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A theory of interaction mechanism between laser beam and paper material

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Abstract

Paper making and converting industry in Europe is suffering from transfer of basic manufacturing to fast-growing economies, such as China and Brazil. Pulp and paper production volume in Finland, Sweden and France was the same in 2011 as it was in 2000. Meanwhile China has tripled its volume and Brazil doubled. This is a situation where innovative solutions for papermaking and converting industry are needed. Laser can be solution for this, as it is fast, flexible, accurate and reliable.

Before industrial application, characteristics of laser beam and paper material interaction has to be understood. When this fundamental knowledge is known, new innovations can be created. Fulfilling the lack of information on interaction phenomena can assist in the way of lasers for wider use of technology in paper making and converting industry.

This study was executed by treating dried kraft pulp (grammage 67 g m-2) with different laser power levels, focal point settings and interaction time. Laser equipment was TRUMPF TLF HQ2700 CO2 laser (wavelength 10.6 μm). Interaction between laser beam and dried kraft pulp was detected with multi-monitoring system (MMS), which consisted of spectrometer, pyrometer and active illumination imaging system.

There is two different dominating mechanisms in interaction between laser beam and paper material. Furthermore, it was noticed that there is different interaction phases within these two interaction mechanisms. These interaction phases appear as function of time and as function of peak intensity of laser beam. Limit peak intensity divides interaction mechanism from one-phase interaction into dual-phase interaction.

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1. Introduction

Paper industry is under many kinds of pressures and threats in Europe and especially in Finland. New bigger and faster machines are being built to Asia and South America and at the same time the paper consumption is decreasing due to growing number of substitutive electronic solutions such as e-books etc. Therefore, this industry must be able to find new technologies, which can lower the costs and enable better quality and more flexibility. In addition, new innovations such as smart packages can enhance industry by creating new products and this way new production.

Nomenclature

| Symbol | Description |
|--------|-------------|
| $A_h$  | hole area, mm$^2$ |
| $BCA_{86}$ | beam cross-section area which contains 86% of all laser power, mm$^2$ |
| $BCA_{max}$ | beam cross-section area of highest intensity, mm$^2$ |
| $BCA_{min}$ | beam cross-section area of lowest intensity, mm$^2$ |
| $BHR_{86}$ | beam-hole-ratio for $BCA_{86}$, % |
| $C_{BHR_{86}}$ | $BHR_{86}$ constant of 176.82, % |
| $F$ | fluence, J mm$^{-2}$ |
| $k_{BHR_{86}}$ | coefficient of 25.92, (mm$^2$·%) J$^{-1}$ |
| $MADM$ | Interaction mechanism A dual-phase mode |
| $MBDM$ | Interaction mechanism B dual-phase mode |
| $P_{laser}$ | laser power, W |
| $P_{max}$ | laser power in $BCA_{max}$, W |
| $P_{min}$ | laser power in $BCA_{min}$, W |
| $tpulse$ | pulse length, s |

Finland has a long tradition of being in the front line when it comes to new innovations in paper industry. These innovations have made it possible to still have paper industry and to have a strong network of companies producing paper machines, their parts and know-how. However, it is a never-ending race against competitors and new challenges regarding environmental regulations etc. Laser technology is one solution, which can provide some competitive edge and keep the industry here a bit longer. At the same time gaining know-how in laser processing may usher in a new group of companies and new high-tech industry may take the place of decreasing smokestack industry.

Laser beam and paper material interaction and fundamentals of it are crucial for total understanding of any process between laser beam and paper material. Interaction phenomena between laser beam and paper materials are essential for understanding what happens during laser cutting of paper materials (Vänskä et al. (2013), Kaplan et al. (2015)). There is only couple of published articles about interaction phenomena of laser beam and paper materials Hüblusch (1991), Kolar et al. (2000), Piili (2007), Piili (2013), Piili et al. (2009), Rämö (2004). Via understanding of the interaction, the process development can be carried further out and even new innovations created. There is clear lack of this kind of information, which also prevents wider utilization of laser technology in papermaking and converting industry.

