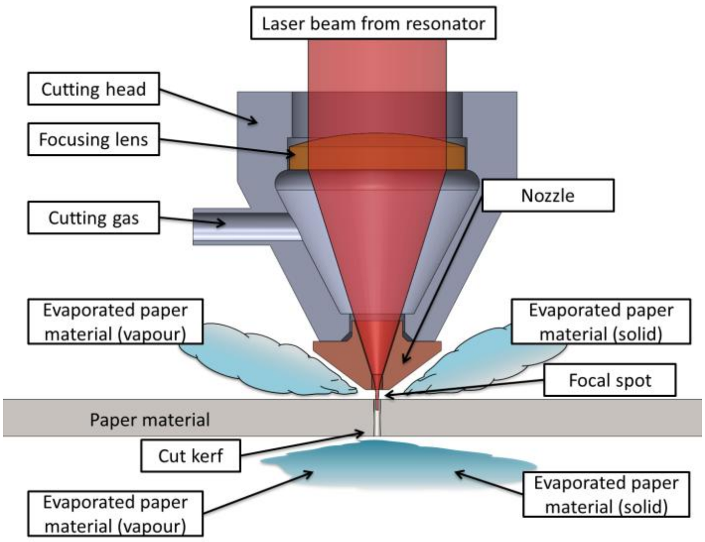


Figure 9. The principle of laser cutting of paper (Piili, 2009).

As can be seen from Figure 9, cutting process of paper with laser is considered as vaporization cutting. When the laser beam reaches the surface of the work piece it heats up the material to its evaporation temperature and causes the material to sublimate. The energy from the laser beam interacts with the paper material and breaks chemical bonds resulting in degradation of the material (Piili, 2009).

Laser beam significantly differs from ordinary light due to its unique characteristics. In comparison to ordinary light, laser beam is highly directional due to photons of same frequency, wavelength and phase. Laser beam allows to achieve high power density per unit of area and focussing characteristics unreachable for ordinary light. This enables the laser beam to be used for material processing of wide range of materials. Moreover, different laser types generate the beam with different properties (Dubey and Yadava, 2008).

2.5.2 CO_2 laser

CO_2 lasers emit the infrared laser radiation with a wavelength of 10.6 µm. Electrical efficiency of CO_2 laser depends on laser type and vary in the rande from 10 to 15%. The laser gas in a CO_2 laser is a mixture of CO_2, N_2 and He gases (ideal mixing ratio 1:4:10), where CO_2 is the laser-active molecule (Ion, 2005).

The main advantage of CO_2 laser, in cutting of paper material, is that it emits wavelength of 10.6 µm which is much easier absorbed by all wood based material than wavelengths from other lasers types (Lum et al., 1999).

There are different designs of commercial CO_2 laser that use different configurations of gas flow and cooling. The CO_2 laser technology includes the following designs: cross-flow laser, fast-axial flow laser, diffusion-cooled laser, slow flow and sealed-off lasers. They can be operated in either the continuous mode or pulsed mode (Steen, 2003).

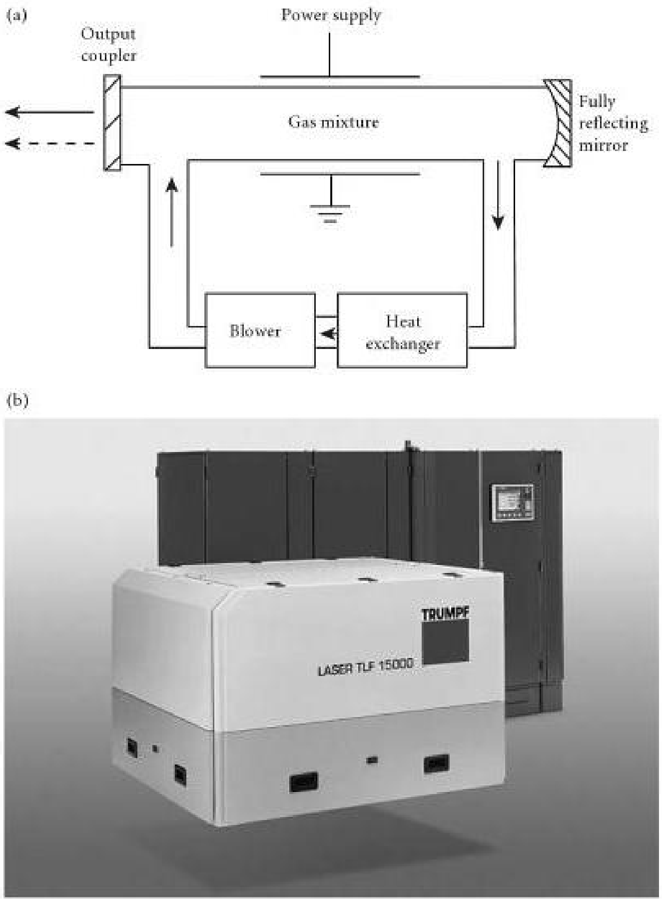


Figure 10. General construction of a fast axial flow CO_2 laser: a) schematic b) industrial Trumpf TLF 15000 laser (Ion, 2005).

Fast axial flow CO_2 laser systems are commonly used in various applications. The construction shown in Figure 10 has an optical resonator consisting of a back end mirror and an output mirror. Different designs of resonators can be used. Turbine blowers are used to produces high speed flow of the gas mixture. This circulating gas mixture is cooled in a heat exchanger. The heat exchangers, which contain deionized water in order to avoid voltage imbalances, cool passing gas mixture heated by the electrode discharge. This type bases its gas cooling on the convection of the gas inside discharge region. Due to the physical principle, fast axial flow design can provide good beam quality what is important in cutting applications. Fast axial flow lasers are limited to about 20 kW power due to requirements for high flow rates of gas what leads to difficulties in maintenance (Ion, 2005).

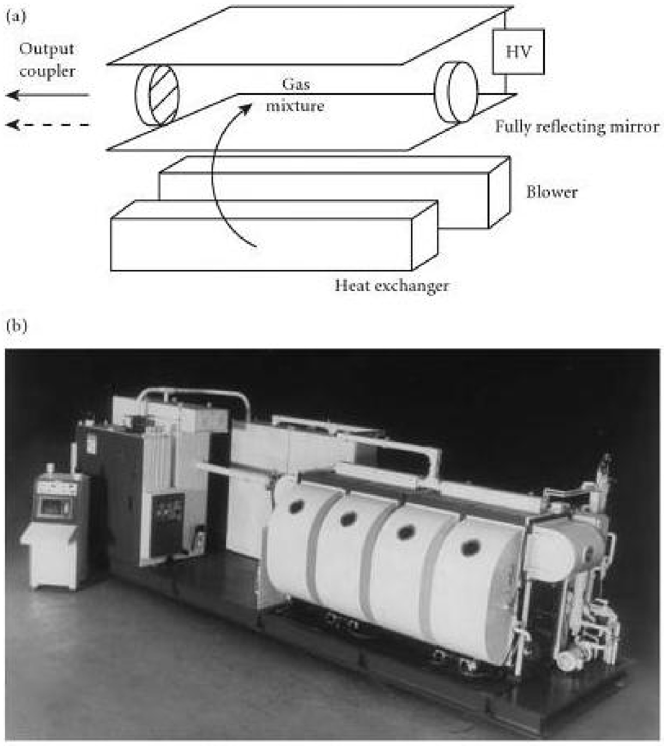


Figure 11. Construction of transverse flow CO_2 laser a) schematic b) industrial Prima Industrie 24 kW laser (Ion, 2005).

Figure 11 shows the construction of transverse flow CO_2 laser. High power output requires ability to excite large volume of gas. This can be achieved with transverse flow laser design. Laser gas flow in this case is oriented transverse to the resonator axis. In this design, a tangential blower is located inside the laser chamber. Relatively slow gas flow (about 10 % of gas flow in fast axial flow designs) is generated what reduces flow rate losses. Transverse flow lasers can be relatively easily made in modules what makes it possible to scale it to high power outputs. Gas consumption and operating voltages are lower compared to fast axial flow lasers. However, beam quality is lower and transverse flow lasers are usually used for such material processing operations as thick section welding and surface treatment of large areas (Ion, 2005).

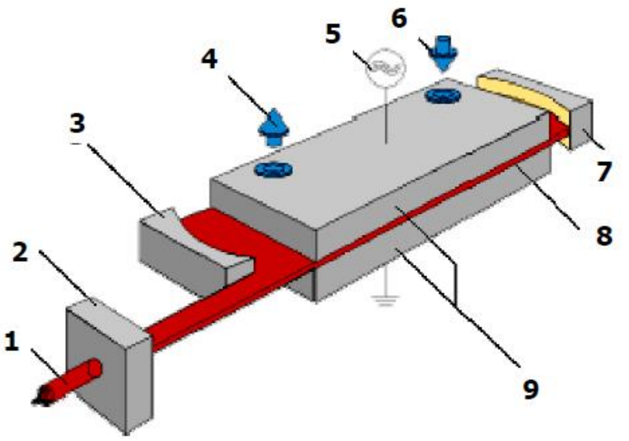


Figure 12. Diffusion-cooled CO_2 laser: 1-Laser beam, 2-Beam shaping unit, 3-Output mirror, 4-Cooling water, 5-RF excitation, 6-Cooling water, 7-Rear mirror, 8-RF excited discharge, 9-Waveguiding electrodes (Steen, 2003).

CO_2 diffusion-cooled lasers can have a relatively compact construction which is comparable to modern fast-flow lasers. This laser type is equipped with large-area electrodes, between which the radio frequency gas discharge takes place. Due to the narrow inter electrode space, heat can be effectively removed from the discharge chamber via directly water-cooled electrodes. Thus, gas flow circulation is not required in this design. Small changeable cylinder of gas mixture, mounted near the head, is required. This design contributes much to its comparatively high power density. Slab laser occupies only about 15 % of volume of a fast axial flow design with equal power (Ion, 2005). Maximum power output is currently reaching up to 8 kW. However, lasers intended to be applied for cutting of non-metallic materials, like wood or textile, are available up to 4.5 kW (Anon., 2015a).

2.5.3 Nd:YAG Laser

Nd:YAG lasers emit light with a wavelength of 1.064 μm. This type of lasers have an electrical efficiency below 5% when excited by means of gas discharge lamps. The host material is a synthetic crystal of yttrium-aluminium-garnet (YAG) that is doped with a low percentage of the rare earth metal neodymium (Nd3+-ion). The excitation of the active medium is produced by optical radiation from flash lamps, arc lamp or laser diodes. Cooling is one of the main restricting reasons for Nd:YAG lasers when power output exceed 2 kW since around 50 % of electricity consumption transforms to heat inside laser rod. Nd:YAG lasers have lower power output and lower beam quality compared to CO_2 lasers (Steen, 2003; Ion, 2005).

The main application of Nd:YAG laser, in relation to processing of paper material, is laser cleaning of paper and parchment artefacts (Kolar et al., 2000). The advantages of Nd:YAG lasers are higher flexibility compared to CO_2 lasers; Nd:YAG lasers are compact and beam of the Nd:YAG laser can be transported via optical fiber (Steen, 2003).

2.5.4 Diode laser

Diode lasers are based on semiconductors like GaAs (Gallium Arsenide) or GaAlAs (Gallium Aluminium Arsenide) and others. They are excited by an electric current into p-n junction. The p-n junction is formed by p-type and n-type semiconductors. These two semiconductors are joined together in a very close contact. The best developed materials of p-n junction are GaAs and GaAlAs. They can emit a radiation with wavelength from 750 to 870 nm. InGaAs (Indium Gallium Arsenide) is able to emit in the range of 900-1000 nm (Steen, 2003).

Diode laser was applied for cutting of paper material. Single emitter diode laser was used for cutting of paper material with infrared-absorbing ink. However, the addition of ink is necessary in order to reach adequate absorption of the diode laser light to be able to cut the paper material (Pages et al., 2005).

2.5.5 Beam focus principles

Laser beam, which is coming out of output mirror of the laser, is not directly used in material processing as it may be between 15 and 70 mm in diameter. Raw beam given as laser source output have to be modified for material processing. Mirrors are used to deliver beam to the work piece. Focusing lenses are used to reduce beam diameter in order to obtain higher energy density. Focal length is the distance from the centre of the lens to the focal point. Optics with large focal length can provide greater distance from workpiece what allows to reduce possibility of damage and provide more space for other equipment. On the other hand, the focal length has a large impact on the size of the focal spot and energy density. (Ion, 2005; Li, 2009)

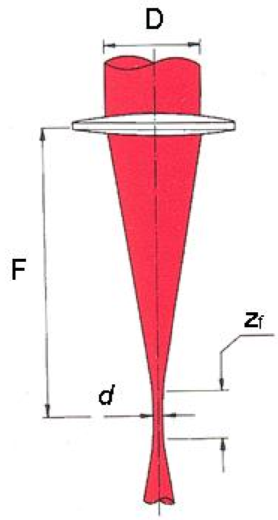


Figure 13. Focus properties of a laser beam (Ion, 2005).

According to scheme of the focus characteristics of a laser beam shown in Figure 13, the size of the focal spot can be obtained with Equation (9) (Ion, 2005).

$$d = \frac{4\lambda}{\pi}\frac{f}{K} \tag{9}$$

where	d	diameter of the focal spot, m
	f	focal number
	λ	wavelength of the laser light, µm
	K	beam quality factor.

Smaller focused spot diameter is obtained with short focal length, shorter laser wavelength and a beam of lower order mode (Ion, 2005).

The depth of focus (also referred as depth of field) is the length of focused beam where approximately the same intensity is achieved. The depth of focus is usually defined as the distance in which the focal spot size variations lie within ±5% range. The depth of focus can be obtained as Equation (10) shows: (Ion, 2005)

$$z_f = \frac{4\lambda}{\pi K}\left(\frac{F}{d_B}\right)^2 \tag{10}$$

where z_f depth of focus, m

d_B diameter of the incident beam, m

The depth of focus is directly proportional to the square of the spot size of the laser beam. Smaller spot size results in shorter depth of focus. These two values should be compromised in practical application. High power density can be achieved with small spot size whereas large depth of focus is required for processing of thick materials. A rough estimation of depth of focus is approximately 2 % of its focal length (Ion, 2005).

2.5.6 Beam transfer equipment

There are two types of optic used for CO_2 laser beam manipulation: transmissive and reflective. Transmissive optic can be used for power levels of about 5 kW whereas reflective optics can be also used with higher power levels (Ion, 2005).

Basic principles of beam manipulations are shown in Figure 14.

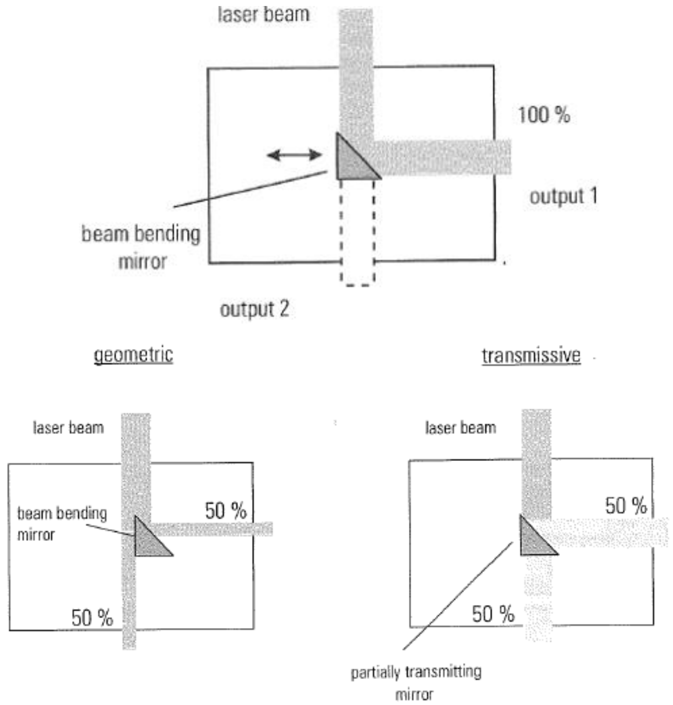


Figure 14. Principles of CO_2 laser beam manipulations: a) bending mirror b) geometric beam splitting c) beam splitting with partially transmitting mirror (Wirth, 2003).

Transmissive optics can be used up to 5 kW power due to thermal expansion of the mirrors and change of refractive index of mirrors material when this limit is exceeded. Cooling is possible around the edges of a mirror. Cooling of lens middle part can be achieved by blowing a gas across lens face but cooling rate is limited. All lenses are sensitive to contaminations. Dirt particles may be burned on the surface creating an area of thermal distortion and diffracted light (Ion, 2005).

Transmissive optic is relatively easy to set up whereas reflective optic requires precise alignment. One of the objective of beam transfer optical system is to reduce number of components because each mirror absorbs about 1 % of incident light (Ion, 2005).

The path of the laser beam in between mirrors can be protected by tubes what is important when working in dirty environment. Contaminations and internal atmosphere control is an important procedures in order to prevent distortions of the laser beam (Ion, 2005).

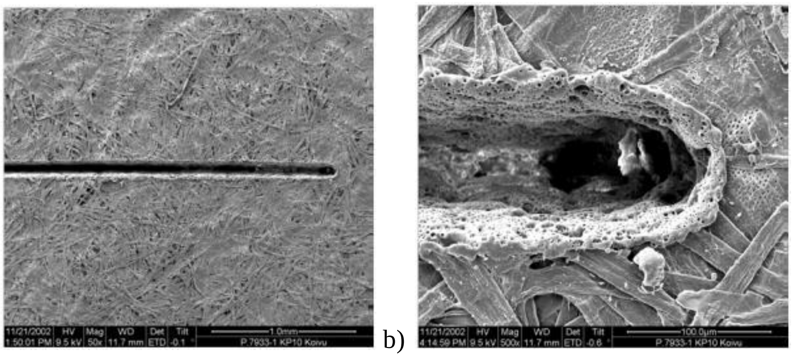
2.6 Laser cutting of paper and pulp

2.6.1 Laser cutting of pulps

Malmberg et al., (Malmberg et al., 2006 (a)) concluded that birch, pine and CTMP pulp could be cut with CO_2 laser. Relation of cutting speed to laser power was observed as linear when increase of cutting speed required higher laser power. Calendaring level, which varied in the range 0 to 180 kN/m, did not have influence on the quality of laser cut kerf. It was noted that the required laser power for high cut quality increased with increase of water content of samples. When suitable cutting conditions were used, cutting kerf width was stable. Laser cut kerf width increased with increase in grammage and thickness (Malmberg et al., 2006 (a)).

The study of Malmberg et al., (Malmberg et al., 2006 (a)) did not show any visible colour change in cutting kerfs of birch and pine pulp samples. Increase of laser power with constant cutting speed did not cause any visible colour change or carbonization in kerfs of pine and birch pulp as well. Only CTMP tended to have visible yellow colour in the cutting edge when excess laser power was used. The cause of visible colour change was in composition of CTMP, which included all wood components, particularly lignin.

