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Laser perforation for computer paper

Claude F. Gattuso

LASER PERFORATION FOR COMPUTER PAPER

by

Claude F. GATTUSO

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Thesis Advisor: Mr. Chester Daniels

Certificate of approval --- Master's Thesis

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This thesis is dedicated to my family and my friends.

Claude GATTUSO

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPHS

page

MICROPERFORATIONS

Optical microscope

Electron beam scanning microscope

ABSTRACT

In today's computer paper printing, cross and edge perforations are done only by mechanical perforators. The mechanical perforation process works fine since the width of the bridges and the length of the holes to be perforated remain large. Concerned with improvements in quality, printers have introduced microperforations. The holes and bridges of the perforation pattern are so small that after the user has torn off the sheet of computer paper along the perforation pattern, the edges of the document are very smooth and clean. Unfortunately, microperforations are reaching the limits of what can be achieved by the mechanical perforators. Because of the physical contact between the perforating tool and the paper, the perforation pattern is damaged. The tensile strength of the microperforation pattern decreases significantly and the paper often jams in the computer printers. Mechanical perforator dies wear and may even break.Therefore, holes are incompletely perforated or missing, so that the document is likely to be damaged when it is torn off along the perforation pattern by the user. Imcomplete or missing perforations increases the tensile strength of the perforation pattern. Therefore, the printer can increase the quality of a perforation pattern by reducing its variability in tensile strength.

This thesis studies the perforation of computer paper by laser beam. It is demonstrated through a microscopic study that laser perforations are free of all the defects which are inherent to the mechanical perforation process. It has been found that laser perforated holes remain open while mechanically perforated holes close back just after being perforated. The tests which have been carried out show that using a laser instead of a mechanical perforator to do

microperforations reduces the variability in the tensile strength from 0.694 kilograms to 0.0751 kilograms. This improvement is significant. However, using a laser instead of a mechanical perforator to do large-size perforations reduces the variability in tensile strength only from 0.0421 kilograms to 0.0338 kilograms. This improvement is not significant.

A mathematical model expressing the relationship between the tensile strength of a perforation pattern, the width of the bridges, and the number of bridges per inch has been established. The correlation found between the model and the experimental values is high ($r = 0.98$). This mathematical model is a simple method which allows the printer to adjust the tensile strength of a laser perforation pattern to the desired value. This model requires only simple calculations, and the knowledge of one basic characteristic -- the tensile strength of the paper.

As a conclusion, the laser beam is a very valuable tool which can achieve very high quality microperforations on computer paper. However, it seems not worth using a laser to do large-size perforations on computer paper since the decrease in tensile strength variability over the mechanical perforation process is not significant. The fact that laser perforated holes remain wide open could improve high speed folding and piling in the press deliveries by allowing the air trapped between the sheets of computer paper to escape through the perforated holes. This property has also already found an interesting application for cigarette filter paper.

Chapter I
INTRODUCTION

THE MISCELLANEOUS USE OF PERFORATIONS

One purpose of perforations is to facilitate the folding of paper. Perforating a signature enhances high speed folding and piling in high speed folder deliveries by allowing the air trapped inside the folded section of the signature to evacuate.

However perforations are mainly used to allow a sheet of paper to tear out smoothly and cleanly at a designated point. Return envelopes, postcards, stamps, tickets, information sheets, and coupons are examples of perforations application which are well known to the public.

Some printing materials, such as business forms or computer paper, require perforations of a much higher quality. This thesis is interested in high quality perforations performed on the edges of the sheets of computer paper. These perforations are linking the 11" x 8 1/2" sheet of computer paper to one-half-inch-wide edge strip on which big holes have been punched. The purpose of these holes is to drive the paper through the computer printer. Once the sheet has been printed by the computer printer, the user removes the edge strips by tearing off the document along the perforation pattern. The user ends up with a 11" x 8 1/2" print which can be directly inserted in a report, or a brochure.