2. Aim and purpose of this study

Aim of the experimental part of this study was to characterize interaction between laser beam and paper material. This study was carried out in Laboratory of Laser Processing at Lappeenranta University of Technology (Finland). Laser equipment used in this study was TRUMPF TLF 2700 CO2 laser (wavelength 10.6 μm) and operates power range of 190-2500 W. Study of laser beam and paper material interaction was carried out by treating dried kraft pulp (grammage of 67 g m$^2$) with different laser power levels, focal point settings and interaction times. Laser beam and dried kraft pulp interaction was characterized by using multi-monitoring system (MMS), which utilizes Simultaneously spectrometer, pyrometer and active illumination imaging system. Pyrometer and spectrometer are used for observation of radiation emitted by process. Active illumination imaging system is used to capture images from bright sources still avoiding the high brightness of the source to cause over exposure of the camera cell. Result of interaction was also analyzed afterwards with microscope.

This study focuses to understand basic phenomena of interaction between laser beam and paper material. Key issue to whole experimental part is to understand input and output parameters, their effect on interaction and relations
between input and output parameters (see Fig. 1). Based on these analyzes a model about phenomena in interaction of laser beam and paper material can be created.

3. Used material and equipment

3.1. Material

Laser treatment of paper material was carried out with dried kraft pulp with grammage of 67 g m-2. Dried kraft pulp was selected to be test material since it is pure natural material without any additional components. The dried kraft pulp mixture selected was such a mixture of birch pulp and pine pulp that it represents usual dried kraft pulp content of commercial paper grades. Dried kraft pulp samples used for study were so called handsheets manufactured in Laboratory of Fibre and Paper Technology of LUT Chemistry at Lappeenranta University of Technology (Finland). Handsheets were manufactured according to standards of SCAN-C 26:76 and SCAN-M 5:76. Properties of dried kraft pulp used in this study are introduced in Table 1.

All cutting samples were conditioned before cutting trials (environment 50 % relative humidity, 23 °C) according to standard SCAN-P 2:75 such that the water content in samples was 6 - 8 % during experiments. Samples were wrapped into aluminum folio and stored in airtight and lightproof plastic bags before cutting trials to keep the water content constant and avoid contact with day light.

3.2. Laser equipment and work station

The laser source used in experiments was a Trumpf TLF 2700 HQ CO2 laser, which produces laser beam with wavelength of 10.6 μm. This wavelength has the highest absorption for paper and board cutting applications available in high power Ramsay and Richardson, (1992), Laakso et al., (2004), Malmberg et al., (2006). This laser equipment was operated in power range from 115 W to 2700 W. Laser beam is delivered to XY table with mirrors, circular polarizer and focused to sample with Precitec DXN cutting head. Focal length of 127 mm was used in this study. Vacuum suction trough the working table of XY station keeps samples fixed to table during laser processing. Suction also removes fumes produced during laser beam and material interaction.

3.3. Beam analysis equipment

Beam analysis was carried out by Primes FocusMonitor device of Department of Production Engineering of Tampere University of Technology (Finland). It provides fully automated caustic measurement with the integrated z-axis and determination of focal point width and position based on the measured intensity distribution. Principle of Primes FocusMonitor is based on rotating pinhole. This pinhole is used to couple out small part of radiation in the
focus region. Signal radiation is directed to the detector with mirrors. Then the electrical signals are digitized with work pieces power densities of several MW/cm².

3.4. Multi-monitoring system (MMS)

The used spectrometer Ocean Optics HR2000+ is used to analyze intensity of radiation emitted by laser beam and paper material interaction over wavelength range of 194-652 nm. Unit of intensity is expressed as Au (arbitrary unit). Maximum spectral intensity was determined to be the highest value of intensity of emitted radiation during measurement over whole wavelength range.

Pyrometer, Temperature-Control-System (TCS), is used for on-line temperature measuring and controlling of laser power for example with laser surface treatment processes. TCS is so called two-color pyrometer, which means that it measures two wavelength ranges 1200-1400 nm and 1400-1600 nm. This allows a 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 is capable of measuring temperatures above 488°C. Maximum temperature was defined to be highest temperature during measurement. Each laser power, focal plane position and pulse length parameter combination was repeated four times, so there was as well four different pyrometer measurements. Average of four repeats was determined for further analyzes for this study.