Cut kerf edge was fused and sealed in pine and birch samples (can be seen in Figure 15 b). In CTMP samples cut edge was also fused but some out sticking fiber ends could be seen (Hovikorpi et al., 2004).



a) b)

Figure 15. SEM (scanning electron microscopy) micrograph from 175 g/m^2 birch pulp sample. Figure a) Cutting edge, b) Close view on the end of cutting edge (Hovikorpi et al., 2004).

Similar observations were made when laser radiation was applied for treatment of wood samples. CO_2 laser was used to irradiate wood surface. Laser radiation resulted in effect similar to melting of laser treated material. Cellulose fibres were exposed to laser radiation as well and it resulted in thin molten layer on top surface (Panzner, 1998).

Melting of cellulose with assist of laser beam was reported as well. Cotton fibres, which are very close to wood cellulose fibres, were exposed to both IR and UV laser radiation. As a result of interaction with laser beam, disappearance of cotton fibres was noticed. Instead, viscous substance was formed, comprising fibre structure inside. It was also noticed that increase of laser intensity resulted in cotton fibres degradation (when laser intensity reached 19 W/mm^2) (Schroeter and Felix, 2005).

2.6.2 Laser cutting of boards

In a study, carried out by Malmberg et al. (Malmberg et al., 2006 (a)), board was found suitable for laser cutting with CO_2 laser. The grammage of the samples varied between 210 and 500 g/m^2, thickness was in the range from 215 to 650 µm. The highest cutting speed possible to cut certain thickness in relation to laser power is linear, except with coated boards where nonlinear behavior can be noted. Cut edge of board samples was fused and sealed. Boards with contents of CTMP/PWG (pressured ground wood) had some visible fiber ends in cut edge (Malmberg et al., 2006).

When laser power is increased without change of cutting speed, it leads to appearance of visible color change in cutting edge. This evaluation of color change was carried out by human eye. Cutting edge turned yellow with excess laser power. The cause of this is related to CTMP/PWG content of material (Malmberg et al., 2006 (a)).

2.6.3 Laser cutting of paper

Malmberg et al. noticed that papers like LWC (light weight, two-side coated), CWF (coated wood free), SC (supercalendered) and newsprint are suitable for laser cutting. Paper grades with higher mineral pigments content required higher amount of laser energy in order to produce complete cut (Malmberg et al., 2006 (a)).

Pages et al. tested laser cutting of paper material with diode laser. Ordinary copy paper was used for laser cutting. However, laser cutting was not possible due to absorption properties of diode laser beam. Laser cutting of paper with diode laser was done with addition of ink, which absorbs the wavelength of diode laser. Addition of ink allowed absorption of diode laser wavelength of 810 nm. Image of cut kerf can be seen in Figure 16 (Pages et al., 2005).

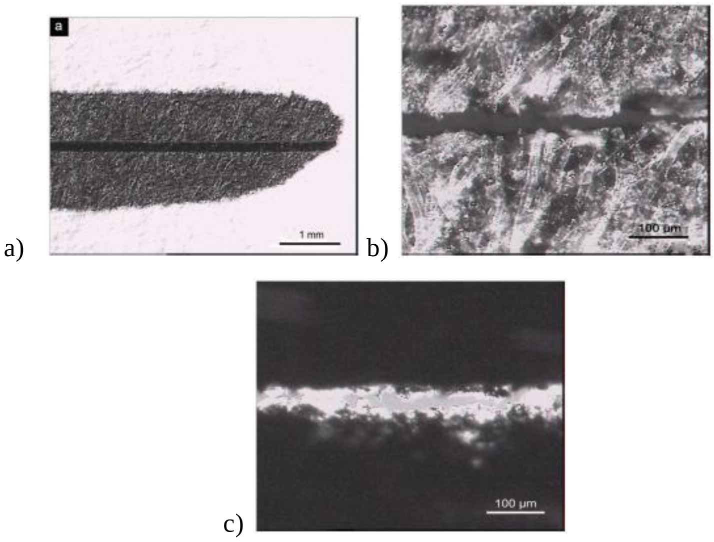


Figure 16. Cutting kerfs: a) cutting kerf in the area with ink; b) magnified image, top view c) magnified image, opposite side of the laser cut sample paper (Pages et al., 2005).

Dark area represents application of ink. Laser beam did not have any effect on the area not treated with the ink, as it can be seen in Figure 16(a): laser cut kerf did not continue out of area treated with ink. Figures 16(b) and 16(c) provide closer view to cut kerfs structure (Pages et al., 2005).

Pages et al. (Pages et al., 2005) reported laser cutting experiments with invisible Near Infrared (NIR) ink. Laser cut edge can be seen in Figure 17.

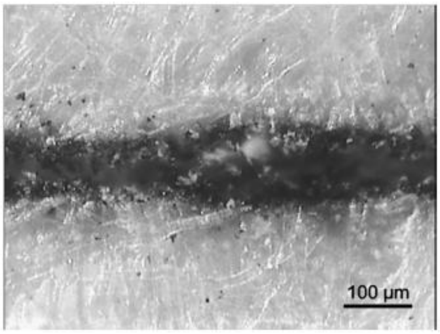


Figure 17. Cut kerf done with laser cutting with infrared invisible ink (Pages et al., 2005).

It can be seen from Figure 17 that relatively narrow cut width could be achieved with diode laser. Severe carbonization of cut edges can be observed as well.

Variation of cutting speed and its effect to cutting quality was reported as well. Increase of speed by 20 % leaded to incomplete cutting of paper material. If tearing was applied, rupture of paper material along laser cut kerf occurred. Incomplete cutting was observed with further increase of cutting speed by 50 % what leaded to formation of foldable cut kerfs (Pages et al., 2005).

2.6.4 Comparison of laser cut and mechanically cut edges

Edge quality of paper material is important in many industrial applications. Out-sticking fibre endings may cause problems in processing of paper material as well as reduce quality of final product. As an example, liquid packaging industry has strict demands for edge quality due to liquid absorption properties into cut edge. (Federle and Keller, 1992; Malmberg and Kujanpää, 2006). Figure 18 represents comparison of laser cut and mechanically cut edges studied with Scanning electron microscope (SEM).

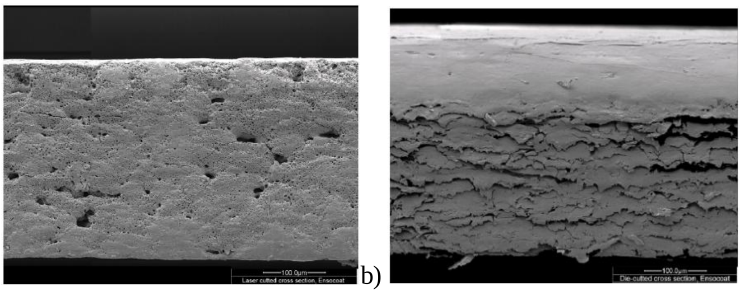
a)  b)

Figure 18. Cut edges: a) laser cut edge b) mechanically cut edge (Malmberg et al., 2006 (b)).

Figure 18 shows advantages in cut edge quality of laser cut paper material compared to mechanical cutting. The amount of dust (solid particles), which was released during laser cutting, was also found lower than in case of mechanical cutting. Laser cutting provided better quality of cut edge, whereas quality of edge cut with mechanical tool was noticeably lower due to application of mechanical force (Malmberg et al., 2006 (b)).

3 PAPER MAKING MACHINE

3.1.1 Overview

Generally, an average paper making machine consists of four sections: forming (or wire) section and press section, which can be called together as wet end, drying section and reel (or tambour). Depending on the paper grade produced, calendering section may be also included. These are the basic sections which are found in almost all papermaking machines. However, individual designs of paper making machines vary significantly depending on paper grades produced (Paulapuro, 2007).

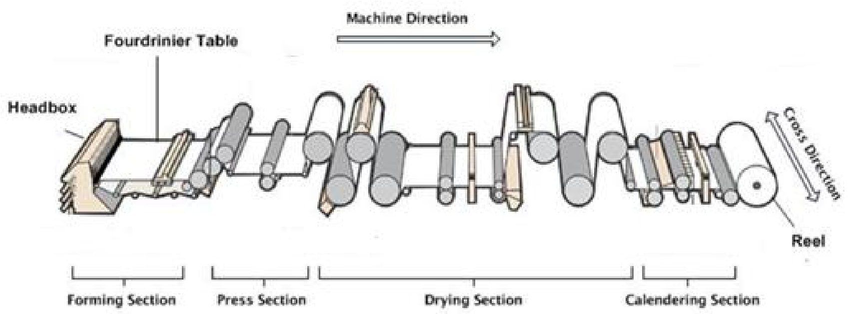


Figure 19. Basic scheme of paper making machine (Chu et al., 2011).

Due to strong tendency of pulp fibres to flocculate, dry matter content of pulp slurry in the headbox is around 1 % whereas water occupies around 99%. Paper making process can be considered as process of continuous water removal along paper making machine. Pulp slurry is fed onto the revolving wire from the headbox. Water removal process starts from this point along with travel of wire. Distribution of fibres and their alignment is controlled in order to obtain uniform properties of paper web. Dewatering process allows to rise pulp content from 0.5% to 25% (Niskanen, 2008).

Dewatering process continues in press section where wet paper web travels through series of roll presses. The aim of the pressing is to remove as much water as possible. Paper web travels with support of felts. The felts serve double purpose of supporting paper web and enhancing water removal by absorption. Dry matter content of paper web consistency can reach up to 40% before drying section (Niskanen, 2008).

Rolls (or cylinders) heated by steam in the drying section cause further water removal through evaporation reducing the moisture content down to around 6%. Such moisture content remains in paper material at indoor atmospheric conditions. In the drying section the paper web can be additionally treated with different methods such as sizing or coating in order to modify the characteristics of the paper surface. Paper surface is covered with calcium carbonate or kaolin for coated papers in order to obtain desired properties. Calendering section allows to increase smoothness of the surface of the paper. Paper web passes between a number of calender rolls in order to treat both sides of paper web. If papermaking machine has a coating unit, calendering changes the characteristics of the coating (Niskanen, 2008).

Efficiency of a paper making machine generally depends on work time. This, in turn, depends on number of planned and unplanned production breaks (Paulapuro, 2007).

Table 3. Efficiency of modern paper making machines (Paulapuro, 2007).

Grade	**Total efficiency, %**
Newsprint	90
Supercalendered paper	90
Lightweight paper	82
Woodfree paper	92
Tissue paper	85
Linerboard	85
Folding boxboard	82

3.1.2 Sheet formation in the wire section

The process of paper web formation starts when the pulp suspension is fed from headbox to the wire. At the same time, water drains away at the bottom through the wire. Filtration and thickening are two predominant paper web formation mechanisms (Paulapuro, 2007).

The design of forming section vary depending on paper making machine type. In fourdrinier paper making machine, horizontal endless wire is used. This concept allows high flexibility of paper web basic weight and consequently different paper grades can be produced on the same paper making machine. The disadvantage of this type of paper making machine is limited drainage as dewatering takes place only from bottom side of paper web (Paulapuro, 2007).

In order to enhance drainage efficiency and overall efficiency, new designs of wire section were developed. During 70’s concept of so-called twin former (can be seen from Figure 20 a) was applied. The twin former is a design where the second wire and suction boxes are added in order to maintain dewatering from the top side of paper web at the same time as from bottom side. Paper web is dewatered from the bottom side by means of suction and gravity and from the top side by means of suction. Due to this design, drainage time is significantly reduced and efficiency of production process is increased. Additional advantage of this system is that it reduces two-sidedness effect of the paper web (Paulapuro, 2007).

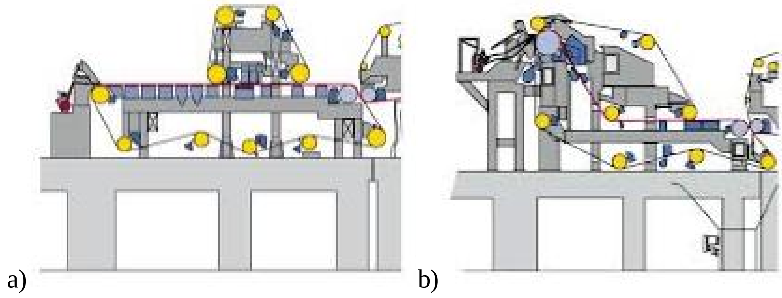


Figure 20. Basic scheme of twin former and gap former (Anon., 2015b).

Twin former concept was often used in rebuilt of Foundrier paper making machines to improve efficiency. Modern high-speed paper making machines required further improvement of dewatering what leaded to concept so-called gap formers (can be seen from Figure 20 b). Dewatering process is maintained from both sides of paper web simultaneously. Pulp suspension is fed directly from the headbox in between two forming wires. Generally dewatering of paper web in forming section allows to obtain dry matter content of 16 -23 % (Paulapuro, 2007).

3.1.3 Press section

After formation of the sheet as such, the paper web has to be further dewatered. The transfer of paper web is done with pick up felt which transfer paper web to press section. Mechanical pressure is used to remove water and increase dry content. Mechanical pressure is applied in between roll presses, which apply specifically set amount of pressure, usually in increasing order from press to press. The water removed by this way from the paper is absorbed and transported by felts. Schematic view of the press section can be seen in Figure 21 (Paulapuro, 2007).

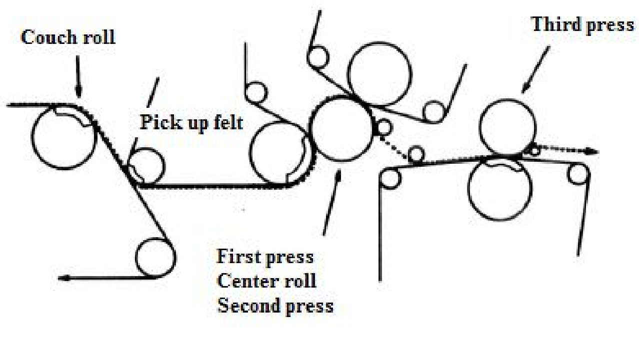


Figure 21. Basic scheme of press section (Paulapuro, 2007).

The main purpose of press section is to remove maximum possible water from the paper web by means of mechanical pressing. Usual dry matter content of paper web when it leaves press section is around 40-50 % (Karlsson, 2009).

3.1.4 Drying section

Paper web has a dry matter content of up to 40-55% when it leaves the press section. Further pressing does not allow removal of remaining water. This water is removed in dry end by vaporization. Paper drying in paper making machines is done through contact of paper web with drying cylinders heated with steam. Paper web is transferred in such a way that it has contact with drying cylinders by both upper and lower side alternatively. Paper web handling in modern paper making machines is done in a way that paper web is always in contact with fabric by one side while the other side is in contact with cylinder (Karlsson, 2010).

The basic principle of paper web drying due to contact with steam heated cylinders remains almost unchanged from its initial development. Another methods of drying are applied in addition to drying with cylinders such as induction, microwave, air-flotation, infrared drying, etc (Karlsson, 2010).

3.1.5 Size press

Size press is used to apply pigments or starch to paper web surface in order to improve surface properties such as surface strength and modify surface chemistry and porosity. Surface sizing also can increase stiffness of paper. Sizing can be also used as pre-treatment before coating. Simple construction of two rubber-coated rolls can be applied for sizing operation (Paltakari, 2009).

Pigments or starch are applied when paper web travels through the press which consist of two soft rolls. Sizing is usually done in dry section when paper web reaches 4 – 11 % of moisture content (Paltakari, 2009).

3.1.6 Calender and rewinder

Improvement of paper surface smoothness and gloss can be achieved in calender. Typical calender consists of number of rolls which allow application of compression, moisture and heat when paper web travels through the rolls. As a result of application of compression, material thickness is decreased after calender. Another modification is improved CD profile of paper web. Calender can be integrated into paper making machine as its part or calender can operate as separate unit (super calender). Paper web properties differ in calender compared to pressing in wet end by lower moisture content (Rautiainen, 2010).

Paper web winding operations include reeling and rewinding. The first operation is winding of tambour roll after paper making machine. The purpose of the rewinder is to convert tambour roll into smaller paper rolls of desired customer size. Edge trimming may be applied in order to remove deficiencies of the paper. Depending on paper type, these reels may be the end product or further cut in cross direction to sheets (Rautiainen, 2010).

Guillotine cutting method can also be applied for paper material processing but usually only for small scale and special applications. This method is not used in high volume production and is not applied in paper making machines. (Rautiainen, 2010).

3.1.7 Cutting operations in paper making machine

Cutting operations are required in many stages of paper making process (Malmberg et al., 2006):

- edge trimming of web in the end of forming section (about 150 – 200 mm cut width),
- edge trimming can be also applied before sizing,
- edge trimming before calender,
- edge trimming of paper web in reel,
- cutting of paper web in cross direction
- cutting (slitting) of web to customer size
- cutting of web in sheets (final product)

Paper making machines need high-capacity machines for high-speed cutting. Conventional cutting methods of paper web are mainly mechanical blade or knife cutting and rotating slitting knifes. Edge trimming with high pressure water jet cutting was applied in paper making industry in 80’s. In late 90´s the first attempts of laser cutting of paper were reported (Malmberg et al., 2006).

In paper making machine, edge trimming of the paper web during web travel is required in certain locations. Edge trimming is used in forming sections, press section and dry section, as well as in calendering or supercalendering and rewinding, using different techniques. In forming and press sections, it is usually water jet cutting, in dry sections mechanical blade cutting is usually used whereas in calendering or supercalendering this trimming step is typically done by means of a mating pair of rotary slitting blades (Caspar, 1997).

Slitting blades, or "slitters" are used to trim paper edges after the coating station. Slitters are also employed in the coating station to cut the paper web prior coating. This is done in order to not allow cracked paper web edges from entering the coater to prevent further associated problems like web breaks (Caspar, 1997).

To avoid the potential hazards associated with directly on paper making machine, slitting of reels is usually done off-machine on a rewinder which is a separate machine used to unwind, edge trim and rewind the parent roll of paper web. Rewinding operation requires significant labor costs to operate in addition to the capital costs of such machine. (Caspar, 1997).

Finding a technique which may lead to reduce of the risk of web brakes (in particular in edge trimming) is important, because one paper web break may cost up to $8000 in lost production time (Caspar, 1997).

Laser cutting of various paper materials was studied, including the aim of laser possibilities to execute cutting in paper making machines. Laser cutting can be applied in paper making machine or in rewinding for slitting of paper web (Schable, 1993). Laser cutting is possible in wet end for edge trimming processes. Hovikorpi et al. reported that laser cutting speed of 4400 m/min was achievable for newsprint paper grade. Such laser cutting speed covered the speed of paper making machine (Hovikorpi et al., 2004). Laser cutting possibilities were also studied for coated boards. Coated paper grades were found suitable for laser cutting. However, formation of plasma plume was noticed. It was concluded that mineral components of coating had direct effect on plasma plume formation. Plasma plume can cause laser beam scattering what leads to power loss. (Malmberg and Kujanpää, 2006).