THE PERFORATION PATTERN AND ITS VARIABLES

Tensile strength. The tensile strength is the maximum loading force applied to a test specimen at rupture or breaking point under prescribed conditions. It is

expressed in kilograms per inch.[1]

Bridge width. The width of the minute strip of paper which links two pieces of paper separated by a perforation pattern.

The number of bridges per inch. The number of bridges which links both sides of a one-inch-wide strip of paper separated by a perforation pattern. This variable is usually used by the printer to characterize a perforation pattern.

The hole length. The largest measurement of the perforation hole. This variable is related to the number of bridges per inch and to the bridge width.

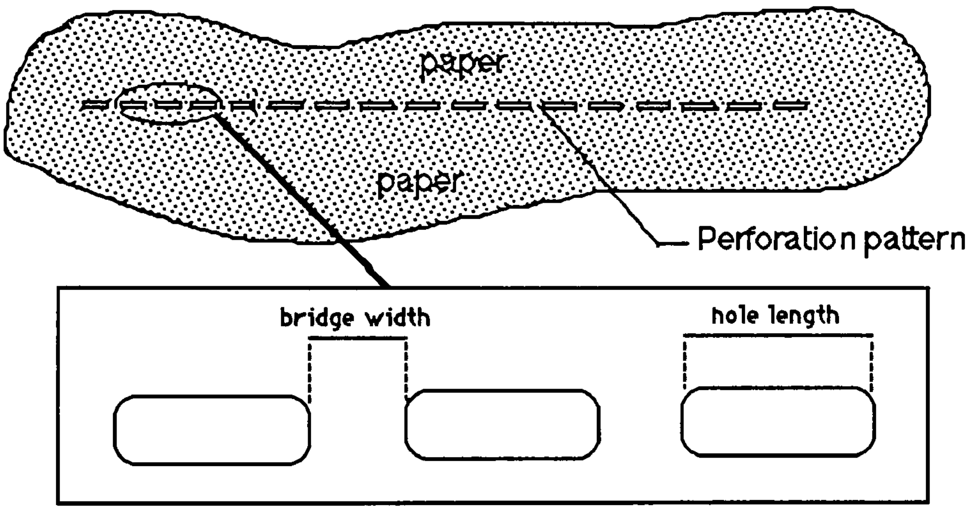


Figure 1. The bridge width and the hole length in the perforation pattern.

THE MECHANICAL PERFORATOR

Computer paper does not usually require a lot of color printing. Neither does it require a large printing width. Therefore, the computer paper is usually printed short run on presses which are especially designed for this type of application. These presses are highly versatile and adaptable. Makeready and changeover operations, such as changing plates, or adjusting the position of the perforation

patterns must be done very easily and quickly. The press may run either into the press either in pack-to-pack or in roll-to-pack configuration.

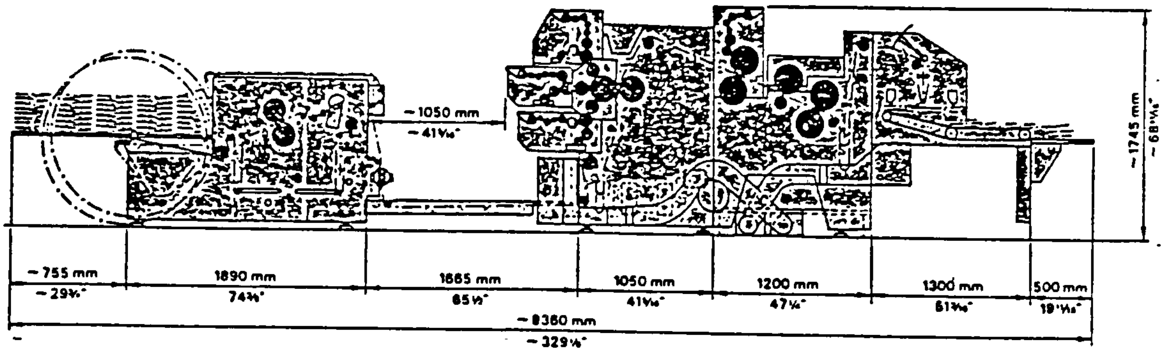


Figure 2. The Grapha-Pronto Forms printing press.(2)