Active illumination imaging system is designed for capturing images of bright objects. Operating principle consists of use of single wavelength light source (diode laser). The single wavelength is used to overcome the light of the process; the camera has an optical filter with transmission to equivalent wavelength. Image capturing was used for each laser power, focal plane position and pulse length parameter combination and it was repeated four times, so there was as well four different set of captured images.

4. Experimental procedure

4.1. Multi-monitoring system (MMS)

In this study, a multi-monitoring system (MMS) consisting of spectrometer sensor, pyrometer and illumination source and camera were used for analysis of interaction between laser beam and paper material in fixed location in XY table with off-axis view to process. Fig. 2 represents set-up used in this study.

4.2. Equations and parameters used

As different pulse lengths were used, pulse energy was determined first, as Equation 1 shows.

$$ E_{\text{pulse}} = \frac{P_{\text{laser}}}{t_{\text{pulse}}} $$  \hspace{1cm} (1)
When pulse energy is divided by $BCA$, fluence can be calculated as Equation 2 shows.

$$F = \frac{E_{\text{pulse}}}{BCA} = \frac{P_{\text{laser}}}{t_{\text{pulse}}}$$.  

Beam cross-section area $BCA$ means that cross-section area of laser beam where beam hits sample top surface whereas ICA means cross-section area which is caused when BCA hits top surface of paper material. Very often beam diameter is represented as diameter of $1/e^2=0.135$ times of total power when Gaussian beam profile (TEM$_{00}$) is discussed. This diameter contains 86 % of all highest laser power Steen (1991), Siegman (1997). Beam cross-section area ($BCA_{86}$) means that cross-section area of laser beam where beam hits sample top surface and cross-section area contains 86 % of the beam power. Table 2 shows parameters used in this test and how $BCA_{86}$ is calculated.

| Test ID | Laser power, W | Focal plane position, mm | Radius of beam, μm | Radius of beam, mm | Area of beam, mm$^2$ | $BCA_{86}$, mm$^2$ |
|---------|----------------|--------------------------|--------------------|-------------------|----------------------|---------------------|
| 1       | 139            | 3.0                      | 246.0              | 0.2460            | 0.1901               | 0.1901              |
| 2       | 145            | 2.0                      | 172.0              | 0.1720            | 0.0929               | 0.0929              |
| 3       | 139            | 1.0                      | 120.0              | 0.1200            | 0.0452               | 0.0452              |
| 4       | 142            | 0.0                      | 65.8               | 0.0658            | 0.0136               | 0.0136              |
| 5       | 140            | -1.0                     | 70.6               | 0.0706            | 0.0157               | 0.0157              |
| 6       | 264            | 3.4                      | 250.0              | 0.2500            | 0.1963               | 0.1963              |
| 7       | 266            | 2.4                      | 190.0              | 0.1900            | 0.1134               | 0.1134              |
| 8       | 264            | 1.4                      | 129.0              | 0.1290            | 0.0523               | 0.0523              |
| 9       | 266            | 0.4                      | 75.4               | 0.0754            | 0.0179               | 0.0179              |
| 10      | 268            | -0.6                     | 68.6               | 0.0686            | 0.0148               | 0.0148              |
| 11      | 384            | 3.5                      | 246.0              | 0.2460            | 0.1901               | 0.1901              |
| 12      | 387            | 2.5                      | 175.0              | 0.1750            | 0.0962               | 0.0962              |
| 13      | 384            | 1.5                      | 118.0              | 0.1180            | 0.0437               | 0.0437              |
| 14      | 384            | 0.5                      | 66.8               | 0.0668            | 0.0140               | 0.0140              |
| 15      | 386            | -0.5                     | 74.0               | 0.0740            | 0.0172               | 0.0172              |
| 16      | 494            | 3.8                      | 244.0              | 0.2440            | 0.1870               | 0.1870              |
| 17      | 494            | 2.8                      | 175.0              | 0.1750            | 0.0962               | 0.0962              |
| 18      | 494            | 1.8                      | 115.0              | 0.1150            | 0.0415               | 0.0415              |
| 19      | 503            | 0.8                      | 68.8               | 0.0688            | 0.0149               | 0.0149              |
| 20      | 503            | -0.2                     | 79.3               | 0.0793            | 0.0198               | 0.0198              |

Beam cross-section area of highest intensity $BCA_{\text{max}}$ and beam cross-section area of lowest intensity $BCA_{\text{min}}$ are defined in table 2. Highest intensity of $BCA_{\text{max}}$ is called $P_{\text{Imax}}$ and lowest intensity in $BCA_{\text{min}}$ is determined to be $P_{\text{Imin}}$. These values can be defined as Fig. 3 shows.