Malmberg et al. (Malmberg et al., 2006) recommended application of laser cutting of paper material in following processes:

- manual cutting
- small scale production
- digital printing applications
- high requirements for accuracy or complex geometries
- experimental production
- in case of high value products
- in case of the need for high flexibility
- tailor made production

3.1.8 Web breaks

Paper making machines would operate in ideal conditions 24 hours per day throughout a year. However, its operation is interrupted by scheduled and unscheduled stops. Both of them result in production and financial losses. Predicted machine maintenance are usually wire or felt change, different cleaning procedures or planned change of machine components, etc. Unplanned stops are usually caused by failure of paper making machine components or paper web breaks. The cost of such unplanned stop can be estimated a tens thousands euros reaching as much as 40 000 euros per hour, depending on paper machine capacity and produced paper grade (Holik, 2006).

Problem of paper web breaks in wet end was studied by Bonissone et al. (Bonissone et al, 2002). Location of centre roll and open draw after it was studied specifically. Losses of production and work time may account to 5 – 12 % due to web breaks. It was reported that up to 35 web breaks can occur per month with variations of number of web breaks per day. The highest number of 15 web breaks in a single day was recorded. It was estimated that production time lost due to web breaks and consequent stop was 1.6 hours per day (Bonissone et al, 2002).

Physical properties of paper web and particularly strength properties play crucial role in occurrence of web breaks. Elastic modulus of wet paper web is only around 10 % of corresponding value of dry paper (Rautiainen, 2010). Central press roll is of particular interest in regard of wet web brakes. If usually paper web is supported by felt along its movement in paper making machine, paper web travels at this particular location unsupported (so called open draw) from central roll to guide roll. Thus, paper web relays only on its strength what makes it susceptible to brakes being exposed to external forces. Open draw section can be seen from Figure 22. (Bjorklund and Svedjebrant, 2009)

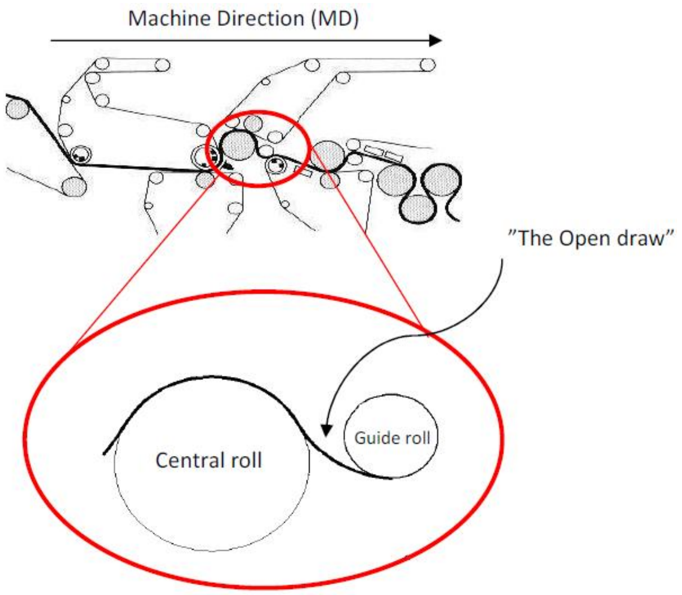


Figure 22. Central roll in a press section and ‘open draw’ (Björklund and Svedjebrant, 2009).

Breaks of the wet paper web after the couch roll or in the wet-press section may be originated in variety of causes. The main reason is paper web properties itself at this stage of the process as tensile strength and stretch properties are very low (compared to dry paper). Any variations in moisture content cause large variations in strength properties of paper web. In older paper making machines, areas of open draw were the reason of web brakes as paper web was transferred unsupported. In modern high-speed machines this problem was eliminated by the use of suction pick up rolls with felt what ensures support of paper web. Web brakes in size press are similar to those in press section. Besides that, application of starch to the surface of paper may cause temporarily weakening of the paper web (Holik, 2006., Cuillo, 1996).

The development of press sections allowed to avoid open draw in pick up. There were several attempts to eliminate open draw in press section but this aim has not been achieved so far. Location of open draw after centre roll is still one of the place where web breaks often occur due to insufficient paper web strength (Paulapuro, 2007)

Distribution of paper web breaks in paper making machine cross direction can be seen from Figure 23.

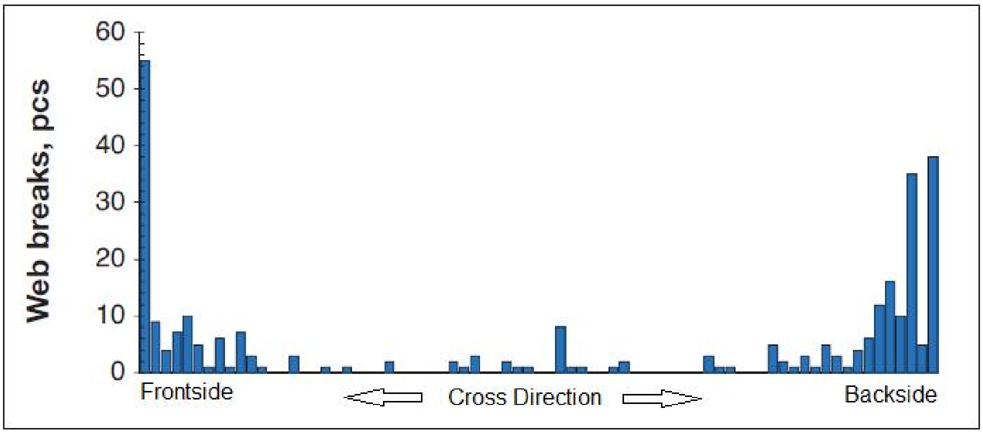


Figure 23. Distribution of paper web breaks in cross direction of paper making machine (Haapala, 2010).

Figure 23 represents observations of web breaks on newsprint paper making machine during 20 weeks. The reasons of web breaks and their distribution in cross machine direction were presented. Holes in paper web did not cause considerable number of web breaks, accounting only 6% of down time during observation period. Edge flips i.e. folding of ragged sheet edges and deposit related web ruptures, accounted for almost 80% of the total detected web breaks during a 20 week survey. Identification of web breakage causes was often problematic as deposits could evolve to holes, which then initiated web failure. Deposits could also be attached to drying cylinders or doctor blades from where the web failure would occur. Edge flips on the other hand are often caused by holes or droplets on the web edges (Haapala, 2010).

As much as 64% of total number of paper web breaks in a paper making machine occur in wet end (Aahola, 2005). Out of this number, 42% of web breaks originated at the edges of the paper web, what can be seen from Figure 23 (Haapala, 2010).

Paper breaks in dry end mainly occurs due to initial defects in paper web. Initiation of the web break is virtually impossible without this defect or local stress concentration. In dry end, 70 – 90 % of the web breaks are observed in calendaring area (Rautiainen, 2010).

In rewinder, reeling defects (most common defect is wrinkles) lead to web breaks. In the past, the reason of reeling defects of paper web was poor function of machine control systems. Nowadays, this problem was significantly reduced by implementing good machine control systems in high-speed paper making machines. However, reeling defects are still present, mainly caused by poor CD properties of paper web (Rautiainen, 2010).

3.1.9 Water jet cutting

Water jet is considered as good alternative in trimming of the paper web edge allowing to avoid the disadvantages associated with the use of mechanical blade cutting. The pressure of the water jet has to be sufficient to cut through paper web. Changes in tension, which can result in wrinkled paper web edge, have no apparent effect on the ability of water jet cutting to provide a clean cut without tearing (Kershaw, 2015)

Water under high pressure (100 – 400 MPa) is guided through nozzle with typical diameter of 0.1 – 0.4 mm. This creates narrow water jet with speed of about 400 – 1000 m/s. Surface pressure, which is created by water jet, has to be higher than strength of the paper material to obtain the cut (Hyvönen et al., 2000). Water jet edge trimming in operation can be seen from Figure 24 (Kershaw, 2015).

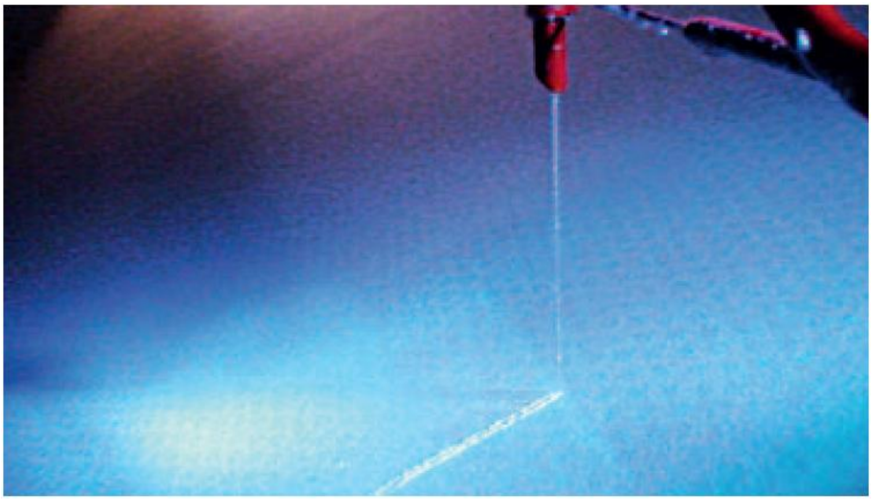


Figure 24. Water jet edge trimming in operation (Kershaw, 2015).

Efficient trimming significantly reduces breaks. Requirement for efficient paper making machine process is trimming paper web edges at the end of the forming part, before the paper enters the press section. High quality of cut edge is essential as it allows to avoid web breaks in press section as well as at locations of open draw after press section when paper web enters drying section and even at further stages of paper making process (Kershaw, 2015).

On Fourdrinier machines the water jet cutting systems are generally installed before the suction couch roll. After the water jet creates a cut, trimmed stripes are transported by wire for recycling. Thus, trimmed stripes are not picked up into press section. Positioning of the edge trim cutting systems on gap-former machines is recommended after the suction couch roll if it is possible in paper machine construction. Positioning before the suction couch roll creates the risk of improper separation of trimmed stripes of paper web after couch roll, especially with a less than optimal cut quality. This causes improper separation at the pick-up, espessially in modern high speed paper making machines. This can be eliminated by positioning of suction zone leaving trimmed stripes out (Kershaw, 2015). Layout of edge trimming water jet unit can be seen from Figure 25.

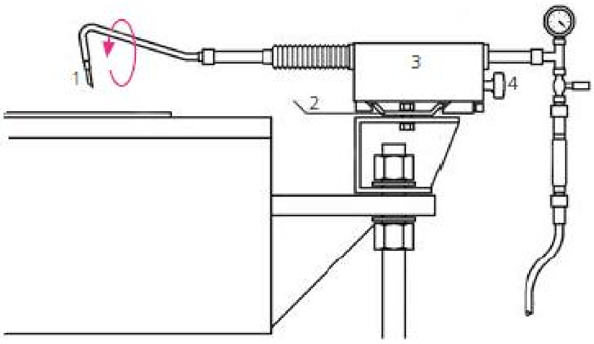


Figure 25. Edge trim nozzle unit layout (Kershaw, 2015).

As Figure 25 illustrates, typical water jet cutting unit consists of nozzle (1), support plate (2), nozzle support (3) with possibility of manual adjustment (4). Support plates of water jet units usually provide possibility of fast removal for fabric change. Water jet should cut through the paper web with good quality (complete cut with clean edge). At the same time, water jet also partially penetrates the forming wire or fabric. Paper making machines with speed of approximately 500 m/min can use single water jet nozzle. This applies for both, single layer and multi-layer fabrics. At medium and high paper making machine speeds, single nozzle can operate satisfactorily for trimming lightweight paper grades. Water jet nozzles require precise positioning in this case (Kershaw, 2015).

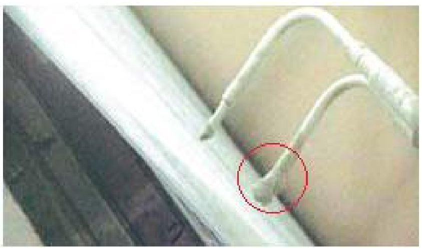


Figure 26. Contamination of the second water jet nozzle due to fibre mist (Kershaw, 2015).

As it can be seen from Figure 26, build up occurred in the second nozzle. The water jet impinges the paper web at speeds which exceed 615 m/s. The energy of this impact transforms the fluid into a gaseous state. Consequently, the cloud of dispersed water and paper material particles results in a cloud which deteriorates the nozzle of the water jet. (Caspar, 1997). Two single nozzles are not usually used in high speed paper making machines, and especially on machines with suction pickup, due to this reason. Twin nozzles allow to solve this problem. This type of system employs two water jets which are positioned slightly out of alignment. First water jet initiates the cut and the second water jet allows to achieve complete cut with good quality to ensure proper separation of trimmed edges at pick up (Kershaw, 2015).

Paper web breaks which occur in the press section, in the drying section, as well as in size press or in the coating machine may be caused by improper functioning water jet system what leads to deterioration of cut edge quality. There are number of problems associated with using water jet which effect trimming operation. Laminar flow is the most essential parameter which determine cutting quality (Kershaw, 2015).

Many problems in cut edge quality are caused by formation of turbulent flow in water jet cutting. Excessive fibre misting can be also caused by turbulent jet flow (Kershaw, 2015).

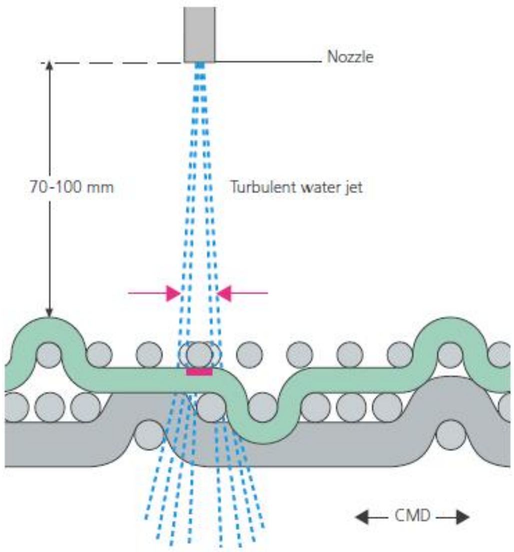


Figure 27. Water jet turbulent flow formation (Kershaw, 2015).

Figure 28. Water jet cut edge quality with turbulent flow (Kershaw, 2015).

Figure 28 shows deterioration of cut edge quality which can be seen as out sticking fibres and curliness. Cut edge quality cut with water jet system depends on many factors such as water jet pressure, diameter of nozzle, distance between nozzle and paper web and speed of the web. Deterioration of cutting quality can occur, especially in case of turbulent flow. Pre-filtration (particle size of 50 µm or less) of water for edge trimming allows to improve system performance. Temperature of nozzles has an effect on contamination build up. Temperature of nozzle higher than ambient air temperature allow to prevent contamination build up on the nozzles. Temperature of water also improves quality, usually it can be set from 50º to 60º C (Kershaw, 2015; Malmberg and Kujanpää, 2006).

3.1.10 Slitting blade cutting

The problem associated with the use of slitting blade cutting is dust formation and wear of blades. Experiments on blades wear characteristics determined the mechanism of wear occurrence to be due to abrasion in both cases with and without presence of paper dust. Open cut distance of 0.35 mm was critical limit for paper grammage of 70 g/m^2 which determined the life time of blades (Anstice et al., 1981).

Abrasion wear of a two-body and three-body mechanisms were confirmed by investigation of worn blades from different paper mills. Carbide particles, which originated from the surface of the blades, were predominant reason of wear. In three-body mechanism, hard dust particles released from the paper web while cutting process were additional cause for wear. Investigation of abrasion tracks dimensions suggested that the three-body mechanism occurred more often in paper web cutting. This was due to quartz, which is a minor constituent of paper fillers, presence in dust. Cracking due to fatigue was another factor influencing wear of blades. Cracking was caused by chipping of blade tips and can be connected early stages of wear when high cyclical stresses occurred. Thus abrasive wear and fatigue cracking results in loss of cut quality and can be attributed to changes of cutting mechanism from shear to tensile cutting (Anstice et al., 1980).

It can be said that there are number of disadvantages associated with the use of slitting blades in paper making process. Blades require high maintenance due to abrasive wear caused by filler materials such as quartz, calcium carbonate or titanium dioxide. Slitter blades may also cause jamming what, in turn, leads to paper web breaks. Also, slitter blades are very sensitive to paper wrinkles that enter the slitting zone and result in tearing of the paper web which starts from the edge (Caspar, 1997).

3.1.11 Laser cutting in paper making machine

Results of laser cutting implementation for edge trimming in paper making machine were reported by Ojala (Ojala, 2006). Trial laser cutting of the paper web edge were performed against cutting table (used for water jet cutting) and roll. The cutting table for high pressure water jet trimming had to be modified to make it suitable for the laser cutting. The same laser parameters and similar paper grades were used. Required laser power was higher in case of laser cutting against the roll compared to cutting table. For the paper roll cutting trials, two laser units were required, one laser source for each edge.

Laser cutting clearly demonstrated its capability to be applied in edge trimming of paper web. All paper grades produced on Changshu PM 1 at their maximum running speed could be cut with the laser. The laser beam focal point position needed to be ± 0.75 mm from the top paper web surface to give the optimal cutting quality. Laser cutting was capable to produce excellent quality of the paper web edge (Ojala, 2006).

4 Economic aspects

An important part of a new technology implementation is economical aspect. The aim of economical estimation is to provide general view on whether new technology brings economic benefits of its use compared to conventional technique or the cost of implementation is on the reasonable level in case if it is more expensive over conventional technique.

Generally, costs can be defined as economic resources needed to accomplish work operations and receive work outputs. Broad classification of the costs consists of fixed and variable costs. Acquisition cost of equipment has to be taken into account as well. Fixed costs are the costs which can be identified specifically to the end product (or function as in case of laser cutting). Variable costs are the costs, which are dependent on performance and rate of production (Harnicarova et al., 2012).

Total cost of laser source ownership is determined by following factors (Rath and Brettschneider, 2014):

- gas consumption,
- consumption of electrical power (including stand by),
- consumption of optical elements and
- consumption of other spare elements (gas mixing elements, filters, spare parts for blowers or turbines)

The rate for one meter cut of water jet cutting was estimated about 4 €/m. The cost of running of water jet cutting system was in the range of 40 - 50 €/h (Radovanovich, 2007).

Zheng et. al. (Zheng et al., 1996) provided comparison of cost on laser cutting and abrasive water jet cutting of steel of different thicknesses. According to the study, cost of laser cutting was found in the range from 37 €/h to 42 € / h. Water jet cutting cost for the same operations was found as 50 € / h. It was found that when higher cutting speed were required, laser cutting is more beneficial. However, the disadvantage of laser cutting was high initial investments.

Comparison of laser cutting and water jet cutting was provided by Immonen (Immonen, 2005). Laser source used was TRUMPF 2.7 kW CO_2 laser. Cost of laser cutting system used for edge trimming was higher compared to water jet edge trimming. Costs dependent on assemble of laser cutting systems as different schemes were studied. Figure 29 provides the comparison of different laser assembles to conventional water jet cutting system (Immonen, 2005).