In the present printing industry, perforations are performed only mechanically. The design of a mechanical perforator is mainly based on two cylinders -- a plate cylinder, on which the perforation pins, scoring lines, and cutting blades are mounted, and a blanket cylinder. The computer paper is perforated as it passes through the nip area. To reduce the nip pressure, straight-line perforations along the web direction are sometimes accomplished by adding anvil rollers onto an auxiliary rubber roller. Pattern perforators allow slight side-lay adjustments. The best ones are equipped with motorized circumferential register, and adjustment control over the pressure in the nip area.
Short-run computer paper presses print and perforate at a speed of up to 400 feet per minute (15,000 impressions per hour). However, in other printing applications, perforators are running at much higher speed. Some high speed perforators can run as fast as 1,800 feet per minute.(3)

THE DEFECTS OF THE MECHANICAL PERFORATIONS

Large-size perforations are performed by sharp dies while microperforations are performed by very thin needles. The perforating device wears during the press run because it is in physical contact with the paper. The dies lose sharpness. The thin needles used to microperforate computer paper may even break. Then, holes are either missing or incorrectly perforated, so that when the user separates the sheet from the disposable edge strips, tearing is likely to go out of the designated pattern of perforation and therefore damage the document.

Perforating with warped pins or with too much pressure can damage the bridges. A weak point is then created inside the perforation pattern which may break either within the production line or during customer use. This defect is responsible for most of the paper jams occurring in computer printers.

During the perforation operation, the perforation pins pass through the paper. The cellulose fibers are not removed but mashed and piled up at the bottom of the perforated hole.(4) This layer of mashed fibers closes back the holes, preventing air from passing through, and creates an additional link between the document and the disposable edges so that the tensile strength cannot be controlled.

THE EXPECTED ADVANTAGES OF THE LASER PERFORATION

Mechanical perforations offer a quality limited by the physical contact between the perforating tool and the paper. The laser (an acronym for Light Amplification by Stimulated Emission of Radiation), on the other hand, is a contactless method of perforation which is expected to be free of all the defects inherent to the mechanical perforation process.(5)

The perforation pattern is produced simply by turning the laser beam on and off for specified travel distances onto the surface of paper. The power of the laser is so efficient that the area of paper struck by the beam is instantaneously vaporized to produce the perforation hole.

Because the laser is a contactless method of perforation:

- No pressure is applied to the paper and the bridges inside the perforation pattern are not damaged.
- The perforating device does not wear.

Therefore:

- The variability in tensile strength of the pattern perforation is very low.
- Maintenance costs are decreased.
- The quality of the product is higher since the perforation process is more in control.

The laser can be computer-controlled, so that any change in size in the perforation pattern along or across the web can be easily effected at full speed during the run just by entering a new instruction in the program.

The beam of the CO_2 laser is very thin and accurate, therefore:

- The diameter of the perforation holes can be as low as three thousandths of an inch.
- The variability in the size of the holes and bridges is low.
- The number of holes which can be perforated per inch is very high so that the edges of the document are perfectly smooth after the edge strips have been removed.
- Because the paper is vaporized, the laser perforation holes remain clean and open.

STATEMENT OF THE PROBLEMS

The large-size of mechanical perforations which is performed by printer X on the 11" x 8 1/2", 20-pound uncoated computer paper has the following measurements: Hole length: 0.190 inch. Bridge width: 0.030 inch. Number of bridges per inch: 4.(6) This size of perforation has been sold everywhere for a long time. However, the problem is that the bridges are too wide. Once the edge strips have been torn apart, the edges of the document are too jagged to be directly inserted in a book or a brochure of very good quality.

A few years ago, concerned with quality improvements, printer X produced the same paper with microperforated edges. The mechanical microperforations have the following size: Hole length: 0.0075 inch. Bridge width: 0.0062 inch. Number of bridges per inch: 72. The improvement in quality was drastic. Once the perforation pattern has been torn, the edges of the document are very smooth and clean.