Fig. 3. (a) $P_{\text{Imax}}$ and $P_{\text{Imin}}$, and (b) $BCA_{\text{max}}$ and $BCA_{\text{min}}$, when laser power of 139 W and focal plane position of 3 mm was used.
BCA86 is a beam cross-section area, which has 86% of all laser power. BHR86 is calculated as Equation 3 illustrates.

\[ BHR86 = \frac{BCA86}{A_H} \times 100\% \]  

(3)

5. Results and discussion

Piili (2013) concluded that interaction of laser beam and paper material has two mechanisms that are dependent on focal plane position range. Assumed interaction mechanism B appears in range of average focal plane position of 3.4 mm and 2.4 mm and assumed interaction mechanism A in range of average focal plane position of 0.4 mm and -0.6 mm. Focal plane position 1.4 mm represents midzone of these two mechanisms. Piili (2013) also concluded that holes during laser beam and paper material interaction are formed gradually: first small hole to interaction area of center of laser beam cross-section is formed and after that as function of interaction time hole expands, until interaction between laser beam and dried kraft pulp is ended. When hole images of small holes in beginning of laser beam and dried kraft pulp interaction are observed, they have very good quality. It is obvious that black color and HAZ appear as function of interaction time. This reveals that there still are different interaction phases within interaction mechanisms A and B. These mechanisms are shortened in this study as MA referring to interaction mechanism A and MB referring to interaction mechanism B.

When interaction mechanism A (MA) was studied closely, it was noticed that it is divided into two interaction phases (see Fig. 4).

As Fig. 4 shows, interaction mechanism A is divided into interaction phase I and interaction phase II. This two-phase characteristic of interaction mechanism A is called mechanism A dual phase mode (MADM). Interaction phase I consists time range when laser beam hits dried kraft pulp and interaction phase II time range slightly before this interaction is ended. It can be noticed from Fig. 4, that during interaction phase I laser beam hits dried kraft pulp and first a small hole which area is much smaller than hole area formed during interaction phase II. As a function of interaction time hole area enlarges until it attains its maximum area in interaction phase II and interaction between laser beam and paper material is then ended. Strong increase in emission of wavelength range of ~475-652 nm is present as two interaction phases appears. This is valid for both interaction phase characteristics of interaction mechanism A and B. These are shortened in this study as MADM referring to interaction mechanism A dual phase mode and MBDM referring to interaction mechanism B dual phase mode. Correspondingly, one-phase mode is shortened as OM, and MAOM referring to interaction mechanism A one-phase mode and MBOM referring to interaction mechanism B one-phase mode.

Further analysis of monitored data leads to conclusion that when limit \( BCA_{\text{Imax}} \) and \( BCA_{\text{Imin}} \) peak intensity are surpassed both interaction mechanism A and B turns from one-phase interaction into dual-phase interaction. Therefore, actually limit \( BCA \) peak intensity is the value that divides interaction mechanism A and B from one-phase interaction into dual-phase interaction. So all limit \( BCA_{\text{Imax}} \) peak intensity values under 1320 kW cm\(^{-2}\) and \( BCA_{\text{Imin}} \) peak intensity 260 kW cm\(^{-2}\) belong to MAOM (interaction mechanism A one-phase mode) or to MBOM (interaction mechanism B one-phase mode) and values over that belong to MADM (interaction mechanism A dual-phase mode) or to MBDM (interaction mechanism B dual-phase mode). Fig. 5 represents different decomposition mechanisms of cellulose in different temperature ranges and mechanism of cellulose pyrolysis (Nowakowski 2002).
As it can be seen from Fig. 5, decomposition process of cellulose is evolution of hydrocarbons when temperature is between 380-500°C. This means that long cellulose molecule is splitted into smaller volatile hydrocarbons in this temperature range. As temperature increases, decomposition process of cellulose molecule changes. In range of 700-900°C, cellulose molecule is mainly decomposed into H₂ gas; this is why this range is called evolution of hydrogen.