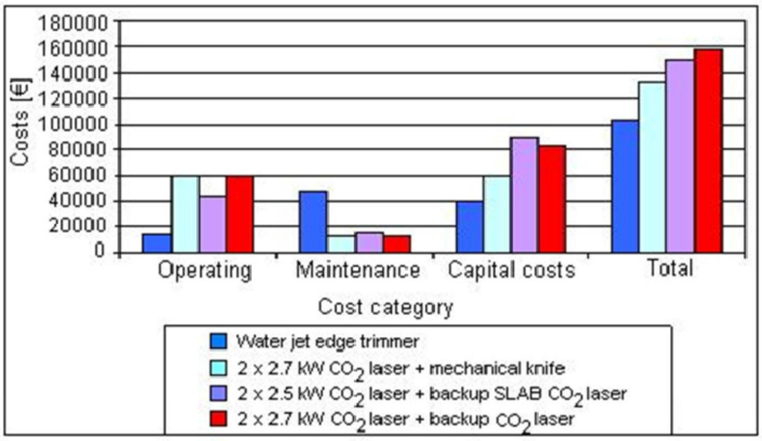


Figure 29. Water jet quality and laser cutting: comparison of costs (Immonen, 2005).

As it can be seen from Figure 29, operating costs of laser systems are 45000 – 60000 €/year, which is nearly four times bigger compared with the water jet cutting system. Because of high electricity consumption due to poor efficiency of laser. The second reason for higher operating costs is laser gas expenses. (Immonen, 2005).

5 EXPERIMENTAL PART

Based on the findings of literature review, preliminary selection of laser application area can be carried out. The selection is based on comparison of laser cutting technology to conventionally applied cutting methods. One of the main criteria in selection process was possibility of laser cutting technology to solve existing problem or problems associated with the utilization of current technology. Discussion on associated risks of laser cutting implementation was also provided.

Experimental part includes calculations of needed laser cutting power to perform cutting for chosen location. Equation (8) for defining needed linear cutting energy was used to obtain laser cutting parameters.

Laser cutting testes were executed according to calculated parameters. Aim of laser cutting tests was to verify calculated linear cutting energy for both dry and moist paper samples. Verified linear cutting energy was used for laser cutting of paper samples for tensile strength measurements and dirt particles tests.

Practically verified linear cutting energy was also used to obtain laser equipment parameters, which provide desired cutting results in conditions of a paper making machine. Based on laser equipment parameters, schemes of laser cutting implementation were suggested.

Economic performance was evaluated as comparison between total costs of laser cutting system and water jet cutting system working in the same conditions.

5.1 Aim of experimental part

Aim of experimental part was to find out possible areas of application of laser cutting in paper making machines. The cutting procedures needed in a paper making machine were described in literature review. Based on the obtained data, areas suitable for laser cutting implementation were defined.

The most promising areas where laser cutting could be applied in a paper making machine were defined to be: edge trimming in wet end, edge trimming in reel or calender and slitting of web to customer width. Figure 30 provides overview of described locations.

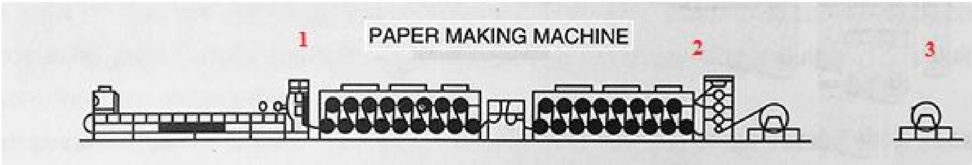


Figure 30. Possible application areas of laser cutting according to cutting need in paper making machine: 1 – wet end (edge trimming with water jet), 2 - dry end (slitting blades) and 3 – rewinder (slitting blades).

Selection of the most promising and reasonable application area of laser cutting was carried out. The application area was chosen based on the findings of literature review. When possible areas of laser cutting implementation were defined, comparison of such implementation was carried out from technical, run ability and economical point of view.

Another aim was to develop a measurement and testing procedure for investigation of possible effect of paper material after interaction with laser light. Appropriate calculation method, necessary parameters which have to be measured and possible ways of data analysis were described according to this purpose.

Laser tests were executed with commercially available copy paper both dry and moist. Laser parameters, such as laser speed, focal position, were verified in such a way that laser cutting could be done at a paper making machine. This means that laser power needed to provide cutting of corresponding paper making machine speed was used for determination of laser equipment.

Economic performance evaluation was done with the aim to compare cutting system used in pre-selected area of intended laser cutting implementation with laser cutting system. Conclusion on the economic benefits of laser cutting implementation was provided. Possible ways of reduction of laser cutting costs were suggested. The calculations were based on the parameters and equipment required from laser cutting system to accomplish cutting of paper web.

The experimental part was carried out in Laboratory of Laser Processing at Lappeenranta University of Technology. The laser equipment was TRUMPF TLF 2700 carbon dioxide laser. The wavelength of this laser was 10600 nm. Tensile strength testing was carried out using Lorenzen and Wettre tensile tester in Pulp and Paper Laboratory of Lappeenranta University of Technology.

5.2 Laser cutting in paper making machine: defining area of application

Laser cutting can be applied for longitudinal cutting in a paper making machine. Thus, this purpose gives three possible areas where such cutting is needed. Edge trimming is usually done, when paper web is transferred from forming section to press section and also in dryer section before sizing, calender or rewinder depending on individual machine construction. Slitter rewinder where parent reels are cut into customer size is another possible area where laser cutting can be applied.

Considering these possible areas, conventional cutting technologies can be generalized for easier comparison. In wet end, water jet cutting is used for edge trimming. Slitter knifes are used in dry end, rewinder and slitter rewinder. Even though number of slitting knifes and their individual properties vary depending on where they are applied, all these areas can be generalized as using principally the same technology. Thus, laser cutting is compared to water jet cutting and cutting with slitting knifes.

Comparison is made based on following criteria:

- Problem solving
- Technical advantages/disadvantages
- Danger/hazard/occupational safety
- Potential of development
- Economic performance

The main criterion for implementation of new technology is possibility to solve problem or problems which occur when using conventional method. Based on literature review, water jet and slitter blade cutting are not problem free. Water jet cutting faces more difficulties to follow up with the increasing of paper making machine speed. Twin nozzles systems currently fulfil requirements but further increase may be limited. Besides that, deterioration of water jet due to deposition of dirt particles on the nozzles also becomes a serious problem. Turbulent flow of water jet has considerable effect on edge quality leading to higher number of web brakes.

Formation of dust is the most often arising problem associated with use of slitting knifes. Another problem is certain instability of cutting quality due to wear of blades. Concerning the web break problem, many of them are caused by paper web defects, which already exist when paper web is transferred to dry end or rewinder, and high pressures used in calender.

The problem, common to all potential areas of implementation, is occurrence of web brakes. Laser cutting can improve cutting edge quality and possibly strength properties of cut edge. Reducing number of web breaks is challenging aim as it would increase runability of the whole paper making machine and bring significant productivity and efficiency benefits.

Laser cutting can virtually be the solution for all above mentioned problems. Laser technology develops rapidly that makes more powerful laser industrially available with reduction of their price at the same time. Current speeds of fastest paper making machines are achievable with industrial lasers. This means that there is no need in developing special new laser. Deposition of dirt particles on laser nozzle is very unlikely: most of possible dirt particles should have organic nature, thus thermal input of laser beam would prevent their deposition. Besides that, shielding gas flow would also contribute for solving this problem if it occurs. Constant cutting quality is one of the strength of laser technology. Properly chosen laser parameters provide constant quality with homogeneous materials. Paper material is not homogeneous but constant cutting quality is achievable. Variations of paper material composition and physical properties have to be taken into account in order to choose correct laser parameters.

Laser cutting can solve problems with existing water jet and slitting blade cutting. However, there are some problems which laser cutting may bring. Solving the problem of dusting, laser cutting produces mixture of solid and/or not completely degraded particles and air. In case of cutting material with high moisture content, mixture consist of solid particles, air and water vapour. These mixtures are potentially dangerous with presence of ignition source. Another problem is originated from laser cutting mechanism. Laser beam evaporates cut material what leads to some fibre losses. Water jet cutting is more beneficial in this aspect.

Selection of the most promising application area of laser cutting can be seen from Figure 31.

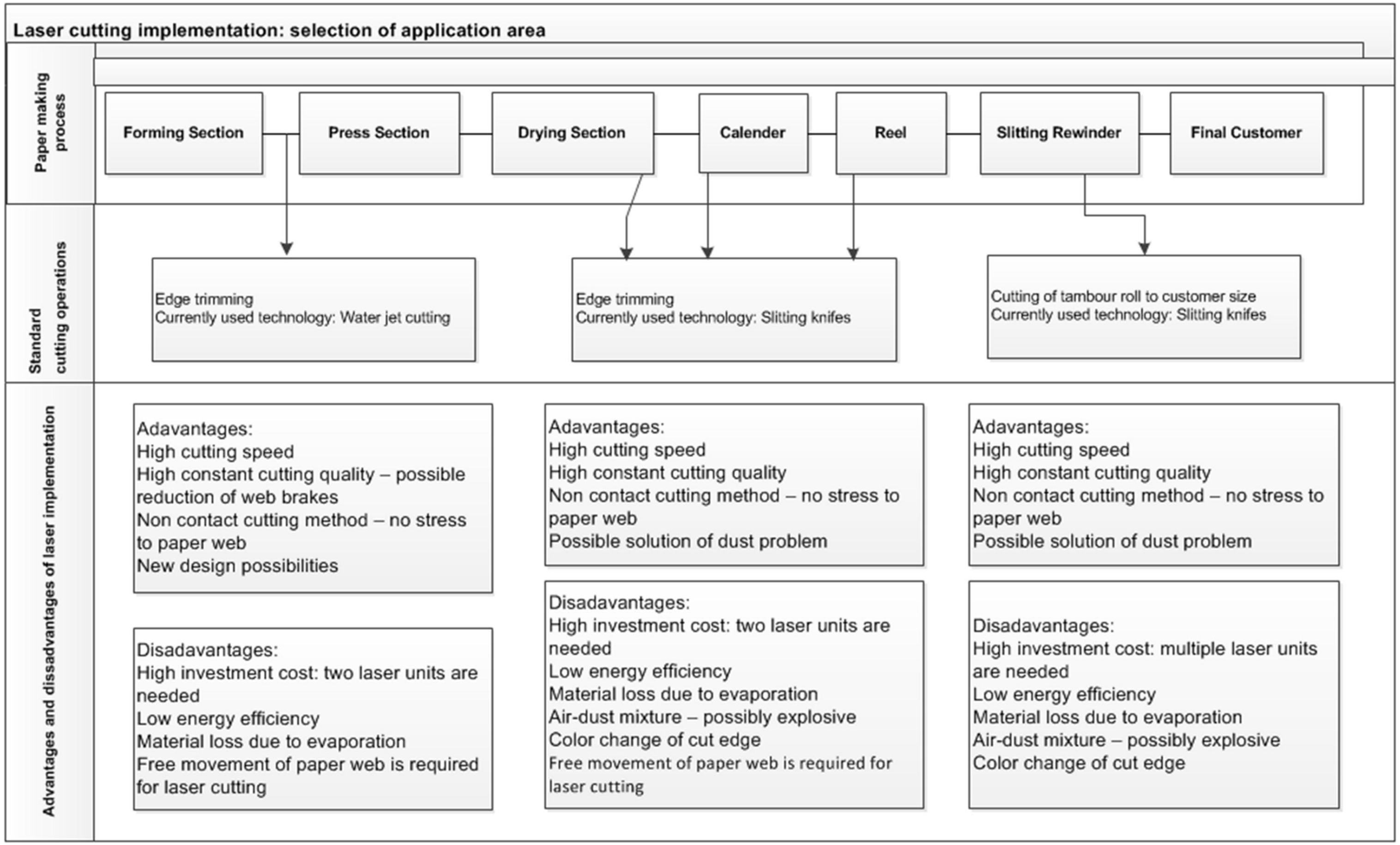


Figure 31. Application area of laser cutting in paper making machine: associated advantages and limitations

Based on literature review findings, possible locations of paper machines where laser cutting can be applied are evaluated. Different locations where cutting of paper web is needed demand specific requirements for cutting process. Evaluation of implementation possibilities is made as comparison of laser cutting technology to existing cutting solutions applied in particular cutting location.

5.2.1 Wet end

Edge trimming in wet end requires special quality of cut edge. Quality is essential as it allows to reduce number of web brakes and thus provide higher productivity of the machine and reduce losses. At the same time, visual or optical characteristics of cut edge are not of high importance because edge trimming operations are repeated at the following stages of the paper making process.

Laser cutting of paper web applied in all areas where cutting operations are normally done in paper making machine can help in solving problems of current technologies. In wet end, laser cutting can be a potential tool which fulfils requirements for increasing speed of paper making machines. It has been revealed in literature review that water jet cutting solution with twin nozzle system may be a bottleneck in the tendency of further increase of the paper making machine speed. Laser cutting is especially suitable as it is non-contact cutting method. Paper web properties at this stage require delicate cutting. Defects of cut edge result in web breaks and losses in production. Laser cutting quality is one of the strength of laser technology and it allows to assume that tensile strength properties of paper web can be improved when laser cutting is applied.

Design and layout of laser equipment is another advantage of laser technology. Laser cutting head can be placed at different angles toward paper web what makes design more flexible. Laser beam does not have limitations of the angle of incidence to paper material as long as the beam transfer can be maintained to cutting head. This makes it virtually possible to place cutting head at any angle but possible contaminations of optical components have to be taken into account. However, laser source have to be installed in close proximity to cutting area due to characteristics of CO_2 laser beam transfer. Laser cutting system should have as low number of beam transfer optical elements as possible in order to reduce losses of power.

Disadvantages of laser cutting system is high initial investment cost compared to water jet cutting systems. Running costs of laser cutting system are also higher. This is the result of low energy efficiency of CO_2 lasers which is in the range of 10 – 15 %. Besides that laser system requires lasing gases and shielding gas supply what leads to additional equipment and materials compared to water jet cutting. Another disadvantage of laser cutting is material loss due to evaporation during cutting. If water jet cutting does not lead to any fibre loss, laser cutting evaporates paper material leading to loss of fibres and creation of fumes consisting of air, CO_2, water vapour and solid residues. Additionally, vacuum suction system to remove fumes from cutting zone is needed. These fumes require filtration and separation of solid particles.

5.2.2 Dry end/reel/calender

Advantages of laser cutting in dry end are high cutting speed and non-contact nature of laser cutting. This allows to reduce stress to paper web caused by mechanical cutting. Laser cutting provides constant cutting quality whereas slitting knifes have some quality variation due to wear. Laser cutting can solve problem of dusting which occur when slitting knifes are used.

Edge trimming in dry end has another requirements for quality of cut edge. Cut edge has to be without defects to prevent web brakes in following stages of the process. Unlike in wet end, visual or optical characteristics of cut edge are of high importance. Paper has to fulfil standards of optical characteristics including cut edge. Yellowing of cut edge cannot be avoided by changing laser cutting process but this problem can be eliminated if edge trimming of paper web is applied in following processes.

Capital investment costs of laser system is significantly higher compared to slitting blades system. Rotating slitting blades system is technologically more simple (compared to laser equipment) and widely used in different industries.

Another severe disadvantage of laser cutting is possible formation of explosive air/dust mixture (or flammable fumes) during cutting. Paper material at this stage of the process has moisture content of 25 - 40 %, thus amount of water vapour in the mixture is low. This leads to much higher risk of fire or explosion due to presence of ignition source (laser beam). Solving a problem of dusting, laser cutting does not eliminate potential risk.

Disadvantages associated with laser cutting in dry end make its implementation not reasonable due to high associated risks and not complete elimination of current technology problems.

5.2.3 Slitting rewinder

The advantages of laser cutting implementation mentioned in dry end section can be also applied for slitting rewinder.

However, number of disadvantages becomes higher when slitting rewinder is considered. Thermal effect on cut edge becomes laser cutting disadvantage, if applied at the final stage of the papermaking process. Yellowing of cut edge is severe problem which currently cannot be avoided. Besides that, capital investment costs rises significantly due to multiple laser sources needed for cutting. All these reasons together with disadvantages, which occur in dry end, results that laser cutting implementation not reasonable at this stage.

5.2.4 Location of laser application

When taking into account all advantages and disadvantages of effect of laser cutting on paper web and technical possibilities of laser application, it can be concluded that wet end is the most promising area where laser cutting can be applied. At this particular location, laser cutting can fulfil the required cutting speed and possibly to improve edge quality. Laser cutting experiments are executed with the aim to verify these statements. Laser cutting can potentially improve runability of paper making machine by reduced number of web breaks. This may be achieved by improved strength properties of laser cut edge of the paper web.

Addressing the same problem in dry end, laser cutting is quite unlikely to improve runability as web breaks are mainly caused by defects which may originate in earlier stages of paper making processes. Besides that, risk of forming of explosive or flammable mixture of fumes, dust and air in presence of ignition source is present. Thus, solving problem with dust due to mechanical cutting, no significant benefit is achieved.

Cutting of parent roll into customer size rolls in rewinder would require multiple laser cutting units that increases capital investment costs to such high level where economic performance play a crucial role. Even though laser cutting implementation is easier as the paper web moves without felt support, only significant runability improvement would make laser cutting implementation reasonable. However, such improvement cannot be predicted. Besides that, risk of forming of explosive or flammable mixture is present.

5.3 Experimental set-up

5.3.1 Material used in this study

Experiments of laser cutting of paper material were carried out with ordinary copy paper. Copy paper is a paper which is usually used for copying and printing purposes. The usual grammage of copy paper is 80 g/m^2. Measured grammage of paper samples showed slight deviation from this value and was equal to 79 g/m^2. According to the purpose of copy paper there are several main properties such as grammage, brightness, opacity and smoothness. The paper samples were chosen so that paper composition was mainly softwood without addition of BCTMP. The analysis of the composition of samples was carried out at Pulp and Paper Laboratory of Lappeenranta University of Technology.

Moist paper samples with dry matter content about 25-30% were obtained by dipping dry samples in water. Weight of samples was controlled in order to receive the same properties.

5.3.2 Paper machine

Calculations and some layout features are taken for generalized paper making machine. This paper making machine has running speed of 2000 m/min. This value is taken as a reference to the fastest speeds reached in paper making industry, but at the same time quite common for new build machines according to technological level of modern machines. The paper grade produced by this machine is copy paper. Copy paper implies higher standards for physical and optical properties that makes it suitable for testing of laser cutting. If laser cutting can fulfil these standards, it can also be applied for other paper grades.

Paper machine width was not considered as it has effect only on customer size reel cutting. However, the main focus of the study was on edge trimming. Thus, width of paper making machine does not have any effect.

5.3.3 Equipment used in this study

5.3.3.1 Laser cutting workstation

The laser cutting tests, which are represented in this thesis, were carried out in Laser Processing Laboratory of Lappeenranta University of Technology. The power source of laser workstation was Trumpf TLF 2700 HQ CO_2 continuous wave (CW) laser which produces maximum nominal laser power of 2700 W. The wavelength of the laser beam was 10.6 µm. The cutting tests were made using an XY table (Figure 32).

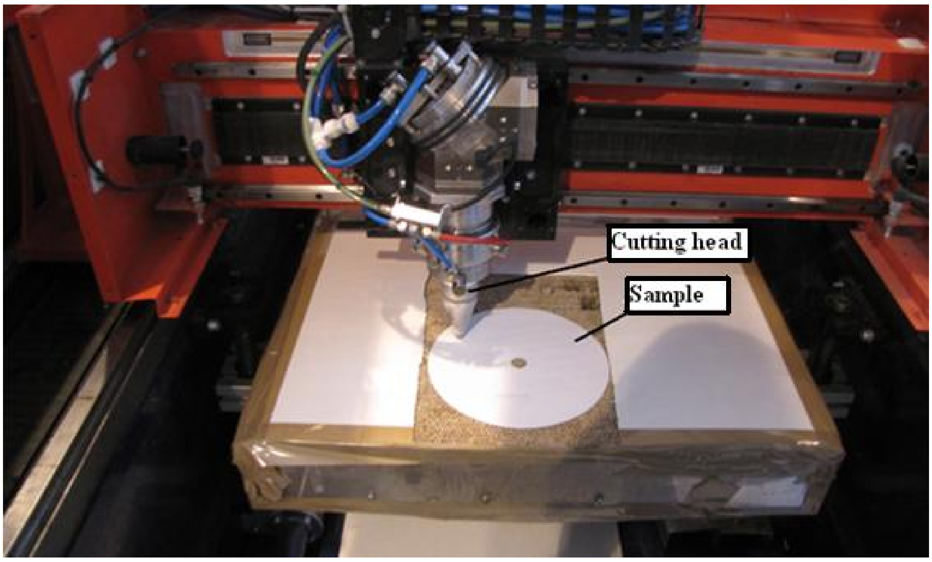


Figure 32. Laser workstation used in this study.

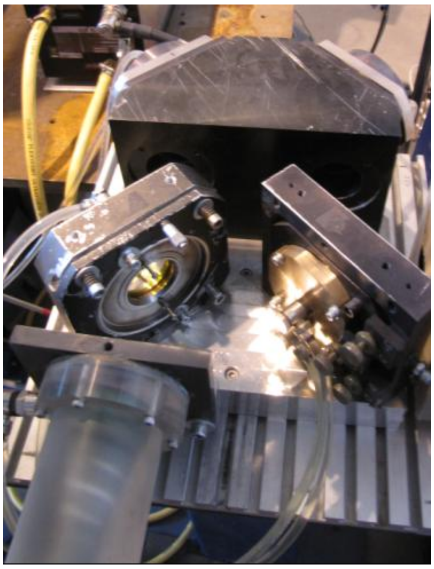


Figure 33. Beam splitter device that cuts of 50% of laser power.

For these cutting tests the focal length of 127 mm (5'') was used. The cutting gas was compressed air of 3 bars pressure. Nozzle diameter was 1.5 mm.

5.3.3.2 Laser beam parameters

Beam analysis was carried out with Primes FocusMonitor. Principle of Primes FocusMonitor is based on rotating pinhole. Principle of device is illustrated in Figure 34.

Figure 34. Schematic view on the set-up used for beam analysis.

This pinhole is used to bind small part of laser beam radiation in the focus region. Signal radiation is transferred to the detector and electrical signals are digitised. The position of the pinhole is movable in y- and z-direction what allows to obtain whole beam caustic properties (Anon., 2015c).

Laser beam properties measurements were executed prior laser cutting tests. From this measurements, laser beam radius was obtained. The radius of laser beam on top surface of paper samples was equal to 130 µm. Example of beam measurement results can be seen in Figure 35.

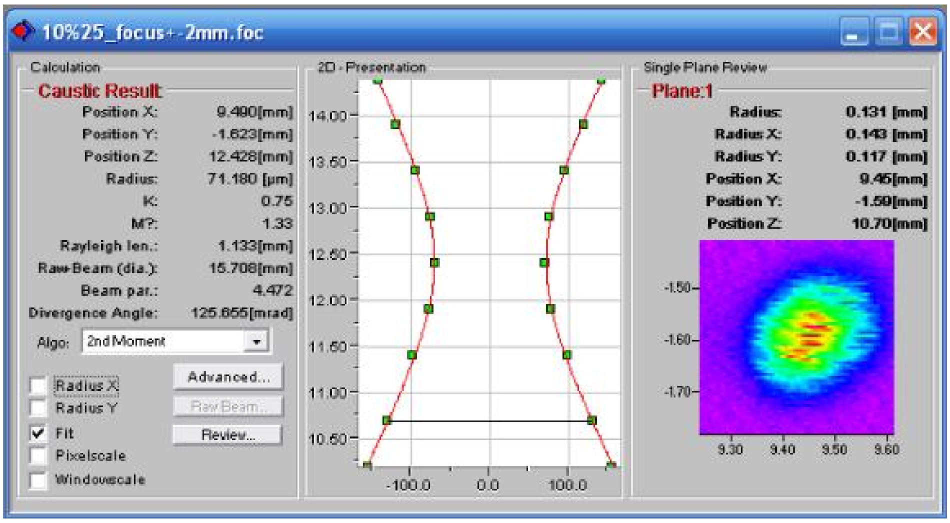


Figure 35. Laser beam measurement with Primes FocusMonitor.

5.3.3.3 Pyrometer

Pyrometer, Temperature-Control-System (TCS), was used for on-line temperature measuring system and it consisted of measuring optics, optical fibre, PC with installed measuring software. The TCS- system is shown in the Figure 36.

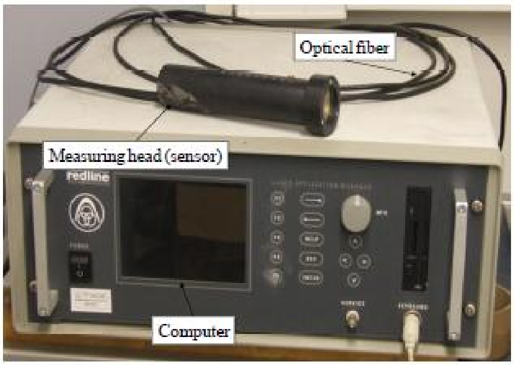


Figure 36. Pyrometer.

Pyrometer was used to measure the thermal effect of laser beam in samples of copy paper. Paper sample was heated due to exposed laser radiation what in turn caused emission of thermal radiation. Measuring optics captures emitted thermal radiation and transmits data into pyrometer, which divides the radiation in two measuring ranges. The first measurement range is from 1200 nm to 1400 nm and the second range is from 1400 nm to 1700 nm. For each of these ranges, a photo detector turns the radiation intensity into a photocurrent. The ratio of these photocurrents does not depend on the spectral emission coefficient of the work piece surface. This allows temperature measurement at different surfaces or materials without knowing the emissivity coefficient of the material and the change of it as function of temperature. Pyrometer round-shaped detecting area can be focused to the area of laser beam treatment of paper material. For more precise measurements, area of background should be minimized (pyrometer's detecting area should not cover zones where interaction of laser beam and paper material does not take place).

5.3.3.4 Tensile strength testing

Lorentzen &Wettre tensile tester was used to measure all strength properties of laser cut samples. It allows to measure four basic properties in a single measurement: tensile strength, stretch at break (strain break), TEA and tensile stiffness. In this study, tensile strength and strain break were used. This measurement method is accepted by paper making industry.

Figure 37. Lorenzen and Wettre tensile tester.

5.3.3.5 Dirt particles testing

Evaluation of dirt particles in mill broke after laser cutting was carried out in Fibre Laboratory of Mikkeli University of Applied Science (Savonlinna unit). Illumination image system was used. Dirt particles were classified on the basis of area in accordance with ISO 5350-1 standard, classification can be seen from Table 4.

Table 4. Size of dirt particles according to ISO 5350-1.

Size	Area, mm^2
5	0.04 – 0.14
4	0.15 - 0.39
3	0.40 – 0.99
2	1.00 – 4.99
1	over 5

Measurement procedure for dirt particles analysis was developed in Lappeenranta University of Technology. Automatic image analysis system was based on the principle of visual inspection of the number of segmented dirt particles.

5.3.3.6 Storage of paper samples and laboratory conditions

All samples were stored in laboratory conditions. The standard conditions in the paper laboratory implied constant temperature, which was equal to 23°C, and constant relative humidity about 55 %. These values were controlled from the beginning of the experiments in order to eliminate any influence of storage conditions on the tests results. The samples of ordinary copy paper were stored in laboratory conditions before preliminary measurements such as grammage and thickness. It is important to note that during the experimental procedure all samples were packed into polyethylene boxes and aluminium foil in paper laboratory and straight after cutting in laser laboratory. The samples were not exposed to influence of atmospheric humidity and daylight.

6 Results

6.1 Linear cutting energy calculation

Linear cutting energy required for cutting of paper material has to be calculated before cutting. The aim of the tests was to find out laser parameters needed to obtain required quality (complete cut without outsticking fibres or burned edges). Laser cutting tests were carried out with the aim to verify capability of laser to provide sufficient cutting quality with cutting speed corresponding to the speed of paper making machine. Equation (8) was used for calculation of linear cutting energy.

Density of paper material can be obtained from literature for common paper grades or measured experimentally. For copy paper used in this study, density is 790 kg/m^3.

Radius of laser beam has been measured and equals to 120 - 130 µm. This value corresponds to the focal point position on top of the cut material. Changing of focal point position will result in increase of laser beam radius and as a result in higher energy needed for cutting. Thickness of paper material was measured as 0.1 mm.

Specific heat of paper material is one of the key parameter in linear cutting energy calculations. Literature sources provides values of specific heat capacity with high variations. Reported value of 1500 J/(K* kg) is more close to pure cellulose (Pages et al., 2005). However, commercial paper grades, such as copy paper used in this study, contain up to 25 % of mineral fillers, pigments, brightening agents what has considerable effect on specific heat capacity. Thus, specific heat capacity reported for fine paper grades of 2893 J/(K* kg) is more applicable (Kawamizu et al., 2009).

ΔT_d is equal to 225 °C what corresponds to degradation temperature of cellulose of 250 °C and ambient temperature of 25 °C. Table 5 represents values used for calculation of Equation (8).

Table 5. Linear cutting energy calculation (dry paper material).

ρ	790.0
R	$130*10^{-6}$
δ	$100*10^{-6}$
C_p	2893.0
ΔT_d	225.0
E	**10.5**

Thus, linear cutting energy needed for cutting was calculated as 10.5 J/m.

Specific heat capacity is calculated based on weight fraction of components and corresponding specific heat capacity values (see Equation (6)). The model is based on the assumption that mixture consist of cellulose fibres and water.

Specific heat capacity of paper material is equal to 1500 J/(K* kg) (Pages, 2005), assuming that at this stage of the process heat capacity is closer to pure cellulose since application of fillers and sizing agents takes place in later stages of paper making., specific heat capacity of water is equal to 4179 J/(K* kg) (Niskanen, 2008). The assumption that there are two pure components, cellulose and water, is taken. Applying Equation (6), specific heat capacity of paper material is equal to 3286 J J/(K* kg). Thickness and density of paper material is changing according to water content.

Table 6. Linear cutting energy calculation (moist paper material).

ρ	2560.0
R	$130*10^{-6}$
δ	$150*10^{-6}$
C_p	3286.0
ΔT_d	225.0
E	**57.9**

Energy needed for laser cutting was found for dry paper material as 10.5 J/m and for moist paper samples as 57.9 J/m.

6.2 Laser cutting tests: verification of calculated values

In order to simulate working conditions of press section, laser cutting tests were carried out using paper material with 25-40 % moisture content. The aim of the tests was to find out laser parameters needed to obtain required quality. Laser cutting tests were carried out to verify capability of laser to provide sufficient cutting quality with cutting speed corresponding to the speed of paper making machine.

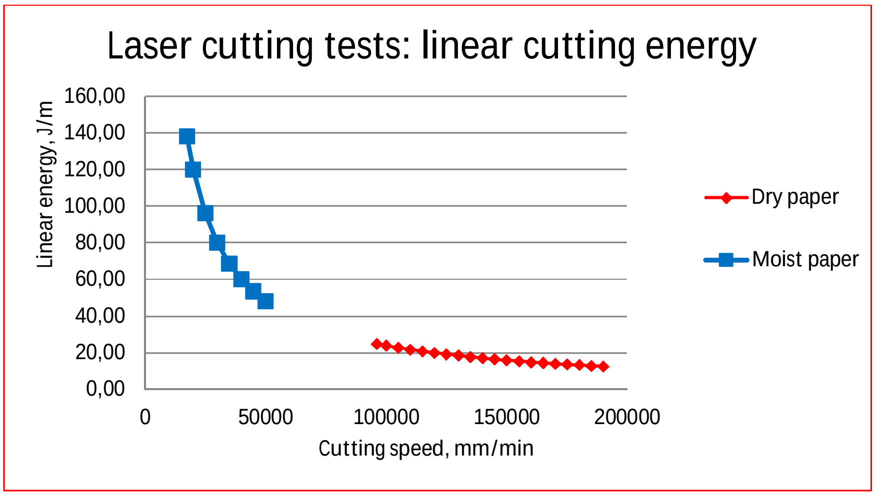


Figure 38. Linear cutting energy: practical verification.

Laser cutting of both dry and moist samples has been executed. Values of linear cutting energy have been obtained after calculations. Laser power was kept constant while cutting speed was gradually increased with 5000 mm/min step. The aim was to define the limit when linear cutting energy was insufficient to produce complete cut. Thus, limit values of linear cutting energy were found practically.

As Figure 38 illustrates, laser energy needed for cutting deviate from calculated values. This behaviour was found in both dry and moist samples. Cutting was incomplete with cutting energy of 13 J/m for dry samples and 48 J/m for moist samples. However, definition of the exact cutting energy limit was difficult by visual evaluation as cutting quality decreased gradually. Visually evaluated good (without out sticking fibres) cutting quality of paper material edge was achieved with linear cutting energy of 20 J/m for dry samples and 70 J/m for moist samples. This indicates deviation by nearly 50 % for dry paper samples and deviation for moist paper samples of nearly 20 %. It has to be kept in mind that certain deviations in paper material structure and physical properties can affect cutting results. Linear cutting energy have to be slightly above this limit value to ensure complete cut with good edge quality.

6.2.1 Improvement of linear cutting energy calculations

Combining Equation (7) for heat input and Equation (8) for linear cutting energy, accuracy of calculation can be increased due to application of laser beam absorption. Linear cutting energy including laser beam absorption can be found as Equation (11) shows:

$$E_1 = \frac{P}{v\eta} = \frac{\rho\, \pi\, R\, \delta\, C_P\, \Delta T_d}{2\eta} \quad (11)$$

Laser beam absorption can be obtained from absorption characteristics curve of cellulose represented in Figure 7. Applying Equation (11) for calculation, linear cutting energy is defined as following:

Table 7. Linear cutting energy calculation (dry paper material).

ρ	790.00
R	130*10^{-6}
δ	100*10^{-6}
C_p	2893.00
ΔT_d	225.00
η	0.45
E	**23.30**

Thus, linear cutting energy needed for cutting was calculated as 23.30 J/m.

Applying the same Equation (11), linear cutting energy needed for laser cutting of moist paper material can be obtained. Calculation results can be found from Table 8.

Table 8. Linear cutting energy calculation (moist paper material).

ρ	2560.00
R	130*10^{-6}
δ	150*10^{-6}
C_p	3286.00
ΔT_d	225.00
η	**0.45**
E	**128.70**

Thus, linear cutting energy needed for cutting was calculated as 128.70 J/m.

Results of calculations of linear cutting energy, linear cutting energy including laser beam absorption and linear cutting energy from laser cutting tests can be compared (Table 9).

Table 9. Linear cutting energy calculation (moist paper material).

	E, J/m	**E,** J/m	**E,** J/m
	without η	**including η**	**practical**
Dry paper material	10.5	23.3	20.0
Moist paper material	57.9	128.7	70.0

Accuracy of calculations of linear cutting can be increased by including laser beam absorption. This can be seen from comparison of linear cutting energy of dry paper material. Value of linear cutting energy including absorption (23.3 J/m) correlates well with practically verified cutting energy (20.0 J/m).

In case of moist paper material, differences of linear cutting energies can be attributed to changes of absorption characteristics of moist paper material.

6.2.2 Effect of laser beam properties on cutting

Distribution of laser beam energy was assumed even over beam diameter. However, distribution of laser energy over beam profile is not even in practice. This fact can lead to inaccuracy of calculated laser cutting energy needed for cutting applied in practice.

Beam profile and power distribution over beam diameter can be found in Figure 39.

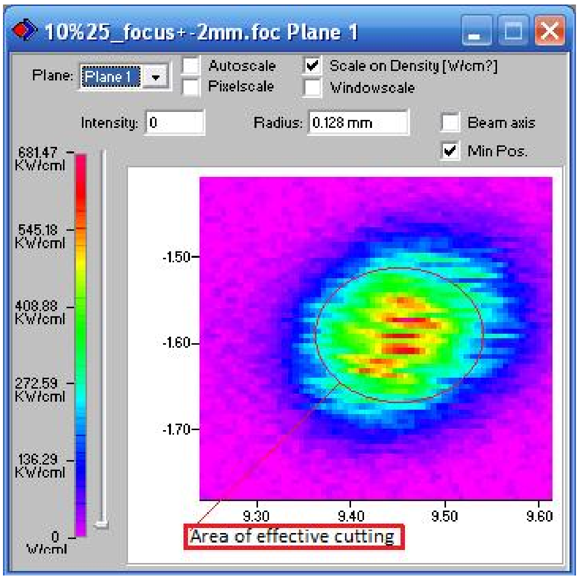


Figure 39. Power distribution over beam diameter used in this study.

As it can be seen from Figure 38, intensity of laser beam is distributed unequally over beam profile. The maximum intensity is found in the centre of the beam and intensity decreases gradually over beam diameter. Thus, area of effective cutting, where complete decomposition of paper material is achieved, can be smaller than actual beam diameter. This leads to narrower cut kerf and lower volume of paper material to be evaporated.

It was reported in literature, that degradation of cellulose occurred at laser intensity over 19 W/mm^2. However, it is not possible to establish correlation of needed intensity of laser beam to achieve melting effect due to difference in materials. On the other hand, cotton fibres used for melting tests are very close to cellulose fibres what allows to suggest that similar effect can be achieved for copy paper. Gradual decrease of laser beam intensity from centre of the beam imply that the melting phenomenon can occur on cut edges of laser cut paper material. This molten layer can compensate possible defects of cut edge and improve strength.

6.3 Tensile strength tests

The purpose of the tests were to find the effect of laser cutting on tensile strength compared to corresponding values of papers cut with conventional technologies. Paper material used for these test was ordinary commercially available copy paper.

The tensile strength shows probability of paper material to break when force is applied at opposite ends. Tensile strength is very important parameter which allows to predict probability of break occurrence of paper web subject to high-speed web pressing. In the tensile strength measurements, the test sheet of 15 mm width is stretched until rupture occurs.

The tensile strength represents the maximum load which is measured at the moment of macroscopic rupture of paper sample. This microscopic rapture of paper can be originated either by fracture of fibre segments or by fracture of bonds in the paper.