It is assumed that MAOM and MBOM are in range of “direct evaporation” of dried kraft pulp. “Direct evaporation” in this context means that dominating decomposition process of dried kraft pulp is evolution of hydrogen in temperature range of 500-700°C. Pyrometer is not able to detect this very fast decomposition of dried kraft pulp to gaseous products of H₂, CO, CO₂ and HCs. However, spectrometer could detect single peak of 588-589 nm and this refers to temperature of ~1750ºC. Therefore, it is obvious that evolution of hydrogen is dominating process. This is also, why quality of laser treatment in range of MAOM and MBOM is very good. When material is “directly evaporated” into gaseous products, no burning or blackening occurs. It is also assumed that when peak intensity of BCA reaches limit $BCA_{\text{Imax}}$ peak intensity of 1320 kW cm⁻² and $BCA_{\text{Imin}}$ peak intensity of 260 kW cm⁻², energy in interaction reaches such level that interaction mechanism is changed. This is point where MADM and MBDM take place.

However, as interaction time between laser beam and dried kraft pulp continues, hypothesis is that three auto ignition processes occurs. Auto ignition of substance is the lowest temperature in which it will spontaneously ignite in a normal atmosphere without an external source of ignition, such as a flame or spark. Three auto ignition processes appears in range of MADM and MBDM, namely temperature of auto ignition of hydrogen atom (H₂) is 500°C, temperature of auto ignition of carbon monoxide molecule (CO) is 609°C and temperature of auto ignition of carbon atom (C) is 700°C, Walton et al. (2007).

These three auto ignition processes leads to formation of plasma plume, which has strong emission of radiation in range of visible light. Formation of this plasma plume can be seen as increase of intensity in wavelength range of ~475-652 nm. Pyrometer shows maximum temperature just after this ignition.

This plasma plume is assumed to scatter laser beam in area of $BCA_{\text{Imin}}$ so that it interacts with larger area of dried kraft pulp than what is actual area of $BCA_{\text{Imin}}$. This assumed scattering reduces also peak intensity of $BCA_{\text{Imin}}$. So result shows that assumable scattered light with low peak intensity is interacting with large area of hole edges and due to low peak intensity this interaction happens at lower temperature. Therefore, interaction between laser beam and dried kraft pulp turns from evolution of hydrogen to evolution of hydrocarbons. This leads to black color of hole edges. Fig. 6 and Fig. 7 illustrates these two mechanisms.
It can be observed that $BHR_{86}$ describes change of interaction mechanism from evolution of hydrogen (one-phase mode OM) to evolution of hydrocarbons (dual-phase mode DM), as Fig. 8 shows.

As Fig. 8 reveals, maximum values of $BHR_{86}$ belongs to OM and minimum values to DM. Interesting note is that average focal plane position 2.4 mm shows that DM starts with high values of $BHR_{86}$. If $BHR_{86}$ limit fluence is examined closely, it can be concluded that they express very precisely, where OM is changed to DM. This leads to conclusion that $BHR_{86}$ limit fluence determines fluence range where interaction mechanism turns from OM to DM. It can be also noticed from Fig. 8 that correlation between fluence and $BHR_{86}$ is good. Equation of fitted natural
logarithm curve to fluence vs. $BHR86$ is, as Equation 4 shows.

$$f(x) = -25.92 \ln x + 176.82$$  \hspace{1cm} (4)

If equation 4 is expressed with fluence and $BHR86$, Equation 5 can be written.

$$BHR86 = -25.92 \cdot \ln F + 176.82$$  \hspace{1cm} (5)

Value of 176.82 can be assumed to be constant $c_{BHR86}$, so Equation 5 can be expressed as Equation 6 shows.

$$BHR86 = -25.92 \cdot \ln F + c_{BHR86}$$  \hspace{1cm} (6)

If value 25.92 is written to be coefficient $k_{BHR86}$ Equation 6 becomes as Equation 7 illustrates.