6.3.1 Tensile strength tests of dry samples

Results of tensile index and strain break measurement are reported in Table 10. Laser cutting was carried out in machine direction. Laser cutting tests were executed varying cutting energy. Optimal cutting energy was 20 J/m, it was varied by ± 50% I order to get excess and shortage of laser energy. All measurement results can be seen from Appendix I.

Table 10: Tensile index and strain break of laser cut samples of commercial copy paper

Sample N	**Strain break,%**	**Standard deviation, %**	**Tensile index, Nm/g**	**Standard deviation, Nm/g**
0 J/m, reference	1.46	0.10	57.48	1.63
10 J/m, 50 % less cutting energy	1.51	0.07	57.10	1.42
20 J/m, Optimal cutting energy	1.45	0.07	57.95	1.32
30 J/m, 50 % more cutting energy	1.41	0.08	57.15	1.88

In case of 10 J/m cutting energy, cut was incomplete. When sample was pulled at opposite ends, tearing along laser cut kerf occurred. Tensile index slightly changes due to effect of laser cutting. However, all tensile index values lie within standard deviation. One of the reasons for such results can be that the area of laser cut edge is much smaller compared to the whole area of the sample.

Presented results of tensile strength measurements do not allow positively confirm the assumption that laser cutting with optimum parameters can improve strength properties. On the other hand, it can be concluded that laser cutting at least does not cause reduce of laser cut paper strength. Reference sample, which was cut mechanically, showed tensile similar strength properties to laser cut samples (taking into account standard deviation).

Chosen measurement method did not specifically targeted tensile strength of laser cut paper edge. The width of measured sample was 15 mm what makes area of laser cut edge negligible. Definitive results on whether tensile strength properties can be improved by application of laser cutting cannot be drawn in this measurement.

Strain break shows the amount of strain that causes material to break when it is applied. Strain break reflects elastic properties of paper material. In other words, strain brake gives the percentage value on elongation which paper sample can achieve.

Similar results were obtained in strain break measurements. Strain break of laser cut paper samples slightly differ among samples cut with different laser parameters as well as mechanically cut reference sample. All measured values of strain break lie within standard deviation. The conclusion from the test results is similar to one in tensile measurements. Results are inconclusive in terms of improving strain properties. On the other hand, the conclusion that laser cutting does not cause lower strain of paper samples can be said.

6.3.2 Tensile strength tests of moist samples

The purpose of the tests were to find the effect of laser cutting on tensile strength of moist paper samples. Results of the test can provide a view on the effect of laser cutting on moist paper material tensile strength close paper material in wet end of papermaking machine. Paper material used for these test was ordinary commercially available copy paper. Samples were moisturised prior laser cutting. This was achieved by dipping paper samples into water allowing it absorb as much water as it could but without failure of paper structure. That was necessary in order to be able to handle paper samples for laser cutting. Mass of the samples was controlled. This method allowed to achieve 70 – 75 % moisture content.

Laser cutting parameters can be seen in Table 11. Laser cutting was carried out in machine direction.

Table 11. Laser cutting parameters.

Sample N	Cutting energy, J/m
1	240
2	120
3	80
4	60
5	48
6	40
7	35

Results of tensile index and strain break measurement are introduced in Table 11. Measurement of moist laser cut samples for tensile and strain properties was not possible. It was probably due to samples strength properties lower that measurement limit of used equipment.

To obtain measurements results, moist samples were dried in laboratory conditions. Thus, measured tensile properties represent values obtained for samples which were moisturized before laser cutting and dried after cutting.

Table 12: Tensile index and strain break of laser cut samples of commercial copy paper (0 – reference sample).

Sample N	Strain break,%	Standard deviation, %	Tensile index, Nm/g	Standard deviation, Nm/g
0	1.97	0.14	45.31	2.89
1	1.84	0.19	43.11	2.55
2	1.85	0.15	45.75	3.61
3	1.90	0.11	44.02	1.97
4	1.72	0.23	42.45	4.38
5	1.71	0.23	40.95	4.38
6	1.84	0.17	44.39	2.57
7	2.08	0.09	48.98	1.89

Measured tensile index and strain break can be seen from Table 12. All measurement results can be seen from Appendix II.

Tensile index of laser cut moist paper samples can be considered in comparison to tensile index of reference (non-laser cut) sample which was treated in the same procedure. Tensile index slightly changes due to effect of laser cutting. However, all tensile index values lie within standard deviation. The reason for that is probably due to the fact that the area of laser cut edge is much smaller compared to the whole area of the sample.

Strain break of laser cut paper samples slightly differ among samples cut with different laser parameters as well as mechanically cut reference sample. Presented results of tensile strength measurements do not allow to positively confirm the assumption that laser cutting with optimum parameters can improve strength properties. Represented values of measured tensile index lie within standard deviation.

6.4 Mill broke tests

Recycling of laser cut samples was carried out. Amount of dirty particles was measured. Based on the results, it is possible to evaluate possibility to re-use mill broke in paper making process when conventional edge trimming technology is substituted with laser cutting. Images of measured handmade paper sheets can be found in Appendix III.

Table 13 represents dirt particles content in samples made of pure copy paper. Laser cutting has not been applied. This implies that no dirt particles should be present in samples.

Table 13: Dirt particles measurement: reference sample (no laser cutting).

	Sheet 1	Sheet 2	Sheet 3	Sheet 4	Sheet 5	Average of four sheets
Size 5	0	0	0	1	0	**0**
Size 4	0	0	0	0	0	**0**
Size 3	0	0	0	0	0	**0**
Size 2	0	0	0	0	0	**0**
Size 1	0	0	0	0	0	**0**

As it can be seen from Table 13, one dirt particle was found in all tested samples. This can be explained by contamination of laboratory equipment while handmade paper sheet preparation.

Table 14 represents dirt particles content in samples made of samples when laser cutting was applied to moist paper samples.

Table 14: Amount of dirt particles: laser cut moist paper.

	Sheet 1	Sheet 2	Sheet 3	Sheet 4	Sheet 5	Average of four sheets
Size 5	2	1	3	3	1	2
Size 4	0	0	1	0	0	0
Size 3	0	1	0	0	0	0
Size 2	0	0	0	0	0	0
Size 1	0	0	0	0	0	0

As it can be seen from Table 14, contamination particles were found in tested samples. Especially, particles of 0.04-0.14 mm^2 size were found in all samples what suggests deposition of solid residues particles on the paper surface during laser cutting.

Table 15 represents dirt particles content in samples of copy paper. Laser cutting was applied to dry copy paper samples. Laser cutting was performed with optimal linear cutting energy obtained from calculations.

Table 15: Dirt particles measurement: optimal laser cutting power.

	Sheet 1	Sheet 2	Sheet 3	Sheet 4	Sheet 5	Average of four sheets
Size 5	0	0	0	0	0	0
Size 4	0	0	1	0	0	0
Size 3	0	0	0	0	0	0
Size 2	0	0	0	0	0	0
Size 1	0	0	0	0	0	0

As it can be seen from Table 15, only one dirt particle was found in all tested samples. This can be attributed to individual incompletely evaporated fibre or part of a fibre. Size of the particle (0.15 – 0.39 mm^2) supports this assumption.

Table 16 represents dirt particles content in samples of copy paper. Laser cutting was applied to dry copy paper samples. Laser cutting was performed with 50 % lower linear cutting energy obtained from calculations. This value corresponds to the lower limit of linear cutting energy when cutting was possible.

Table 16: Dirt particles measurement: 50 % more laser power than optimal.

	Sheet 1	**Sheet 2**	**Sheet 3**	**Sheet 4**	**Sheet 5**	**Average of four sheets**
Size 5	1	1	1	0	2	1
Size 4	0	0	0	0	0	0
Size 3	1	0	0	0	0	0
Size 2	0	0	0	0	0	0
Size 1	0	0	0	0	0	0

As it can be seen from Table 16, dirt particle were found in tested samples. Most of dirt particles had size of 0.04 – 0.14 mm^2 that suggests deposition of solid residues particles. However, thermal effect of excessive cutting energy outside of cutting area due to heat transfer cannot be excluded.

Table 17 represents dirt particles content in samples of copy paper. Laser cutting was applied to dry copy paper samples. Laser cutting was performed with 50 % lower linear cutting energy obtained from calculations. This value corresponds to the lower limit of linear cutting energy when cutting was possible.

Table 17: Dirt particles measurement: 50 % less laser power than optimal.

	Sheet 1	**Sheet 2**	**Sheet 3**	**Sheet 4**	**Sheet 5**	**Average of four sheets**
Size 5	0	0	0	0	0	0
Size 4	0	0	0	0	0	0
Size 3	1	0	0	0	1	0
Size 2	1	0	0	0	1	0
Size 1	0	0	0	0	0	0

As it can be seen from Table 17, dirt particle were found in tested samples. Dirt particles had size of 0.40 – 4.99 mm^2. This can be attributed to incompletely evaporated fibres or part of fibres. Size of the particle (0.4 – 0.99 mm^2) supports this assumption.

6.5 Solid residues in fumes after laser cutting

Mechanism of laser cutting is direct evaporation of paper material. However, there is some amount of solid residues present in fumes. Table 18 represents amount of solid residue depending on temperature.

Table 18. Percentage of solid residues as a result of thermal decomposition of cellulose depending on temperature (valid for conditions under vacuum) (Soares et al., 1995).

T, ºC	Solid residue
250	69
275	32
325	14
420	4

In order to determine amount of solid particles in fumes after laser cutting, temperature of laser cutting has to be defined. Laser cutting tests were carried out in a pulse mode with different pulse length and different laser powers. Temperature was recorded using pyrometer, measurement results can be found in Table 19.

Table 19. Temperature measurement of laser beam and paper material interaction.

Laser power, W	Pulse length, ms	Measured temperature, °C			
		1	2	3	4
144	10	1324	1384	-	1390
	45	976	1433	1336	1441
	90	-	1328	1332	1368
266	10	-	1367	-	-
	45	1419	-	1539	1359
	90	560	993	-	1193
384	10	-	-	620	-
	45	1328	-	1337	1132
	90	730	1488	-	1359
494	10	1252	1491	1332	1375
	45	1389	-	-	-
	90	1497	1194	1428	1414

As it can be seen from Table 19, temperature tests did not provide results for each measurements. The reason for that may be related to the limitation of used equipment. Pyrometer used in this study measured temperatures above 500 °C. Thus cellulose degradation temperature was bellow pyrometer measurement limit.

However, obtained results allow to suggest that under proper cutting conditions of laser cutting complete degradation of cellulose can be achieved. Mineral components of paper material play significant role in this process as it allows to rise temperature of laser cutting significantly above degradation temperature of cellulose.

Taking an assumption that paper material in the area of laser beam influence is in conditions close to vacuum, mass of solid residues can be calculated as Equation (12) shows.

$$M_{sr} = M_e * 0{,}04 \qquad (12)$$

where M_{sr} mass of solid residues, kg/h

M_e mass of evaporated material due laser cutting, kg/h

0,04 mass fracture of solid residues

Mass of evaporated material can be derivated as Equation (13) shows.

$$M_e = V_e * \rho \tag{13}$$

where V_e volume of laser cut material, kg/h

ρ density of paper material, kg/m^3

Volume of evaporated paper material can be calculated as Equation (14) illustrates.

$$V_e = v * D_{lb} * \delta * 3600 \tag{14}$$

where v cutting speed, m/s

δ thickness of paper material, m

D_{lb} diameter of laser beam, m

Numerical values of used values are represented in Table 20.

Table 20. Solid residues mass fraction calculation: numerical values.

v	33,33
ρ	790.00
D_{lb}	$260*10^{-6}$
δ	$100*10^{-6}$
$\boldsymbol{V_e}$	$3120*10^{-6}$
$\boldsymbol{M_e}$	2,47
$\boldsymbol{M_{sr}}$	**0,01**

Thus, edge trimming with laser beam would result in material loss of 2.47 kg/h due to evaporation. Mass of solid residuals is 0.01 kg/h from this amount. Since both edges of paper web have to be trimmed, this amount has to be doubled. It also can be assumed that increase of mineral portion in paper material composition results in higher mass of solid residues. Material used in this study had mineral content of 20 -25 %. Thus, final value of mass of solid residues can be equal to 0.125 kg/h. Edge trimming of both edges produces 0.25 kg/h of solid residues.

6.6 Colour change of laser cut edge

Laser cutting of paper material is associated with colour change of cutting kerf due to thermal influence. This may lead to contamination when mill broke is returned into the process. Colouration phenomena of laser cut paper edges was not specifically studied in this research, but visual evaluation of images of laser cut paper samples is provided.

Area of colour change caused by laser cutting can be seen from Figure 40.

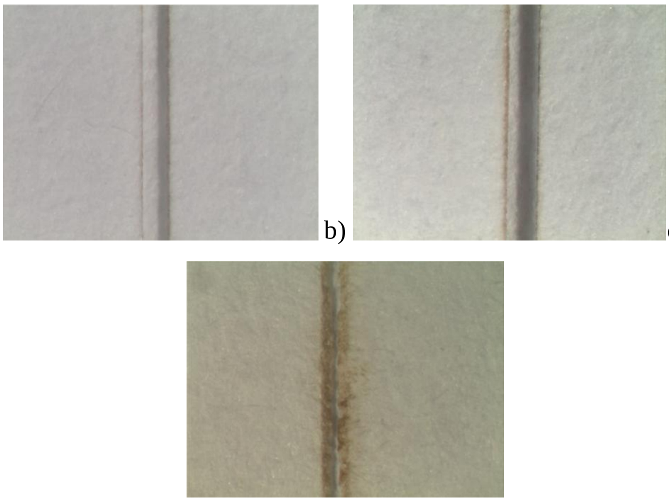


Figure 0 Laser cut sample and coloration of cutting kerf.

As it can be seen from Figure 40, laser cutting parameters affect colouration of cut edge. This effect may be very limited (see Figure 40a) only by cut edge, moderate (see Figure 40b) when higher laser power was used or strong colouration (see Figure 40c). In case of strong colouration it has to be noticed that laser power was insufficient to cut through paper material.

In order to reduce colour change of cut edge, thermal effect on paper material has to be reduced. However, this is in conflict with the cutting needs. Laser cutting has to be done with excess amount of energy to ensure complete cutting. Another need of high temperature in the cutting zone is the amount of solid residues. In order to obtain less volume of solid residues, temperature has to be higher than 450 ^{o}C.

Colour change of cut edge is not of high importance in case of edge trimming in wet end. It can be assumed that colour change does not indicate lower strength properties. Thus, only optical properties are affected what makes colour change a limiting factor for application of laser cutting in final stages of paper making process.

7 Discussion

7.1 Proposed laser cutting scheme

Area of potential implementation of laser cutting in paper making machine was defined to be wet end. The purpose of laser cutting is edge trimming of paper web. Few possible designs and equipment sets are possible for serving this purpose.

Using Equation (8) for linear cutting energy, assumed speed of paper making machine and practically verified value of energy needed for cutting (it was found as 70 J/m), required power of laser source can be obtained according to Equation (15).

$$P = E_1 * v \tag{15}$$

Thus, laser source needed for edge trimming of wet paper web has to be 2333 W. It has to be noticed that this laser power has to be delivered to the paper material surface. Losses of power during beam delivery may reach as much as 30 % depending on the number of components in optical system. To include possible losses and provide some power reserve, laser source of 3 kW would be needed. These power requirements were calculated for trimming only one edge.

The proposed schemes has to fulfil following requirements:

- High reliability
- Possibility of fast change in case of brakes
- Reasonable economical performance

7.2 Cutting scheme for wet end

Different schemes of laser cutting system implementation are possible. Laser technology offers different options for power of laser sources, optical and beam transfer equipment.

The set of equipment includes one laser source of 6 kW power, two cutting heads, one partially reflective mirror and one bending mirror. The schematic layout of equipment is represented in Figure 41.

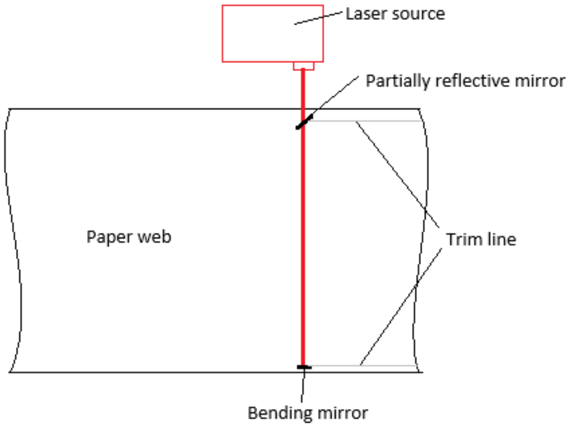


Figure 41. Schematic layout of equipment: scheme 1.

Laser source provides laser beam for both cutting zones. Laser beam from output mirror travels to partially reflective mirror where beam splitting takes place: about 50 % of laser beam is supplied to first cutting head whereas another half of the beam travels further to the second cutting head. Geometric beam splitting can be also applied when laser power required for cutting exceeds 5 kW. Bending mirror can be integrated into cutting head in this case.

This scheme employs only one laser source that allows to reduce initial investment cost into equipment. However, such system has low reliability from technical point of view. Paper industry requires high reliability of equipment in order to provide continuous work of paper making machine. Parts of equipment which have a risk of brakes have to be designed in such a way that broken part can be replaced within short time. The disadvantage of this scheme is low reliability. In case of failure of the laser, there is no backup system. Spare laser source cannot be applied due to long time of installation and beam alignment.

This brings the conclusion that two separate laser sources have to be used in order to increase reliability. It has to be noticed that use of spare laser source as a backup in case of failure is not reasonable. This increases investment costs into equipment. Laser beam alignment may require significant time, thus production would be stopped during alignment and positioning of the beam.

The set of equipment includes two laser source of 3 kW power, two cutting heads and four bending mirrors. The schematic layout of equipment is represented in Figure 42. Laser sources are placed next to each other and beam is supplied to the second cutting zone by system of mirrors. This is essential as one side of a paper making machine has to be free from equipment to provide access for fabric change and maintenance work.

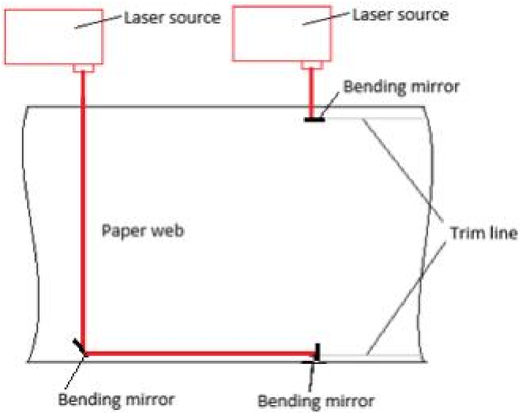


Figure 42. Schematic layout of equipment: scheme 2.

Each laser source provides laser beam to its own cutting zone. Laser cutting heads with integrated bending mirrors can be used. Laser sources of lower power are needed (a half of the laser power described in the first scheme). This may be essential, if required laser power is below about 4.5 kW. Laser power required for edge trimming of paper web in machine with speed of 2000 m/min is about 3 kW for one cutting zone. CO_2 slab lasers can be applied in this case. Higher energy efficiency of these lasers can reduce energy consumption and improve economical performance. This scheme also allows to reduce investment costs significantly due to lower power lasers applied. However, failure of a laser would result in production stop and consequent losses in production.

The set of equipment includes two laser source of 6 kW power, two cutting heads, one partially reflective mirror and four bending mirror. The schematic layout of equipment is represented in Figure 43. Detailed description of beam transfer can be found in Appendix IV.

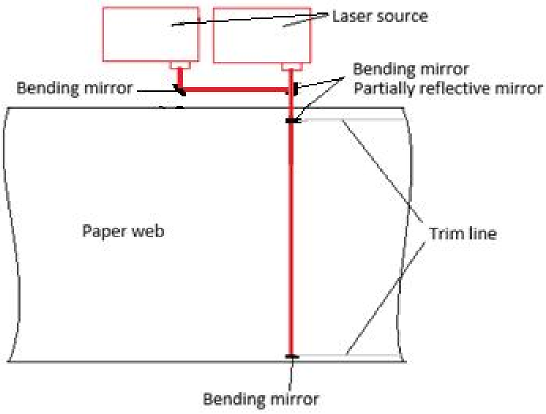


Figure 43. Schematic layout of equipment: scheme 3.

The scheme shown in Figure 43 combines above mentioned schemes. Each laser source provides laser beam to its own cutting zone. Power of one laser source is two times higher than required for cutting. Laser cutting heads with integrated bending mirrors cannot be used. Instead, bending mirrors are installed in such a way that allows fast removal. Partially reflective mirror is installed in the system so that it can replace any bending mirror.

In case of failure of one laser source, bending mirror can be replaced with partially reflective mirror. Laser source power has to be doubled to supply laser beam for both areas. In this way reliability can be increased as failure of both laser sources simultaneously is less probable.

Proposed scheme implies the higher investment costs but reliability of the system is of higher importance in this case. Fast axial flow CO_2 laser should be applied as both high power output and good beam quality are required. Power of CO_2 slab laser stated by manufacturer for cutting application of non-metallic materials (wood, textile, etc.) does not allow its application due to output power limitation.

7.3 Laser cutting against the roll

Laser cutting of paper web has to be done while paper web travels without support of wire. In modern paper machines, there is usually no such free transfer of paper web (as it was in older machines when paper web was transferred from forming section into press section). This requires finding a solution for laser cutting.

Possible solution can be cutting against a roll. Such roll have to include:

- Groove on the surface (the dimensions of the groove have to be in relation to laser beam diameter)
- Vacuum suction zone for removal of fumes
- Beam dump bellow vacuum zone for dumping excessive laser power
- Channel for cooling of beam dump and fumes removal

This roll can be also combined with some existing rolls in press section. Such combination can be proposed particularly to central roll as it has area of free paper web movement. Proposed schemes are shown in Figure 44.

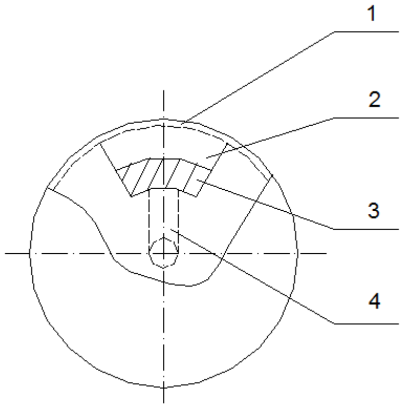


Figure 44. Schematic view of roll for laser cutting.

Finding an exact location for edge trimming in wet end is challenging task. Laser edge trimming cannot be done when paper web is supported by wire or felt. Laser energy have to be slightly higher than needed for cutting to ensure complete cutting and compensate variation of paper web composition. Thus, some part of the laser beam will pass through paper web and need to be dump. Laser beam of CO_2 laser will cause cutting of felt as it is made of materials which absorb corresponding wavelength. Wires are usually made of bronze which reflects major part of the beam. Laser cutting with accurate control of laser energy probably could be possible against the wire but the problem of fumes removal from cutting zone arises. Besides that, solid residues after cutting would contaminate the wire and mill break what leads to serious problems in trimmed stripes recycling.

In the implementation scheme (Figure 45), laser cutting is done at the location of central roll. Paper web passes first press untrimmed in this case. Distribution of pressure applied in each press has to be done in such a way to avoid web breaks that lower pressure applied in first press and this loss of pressure is then compensated in the following presses. This scheme employs existing part when paper web travels without support of felt on top of central roll. Granite rolls would be impossible to implement proposed laser cutting zone for laser cutting implementation. Ceramic rolls seem to be better option in this case.

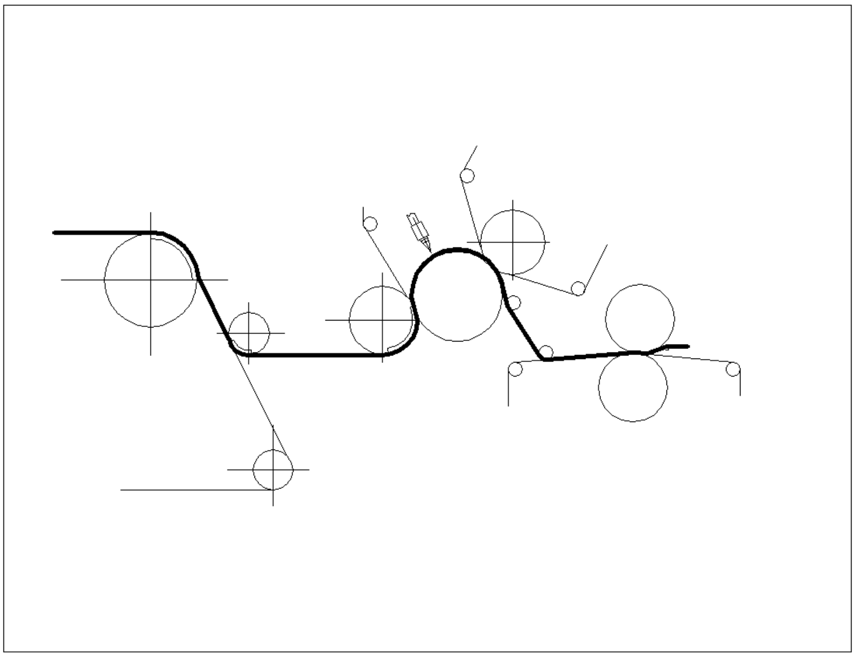


Figure 45. Schematic view of location of laser cutting implementation in press section of paper making machine.

Scheme shown on Figure 45 is not ideal as paper web goes through first pressing zone untrimmed. This may cause web breaks due to high pressure. However, proposed scheme can be beneficial in case if edge trimming is done in two locations: at the pick up and before size press. Then, edge trimming of paper web would be done with existing water jet cutting at pick up but the second location would be moved to central roll according to proposed scheme. Additional edge trimming before open draw (after second press zone) can improve runability of paper making machine.

Even though, other ways of laser cutting implementation are difficult in other locations of existing layouts of press sections due to paper web travel with support of felts. Possibilities offered by laser cutting has to be kept in mind for further development of press sections where better implementation strategies can appear.

Considering the proposed scheme, laser cutting system layout can be seen in Figure 46.

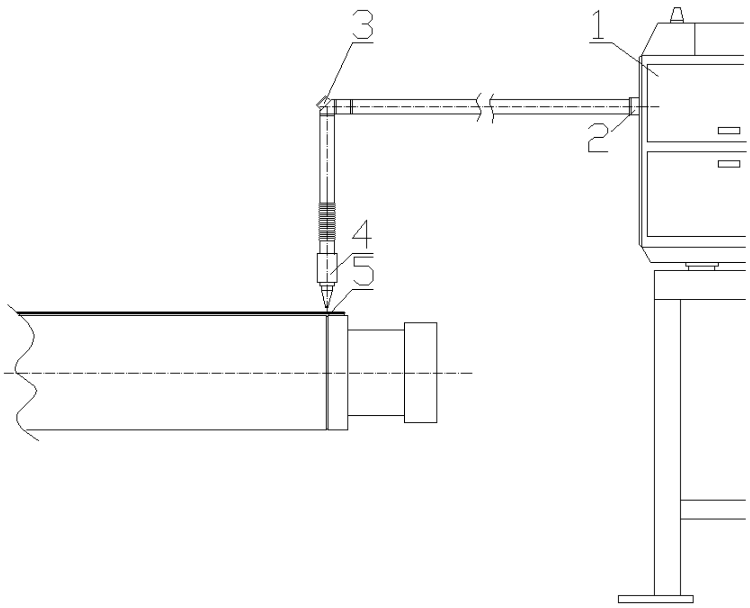


Figure 46. Schematic layout of laser cutting system for edge trimming (one cutting area).

As it can be seen from Figure 46, laser cutting system consists of laser source (1), output mirror (2) from which beam is transferred to bending mirror (3). Set of interchangeable optical components should be installed at this position, including:

- bending mirror, used as primarily equipment,
- partially reflective mirror

Partially reflective mirror can be used in case of failure of the second laser source to provide laser beam for cutting the second edge. After the beam is supplied to cutting head (4) where it is focused and performs laser cutting in cutting zone (5).

Laser cutting system can also bring the advantage considering felt change when implemented in paper making machine. Water jet cutting system has to be removed in order to get the access to felt. This problem can be eliminated with laser cutting system what also improves runability to certain extend.

7.4 Parameters relevant to successful laser cutting performance

Paper parameters which need a special attention when laser cutting is intended to be applied:

- Specific heat capacity
- Moisture content

- Thickness
- Mineral pigments content

Specific heat capacity has significant effect on required laser cutting energy. The best way of achieving accurate calculations would be direct measurement of paper grade produced in paper making machine.

Moisture content has direct effect on required laser cutting energy as additional amount of water has to be evaporated. Specific heat capacity and density are dependent on moisture content. Besides that, laser beam absorption also changes due to presence of water in paper material and water vapour released during cutting.

Thickness variations are important considering upper limit of laser power. Laser cutting has to be done with excess power to be able to produce complete cut in case of undesirable changes of paper web thickness. Thickness of the paper material is of high importance when choosing focusing properties of laser beam.

Mineral pigment content has to be taken into account because it has effect on laser beam interaction with paper material. Laser beam absorption, scattering and reflection properties may be significantly changed due to variations of mineral content.

Laser parameters to obtain high cutting quality are:

- Laser power
- Cutting speed
- Beam focusing properties

Laser power and cutting speed determine ability of laser to cut a material through. Laser power and cutting speed are usually varied in laser cutting. In case of laser cutting implementation in paper making machine, variation of cutting speed is not possible. Laser power has to be sufficient to maintain speed of paper making machine.

Focus spot of laser beam determines cut width and thus the amount of evaporated material. In order to reduce losses of the material, the smallest possible beam spot has to be used. This can be relatively easily achieved due to small thickness of paper material. Thus, depth of focus and focused spot diameter are not in conflict in this case. Focal length has to be chosen according to conditions of particular installation. Distance between cutting head nozzle and paper web surface has to maintain safe conditions in terms of paper web contamination, dirt particles deposition on the nozzle and room for equipment available.

7.5 Economic performance evaluation

The cost estimation was studied using simple model which included cost of equipment acquisition, fixed costs and variable costs. Division of the costs into above mentioned groups was made based on their nature:

- acquisition costs include investments into equipment
- fixed costs are the costs which have to be paid in a certain period of time on constant basis
- variable costs are assumed costs which however do not have any constant character

The approach was to study the costs of laser cutting machine only; the costs of supporting equipment was not taken into account as they vary according to the particular way of implementation. The total cost can be calculated as Equation (16) shows.

$$Cost_{system} = Acquisition\ cost + Fixed\ cost + Variable\ cost \tag{16}$$

where $Cost_{system}$ - cost of system implementation and running, € / h.

There are number of assumptions taken for calculations:

- paper making machine runs for 8000 h per year (330 days a year),
- paper making machine runs at speed of 2000 m/min and
- depreciation period of equipment is 7 years

Acquisition cost can be calculated as Equation (17) illustrates.

$$Acquisition\ cost = \frac{Laser\ unit + cutting\ head}{depreciation\ period} \tag{17}$$

The cost of laser unit is estimated to be 500000 € and the cost of cutting head 5000 €. These estimations are based on general price level for CO_2 lasers, the final cost of a unit may vary depending on particular model and manufacturer. The power of the unit is based on calculated linear cutting energy needed for successful cutting of paper web and assumed machine speed. This brings the required laser unit of 6 kW power. Two laser cutting units are needed to execute edge trimming of both edges of paper web.

Fixed costs can be calculated as Equation (18) shows.

$$Fixed\ costs = \frac{Labor\ cost + Maintainance\ costs}{8760} \tag{18}$$

It is assumed that laser cutting units do not require special operator but operation of the units is done by regular staff members. Maintenance works such as cooling water changing and lens cleaning can be done by regular staff whereas maintenance of laser unit has to be done by laser provider. These expenses do not depend on rate of production.

Variable costs can be calculated as Equation (19) illustrates:

$$Variable\ cost = cost\ of\ lenses + cost\ of\ gases + energy\ costs \quad (19)$$

Variable costs depend on production rate. Assumed work time is 8000 h per year. The price of electricity of 0.12 e/MWh which was approximate price of electricity in Finland in 2015. Cost of lenses was obtained depending on their expected working time. Cost of gases includes laser gases (CO_2, He, N_2) as well as shielding gas (compressed air). Cost estimation can be found in Table 21.

Table 21. Estimation of laser cutting costs.

Cost	**Laser cutting**
Acqusition cost	
Laser units	726000.00 €
Cutting heads and beam transfer elements	105600.00 €
Total	14.85 €/h
Fixed costs	
Labor cost	10.00 €/h
Maintenance cost	10000.00 €/year
Total	11.14 €/h
Variable costs	
Cost of lenses	0.80 €/h
Energy consumtion	14.40 €/h
Cost of gases	1.00 €/h
Material loss	3.98 €/h
Total	20.18 €/h
Total costs	
Cost per hour	46.17 €/h

Thus, cost of laser cutting system implementation and running is estimated to 46.17 €/h for both laser units. As it can be seen from Table 21, main costs are acquisition cost of laser equipment and variable costs. Fixed costs are mainly dependant on labour costs.

Water jet cutting costs described in literature (Radovanovich, 2007) has to be modified to conditions of paper making machine.

Table 22. Estimation of water jet cutting costs.

Cost	Water jet
Acqusition cost	
Water jet unit	120000.00 €
Total	3.91 €/h
Fixed costs	
Labor cost	10.00 €/h
Maintenance cost	5000.00 €/Y
Total	10.57 €/h
Variable costs	
Cost of nozzles	0.78 €/h
Energy consumtion	5.40 €/h
Water consumption	0.12 €/h
Total	13.80 €/h
Total costs	
Cost per hour	28.28 €/h

As it can be seen from Table 22, cost of water jet system is estimated to 28.28 €/h for both units. This is considerably lower compared to estimated costs of laser cutting.

Laser cutting costs fulfils the general perception being more expensive compared to water jet cutting. Acquisition cost of laser equipment is significantly higher than of water jet cutting system. Fixed costs, which consist of labour force cost and regular maintenance cost, are comparable. Variable costs (or running costs) are higher in case of laser cutting system.

Development of laser technology suggests some possibilities in reduction of acquisition cost of laser equipment. Laser unit of 6 kW power is a serial industrial laser by the year 2015 what makes it easily available. This means that laser cutting system does not require development of a new special laser for that purpose. This has a positive impact on price level of laser equipment.

Fixed costs can be influenced by labour costs. However, not much improvement can be expected in this cost category.

Running costs are mainly dependant on energy consumption. Low energy efficiency of CO_2 lasers lead to high electricity consumption. Significant improvements of energy efficiency of CO_2 lasers cannot be expected. Thus price level of electricity or own generation of a paper mill can reduce variable costs.

8 Conclusions

There are number of cutting needs in paper making process which are currently done by various mechanical and water jet cutting technologies. Cutting needs in a paper making machine can be generally divided into two types: longitudinal cutting of paper web in machine direction (MD) and cutting in cross direction (CD). Technologies which are currently used in paper making machines include water jet cutting in wet end and rotating slitting blades in dry end and reel as well as rewinder (with different arrangements depending on the area of application and cutting purpose).

Cutting operations were done with rotating slitting blades in paper making machines until 70's when high pressure water jet cutting was demonstrated for edge trimming of paper web. This evolution of technology showed that the basis of new technology application was the desired result; when conventional technology did not fully provide the desired results, it opened possibility for a new technology to replace it. This was taken as the main justification for laser cutting implementation. Laser cutting had to provide solution for problems associated with the utilization of current cutting technologies.

Basic principles of interaction of laser beam and paper material were represented in literature review. According to absorption characteristics of paper material, CO_2 laser was found the most suitable laser for paper cutting due to its wavelength. This conclusion was drawn on the basis of absorption characteristics of cellulose as the main component of paper material. Wavelength of 10.6 µm emitted by CO_2 laser is the most suitable for paper material processing.

Basic principles of CO_2 laser construction and operation was described. Particular attention was paid to industrial lasers. By year 2015, CO_2 laser of 6 kW power was serial type industrials laser widely available. This supports the statement of laser being common industrial tool. It is important to have readily available laser system when implementing laser cutting system into a paper making machine. Thus, there is no limitation in such implementation from side of laser technology.

Examples of laser cutting found in literature were represented. Published research results proved capability of laser cutting to produce high quality cutting with speeds corresponding to paper machine speeds. Moreover, laser cutting offers cutting speeds which exceed paper making machine speeds. This is an important advantage of laser cutting technology of being the substitute tool for cutting in paper making machines.

Cutting needs have been described and these types of cutting can be also done using laser technology. There are a few areas where laser cutting can be applied: wet end, dry end and rewinder. Selection of the most promising area of laser cutting implementation was carried out on the basis of possibility of laser cutting technology to solve following problems:

- associated with conventional cutting systems,
- associated danger of laser technology, technological advantages and disadvantages, design possibilities and
- economic performance.

Laser was found to be capable of solving some problems associated with conventional cutting systems. In wet end, laser cutting can fulfil required cutting speed and provide capacity for further speed increase. Increased machine speeds will require new solutions in terms of edge trimming when systems like twin nozzle water jet will reach their limit. more powerful lasers become available along with development of laser technology,. Thus, trends of paper making machine speeds increase and increase of power of laser sources correlate with each other. Moreover, laser cutting can potentially improve cut edge properties due to high quality achieved. Due to evaporation of paper material in the area exposed to laser beam, even cut edge can be obtained without out-sticking fibres. This is essential for runability of paper making machine as well as post processing of paper (e.g. printing). Improving the quality of cut edge, number of paper web brakes can be reduced resulting in longer work time, less stand by time and higher production rate. In dry end and rewinder laser cutting can solve problem of dust formation.

Rapid development of laser technology offers new possibilities of laser cutting implementation from economical point of view. Cost of laser cutting compete with conventional technologies in some industrial fields, mostly in metal processing. However, comparison of laser cutting method and water jet cutting in conditions of paper making machine showed laser cutting to be more expensive.