$$BHR86 = -k_{BHR86} \cdot \ln F + c_{BHR86}$$  \hspace{1cm} (7)

If Equation 7 is derivated, Equation 8 can be defined.

$$\frac{dBHR86}{F} = -k_{BHR86}$$  \hspace{1cm} (8)

When $\frac{dBHR86}{F} \geq 0.1$, $BHR86$ limit fluence $F_{limit}$ can be defined as Equation 9 represents.

$$F_{limit} = k_{BHR86} \cdot \frac{1}{0.1}$$  \hspace{1cm} (9)

Values for $k_{BHR86}$ representing different average focal plane positions are shown in Table 3.

| Average focal plane position, mm | $k_{BHR86}, \text{(mm}^2 \cdot \%\text{)} F^{-1}$ |
|---------------------------------|---------------------------------------------|
| 3.4                             | 27.08                                       |
| 2.4                             | 35.00                                       |
| 1.4                             | 17.12                                       |
| 0.4                             | 2.01                                        |
| -0.6                            | 1.53                                        |

### 6. Conclusions

Large-scale industrial implementation of laser cutting of paper materials can be done only after full understanding of phenomena involved. When basic issues in laser beam and paper material interaction are studied, also new innovative ways for further developing laser processing of paper materials can be done and even new applications found. Laser equipment used was TRUMPF TLF 2700 CO$_2$ laser (wavelength 10.6 µm) with power range of 190-2500 W. Interaction between laser beam and paper material was characterized by using on-site multi-monitoring system (MMS). This carried out by treating dried kraft pulp (grammage of 67 g m$^{-2}$) with different laser power levels, focal plane position settings and interaction times. This was monitored with spectrometer, pyrometer and active illumination imaging system. This way it was possible to create an input and output parameter diagram and study the effects of input and output parameters.

It was concluded in this study that interaction of laser beam and paper material has two mechanisms, which are dependent on focal plane position range. Holes during laser beam and paper material interaction are formed gradually: first small hole is formed to interaction area in the center of laser beam cross-section and after that, as function of interaction time, hole expands, until interaction between laser beam and dried kraft pulp is ended. This reveals that there still are different interaction phases within interaction mechanisms A and B. These interaction phases appear as function of time and as function of peak intensity of laser beam.
Limit peak intensity is the value that divides interaction mechanism A and B from one-phase interaction into dual-phase interaction. So all peak intensity values under limit peak intensity belong to MAOM (interaction mechanism A one-phase mode) or to MBOM (interaction mechanism B one-phase mode) and values over that belong to MADM (interaction mechanism A dual-phase mode) or to MBDM (interaction mechanism B dual-phase mode).

Interaction in this range starts (as in range of MAOM and MBOM), when a small good quality hole is formed. This is due to “direct evaporation” of pulp via decomposition process of evolution of hydrogen. Moreover, this can be seen can be seen in spectrometer as high intensity peak of yellow light (in range of 588-589 nm) which refers to temperature of ~1750°C. Pyrometer does not detect this high intensity peak since it is not able to detect physical phase change from solid kraft pulp to gaseous compounds.

As interaction time between laser beam and dried kraft pulp continues, hypothesis is that three auto ignition processes occurs. Auto ignition of substance is the lowest temperature in which it will spontaneously ignite in a normal atmosphere without an external source of ignition, such as a flame or spark. Three auto ignition processes appears in range of MADM and MBDM, namely temperature of auto ignition of hydrogen atom (H₂) is 500°C, temperature of auto ignition of carbon monoxide molecule (CO) is 609°C and temperature of auto ignition of carbon atom (C) is 700°C.

This plasma plume is assumed to scatter laser beam so that it interacts with larger area of dried kraft pulp than what is actual area of beam cross-section. This assumed scattering reduces also peak intensity. Therefore, result shows that scattered light with low peak intensity is interacting with large area of hole edges and due to low peak intensity this interaction happens in low temperature. Therefore, interaction between laser beam and dried kraft pulp turns from evolution of hydrogen to evolution of hydrocarbons. This leads to black color of hole edges. This is extremely important result as coloration of cut edge of paper material has been one of major things to restrain industrial implementation of laser cutting of paper materials.

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