New possibilities in design can be provided when laser cutting is considered. Laser cutting head gives high variations of angle of incidence to the work piece. Angle of laser cutting head to paper web can be varied what gives additional possibilities for design and layout of equipment especially if room for equipment is limited.

In recently developed gapformer paper making machines, laser cutting can utilize its main advantages: high cutting speeds and high cutting quality. However, one of the focus in development of such paper making machines was to eliminate open draws. This makes laser cutting implementation into existing scheme challenging as cutting against wire or felt is not possible. Laser cutting against wire or felt would cause their damage due to laser beam influence, contamination with solid particles after laser cutting and consequently contamination of mill broke. Besides that, extraction of fumes would be difficult as well.

However, laser technology brings not only advantages. Potential drawbacks of laser cutting have been shown as well. Laser cutting require so-called open draw where paper web moves without support of felt or fabric. This causes severe difficulties in finding the location where edge trimming with laser can be done. In Fourdrinier machines such open draw can be found easily, when paper web is transferred from forming section to press section, and implementation of laser cutting would be relatively easy. However, laser implementation is not reasonable in this case due to sufficient work of existing methods of edge trimming.

Laser cutting can cause yellowing of cut edge due to thermal input; severe colour change is caused by both excess laser power and insufficient laser power. Colour change occur during and after laser cutting. Choosing correct laser cutting parameters, colouration of cut edge can be minimized. Current cutting technologies does not cause this problem. Colour change of cut edge limits application of laser cutting at the final product stages where optical parameters of paper and board play significant role. However, laser cutting of paper web can be done at paper making process stages followed by another cutting or trimming.

Energy efficiency of CO_2 lasers is a severe drawback. Efficiency of CO_2 lasers is about 10 – 15 % leading to high energy consumption. This in turn has a great influence on running cost of the laser system utilization.

Potential hazard due to presence of ignition source (which is laser beam in this case) and formation of dust/air flammable and explosive mixture was noticed. Laser cutting produces mixture of dust and air, especially if cutting conditions are favourable for incomplete decomposition of cellulose. Possibilities of forming explosive mixture have not been evaluated in this study. Intended laser cutting implementation was in wet end, thus risk of fire or explosion was low due to presence of high volume of water vapour in fumes after cutting.

It was concluded that the most beneficial location of laser cutting implementation would be wet end of a paper making machine. Laser cutting can be applied for edge trimming of paper web. Fourdrinier paper making machines have open draw at the area of paper web transfer from wire section to press section. Laser cutting could be applied relatively easily at this type of machines. Cutting table conventionally used for water jet edge trimming has to be modified to provide removal of fumes from cutting zone. However, laser cutting implementation is not reasonable due to economic aspects.

Development of high speed paper making machines eliminates area of free transfer of paper web to reduce risk of web brakes. Implementation of laser cutting in modern high speed machines is more beneficial. For that purpose, special equipment to maintain laser cutting process is required. Scheme of roll for laser cutting was proposed. This roll has to have suction zone in cutting area to remove cutting fumes, beam dump for dumping excess laser power and channels for cooling and vacuum supply. Extracted fumes have to also be filtered in order to separate solid residuals. It also seemed reasonable to integrate such roll with existing pressing rolls used in paper making machines.

Such integration can be done for central roll at the area where paper web moves without support of felt. This way of implementation would not be possible with granite roll but ceramic rolls can be used. Laser cutting implementation would then employ existing possibilities without need for structural changes in press section. It potentially can also improve tensile properties of paper web before open draw where web breaks often occur. With the chosen tensile strength testing method, this claim was not completely proven. However, it can be concluded that laser cutting did not cause reduce in strength properties.

Laser cutting is cutting tool which has potential to be implemented in paper making machines for longitudinal cutting. Laser equipment needed to perform cutting with required cutting speeds, equipment for beam transfer and focusing optic is readily available. Laser cutting has to be done against the roll taking into account paper web handling requirements, as a system which can easier be integrated into paper making process. This kind of roll have to be specially designed. Finding exact location for laser cutting was challenging as it requires paper web travel without support of fabric. Laser cutting of paper web at location of central roll was proposed. However, needs for edge trimming may occur in other locations and each case have to be considered individually depending on paper making machine layouts. Laser cutting implementation has to be done at the stage of design new paper making machines instead of integration into existing ones. In this way, requirements of both paper web handling and laser cutting can be compromised in the best way.

Economical evaluation of laser cutting implementation was done as comparison of acquisition, fixed and variable costs of laser cutting to water jet cutting. Laser cutting was found less efficient in terms of economic performance compared to water jet cutting. Primarily this was due to high initial cost of equipment and low energy efficiency of CO_2 laser technology. Economical factor cannot play major role in motivation for edge trimming with laser. However, if possibility of improved tensile strength of cut edge due to laser cutting and lower number of web could be proven, efficiency of laser cutting system from economical point of view would increase.

8.1 Future research topics

This study shows that implementation of laser cutting technology is possible in paper making machine. Laser cutting equipment is available and has needed capacity to perform cutting in conditions of paper making machines. Laser cutting does not cause negative effect on strength properties. However, tensile strength measurements of laser cut edge specifically is the topic for future studies. If it can be proven that laser cutting improves strength, amount of web breaks can be reduced.

Laser cutting of dry paper was found associated with some difficulties. However, it does not indicate that such cutting is impossible. It would be critical to obtain information on possibly flammable mixture of air, dust and gases released during cutting in order to evaluate associated risks.

Ways of increasing laser efficiency would be also a topic for future research. Energy efficiency has a great influence on running costs and, thus, higher laser efficiency would lead to better economic performance of laser cutting systems.

Equation for calculation of needed laser cutting energy for cutting has to be modified. Difference between calculated cutting energy and practically verified cutting energy was quite significant. Used equation did not take into account absorption characteristics of paper material. This difference was especially visible when moist paper material was used. Thus, variations of laser beam absorption properties have to be taken into account. Adopting this equation to different materials and materials mixtures is also future research topic.

If laser cutting of dry paper is not associated with explosion or fire risks (or this risks can be eliminated), application of laser cutting for on-machine reel cutting into customer size paper rolls can be considered. However, colouration of laser cut edge seem to be the limiting factor for such implementation.

Vibration level in conditions of paper making machine have to be studied. Level of vibration has to be taken into account due to high sensitivity of optical components of laser equipment, especially focusing equipment.

Laser beam delivery system with mirrors becomes quite complex and requires precise alignment.

Effect of laser cutting on multi-layer paper grades is another future research topic. Due to non-contact cutting mechanism, laser cutting may offer significant advantages as it does not cause shear stress of paper layers.

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Appendix I

Table 1: Tensile strength measurements results

	0 J/m	10 J/m	20 J/m	30 J/m
Tensile strength, kN/m	4.60	4.57	4.64	4.57
Tensile index, Nm/g	57.48	57.10	57.95	57.15
Breacking length, km	5.86	5.82	5.91	5.83
Strain break, %	1.46	1.51	1.45	1.41
TEA, J/m^2	43.39	44.78	43.55	41.70
TEA index, mJ/g	542.36	559.74	544.37	521.25
E-modulus, MPa	6.37	6.27	6.53	6.49
Tensile stiffnes, kN/m	618.30	608.00	633.40	629.70
TSI, kNm/g	7.73	7.60	7.92	7.87

Table 2: Tensile strength measurements results; standard deviations

	0 J/m	10 J/m	20 J/m	30 J/m
Tensile strength, kN/m	0.13	0.11	0.11	0.15
Tensile index, Nm/g	1.63	1.42	1.32	1.88
Breacking length, km	0.17	0.14	0.13	0.19
Strain break, %	0.10	0.07	0.07	0.08
TEA, J/m^2	4.37	3.08	3.41	3.80
TEA index, mJ/g	54.63	38.54	42.60	47.44
E-modulus, MPa	0.12	0.24	0.15	0.12
Tensile stiffnes, kN/m	11.99	22.90	14.25	11.30
TSI, kNm/g	0.15	0.29	0.18	0.14

Appendix II

Table 1: Tensile strength measurements results

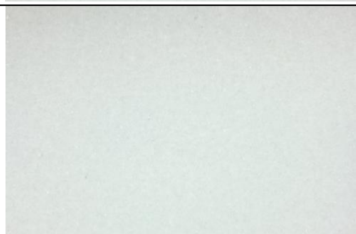
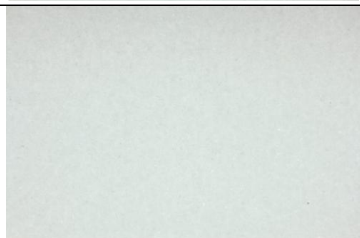
	0 J/m	35J/m	40J/m	48J/m	60J/m	80J/m	120J/m	250J/m
Tensile strength, kN/m	3.62	3.45	3.66	3.52	3.40	3.28	3.55	3.92
Tensile index, Nm/g	45.31	43.11	45.75	44.02	42.45	40.95	44.39	48.98
Breacking length, km	4.62	4.40	4.67	4.49	4.33	4.18	4.53	4.99
Strain break, %	1.97	1.84	1.85	1.90	1.72	1.71	1.84	2.08
TEA, J/m^2	45.67	40.61	42.63	41.82	36.62	34.82	41.40	51.84
TEA index, mJ/g	570.93	507.69	532.19	522.72	457.69	435.31	517.44	647.95
E-modulus, MPa	3.87	3.80	3.71	3.49	3.58	3.30	3.78	3.89
Tensile stiffnes, kN/m	371.10	365.20	356.30	334.80	343.70	316.70	362.30	373.30
TSI, kNm/g	4.64	4.56	4.45	4.19	4.30	3.96	4.53	4.67

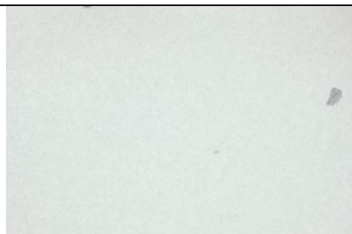
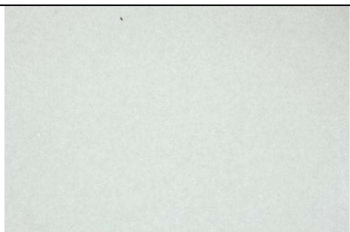
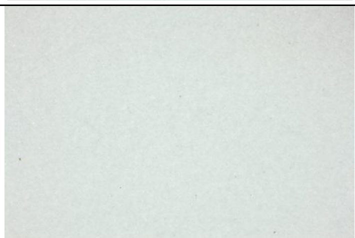
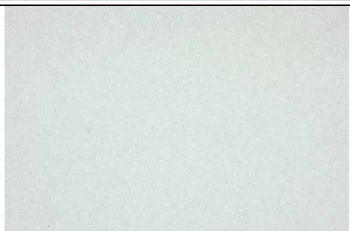
Table 2: Tensile strength measurements results; standard deviations.

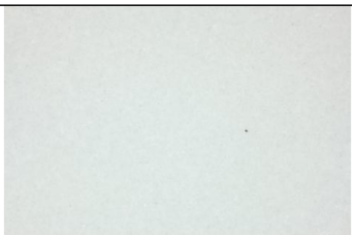
	0 J/m	35J/m	40J/m	48J/m	60J/m	80J/m	120J/m	250J/m
Tensile strength, kN/m	0.23	0.20	0.29	0.16	0.35	0.35	0.21	0.15
Tensile index, Nm/g	2.89	2.55	3.61	1.97	4.38	4.38	2.57	1.89
Breacking length, km	0.29	0.26	0.37	0.20	0.45	0.45	0.26	0.19
Strain break, %	0.14	0.19	0.15	0.11	0.23	0.23	0.17	0.09
TEA, J/m^2	6.01	6.53	6.97	3.66	8.46	8.66	5.47	4.21
TEA index, mJ/g	75.18	81.57	87.17	45.76	105.77	108.31	68.37	52.66
E-modulus, MPa	0.45	0.34	0.45	0.50	0.46	0.48	0.32	0.42
Tensile stiffnes, kN/m	43.40	32.80	43.25	48.47	43.83	46.19	30.64	40.60
TSI, kNm/g	0.54	0.41	0.54	0.61	0.55	0.58	0.38	0.51

Appendix III

Table 1: Images of hand sheets done for mill broke tests

	0 J/m (reference sample)	20 J/m
Image 1		
Image 2		
Image 3		
Image 4		
Image 5		

	70 J/m (moist sample)	10 J/m
Image 1		
Image 2		
Image 3		
Image 4		
Image 5		

	30 J/m	
Image 1		
Image 2		
Image 3		
Image 4		
Image 5		

Appendix IV

Clarification of beam transfer system

Two laser sources with integrated telescope are used to provide laser beams for two cutting zones. In normal working conditions each laser source maintain laser cutting in single cutting zone. However, both cutting zones have to be served by one laser source in case of failure of another laser source. For that purpose, mirror beam transfer system has to be able to deliver laser beam to both cutting zones from either of laser sources.

Laser beam path from laser source 1 can be seen in Figure 1.

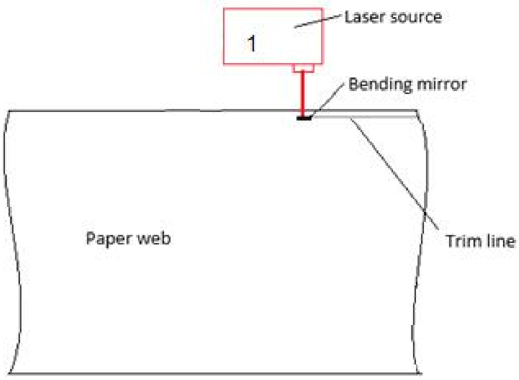


Figure 1. Schematic layout of laser beam transfer from laser source 1 to cutting zone.

Laser beam is transferred from laser source 1 (Figure 1) to cutting head using one bending mirror. The beam path is relatively short what allows to use standard bending mirror.

Laser beam path from laser source 1 can be seen in Figure 2.

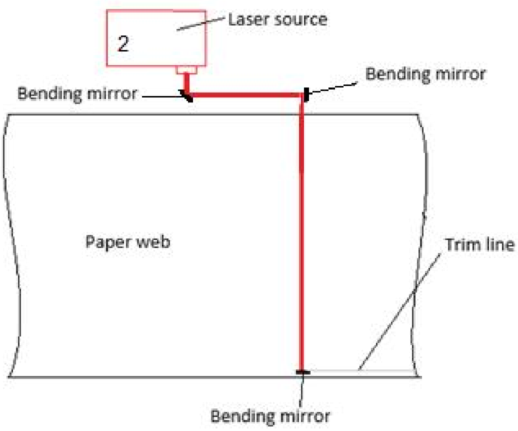


Figure 2. Schematic layout of laser beam transfer from laser source 2 to cutting zone.

Laser beam is transferred from laser source 1 (Figure 2) to cutting head through system of bending mirrors. The path of laser beam is above the path of laser beam from laser one. The last bending mirror has to be adaptive in order to compensate expansion of laser beam which travels across paper making machine.

Laser beam path from laser source 1 in case of failure of laser source 2 can be seen in Figure 3.

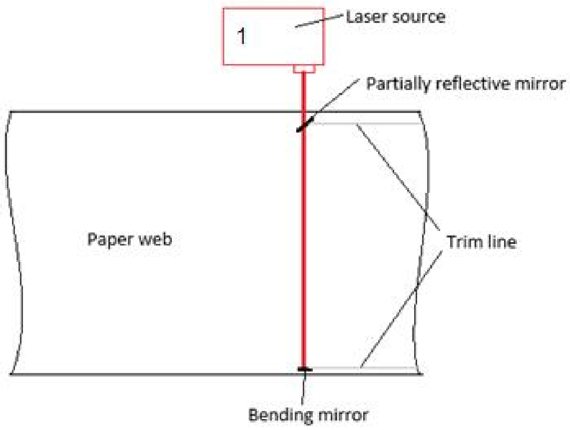


Figure 3. Schematic layout of laser beam transfer from laser source 1 to both cutting zones in case of failure of laser source 2.

In case of failure of second laser source, laser cutting has to be maintained with one laser source. Bending mirror has to be replaced with partially reflective mirror which splits the beam into two. Part of the beam is guided into cutting head whereas the second half of the beam travels across paper making machine to the second cutting zone.

Laser beam path from laser source 2 in case of failure of laser source 1 can be seen in Figure 4.

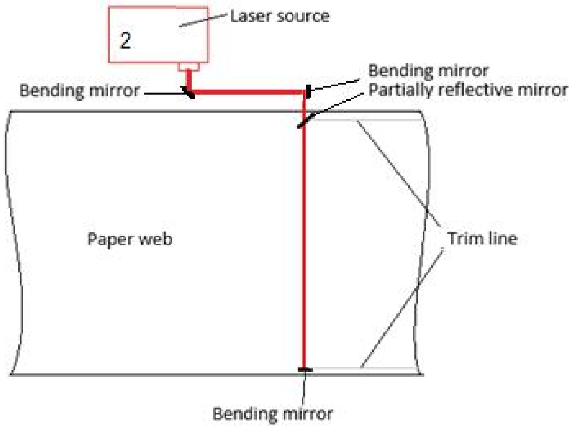


Figure 4. Schematic layout of laser beam transfer from laser source 2 to both cutting zones in case of failure of laser source 1.

In case of failure of first laser source, laser cutting is executed by laser beam from source two. Partially reflective mirror is moved up to split the beam. Thus, part of the beam is guided to first cutting head and the other part maintains cutting in the second cutting zone.

The complete view of the system can be seen in Figure 5.

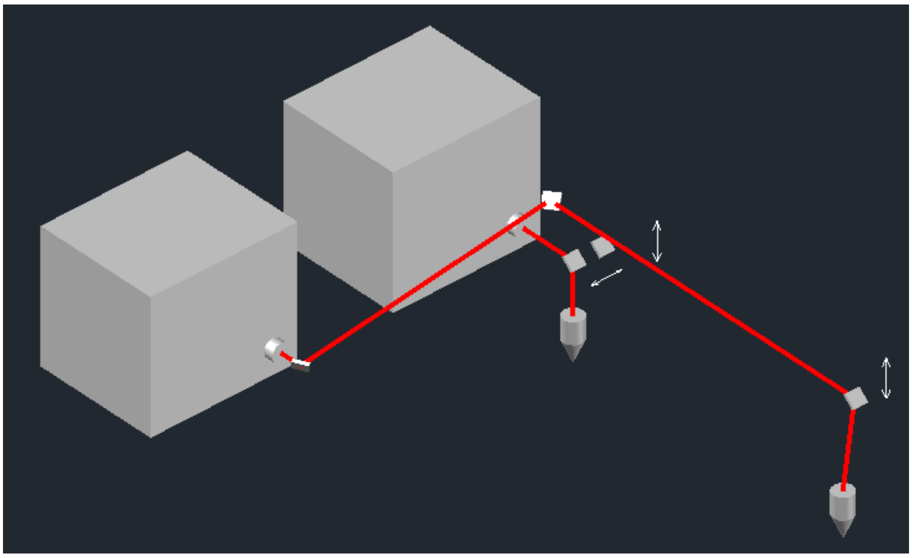


Figure 4. Beam transfer system.

Figure 4 represents 3D view on laser beam transfer system.

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