However, microperforations have reached the limits of what can be done by the most sophisticated mechanical perforators. The bridges are minute, and very fragile. Consequently, they are affected very significantly by all the problems of the mechanical perforations which have been described previously.(7) The perforation pattern is damaged in many points. An inquiry effected in computer labs, research labs, and suppliers has shown that the variability in tensile strength of the mechanical microperforations is too high. The perforation pattern breaks too easily in the computer printers and the paper often jams. Because of that problem, many customers are returning to the use of the large-size perforations.

An additional problem is that printers do not know how to adjust the bridge width and the number of bridges per inch to give the perforation pattern the

tensile strength required by the user. Such adjustments are usually a "guess" from past experience, or result from a series of costly trials effected directly on press.

THE GOAL OF THE THESIS

It is believed that the laser perforation process can achieve large-size perforations and microperforations which are free of all the defects affecting the mechanical perforation process. Laser perforations should have all the advantages described in the previous paragraph.[8] The goal of this thesis was to show that because the laser is a contactless method of perforation, the variability of the tensile strength of the perforation pattern obtained by this process is much lower. Therefore, manufacturers would be able to adjust the tensile strength of the laser perforation pattern to a very precise value and would have a very good control over the variations of the tensile strength of the perforation pattern.

The goal of this thesis was also to show that the tensile strength of a perforation pattern can be calculated from three basic characteristics which are available to the printer: the bridge width, the number of bridges per inch N, and the tensile strength of the paper.[9] The tensile strength of the paper can be communicated to the printer by the paper mill. Laser perforations are expected to improve reliability and quality of the 20-pound, uncoated computer paper and thus overcome the problems created by the mechanical microperforations.

FOOTNOTES FOR CHAPTER I

(1) TAPPI Standards. "Tensile Breaking Properties of Paper and Paperboards (Using constant rate of elongation apparatus)." TAPPI Standards, T494-om-81, 1981.

(2) Müller Martini. "Grapha-Pronto." Zofingen, Switzerland: Müller Martini Corporation.

(3)Taken from: Special product Engineering Corporation. "Pattern Perforator." Needham, Massachusetts: Special Product Engineering Corporation,1987.

(4) See photograph 7, page 43D.

(5) See Chapter I, page 4: The defects of the mechanical perforations.

(6) Some of the characteristics of the computer paper used for the experiments of this thesis are described in Appendix E, page 85.

(7) See Chapter I, page 4: The defects of the mechanical perforations.

(8) See Chapter I, page 4: The expected advantages of the laser perforation.

(9) See Chapter IV, Hypotheses, page 24.

Chapter II
REVIEW OF THE LITERATURE

OVERVIEW OF THE APPLICATIONS OF THE LASER PROCESS

A multitude of interesting laser applications to industrial processes were reported in the review published by the Coherent General.[1] Lasers are presently used to cut, perforate, weld, scribe on, or harden the surface of miscellaneous materials. Cutting and perforating are done on metals, plastics, ceramics, and glass. Metals can be laser-welded with extreme precision and strength. The laser dissipates a very low amount of energy around the area affected by the beam. In electronics, very small heat-sensitive components are microwelded by laser. The good thermic efficiency of the laser beam makes the process available for hardening the surface of metals. However, according to the book Nontraditional Machining Processes, today's main applications of the laser are cutting and perforating.[2]

THE MISCELLANEOUS MATERIALS PERFORATED BY LASER

Metals

The laser may be operated either in a continuous wave or in an enhanced pulse mode.[3] At high power, the continuous wave mode offers high cutting-speed and high-quality cut. For metal cutting, the continuous wave mode is usually used. The enhanced pulse mode allows the generation of short laser beam pulses that can be used to perforate metals without thermal distortion due to excessive heat.[4] Laser perforating is a contactless process, and can cut

contours and patterns of perforation which are impossible to do with conventional tools. Metals can be perforated at a very high speed; however, some metals have a very high reflectivity factor and are therefore not be processable by laser.

Plastics

The laser is well-suited to plastic and rubber processing. According to the brochure Everlase: Laser Machine Tools, most plastics and rubbers absorb the 10.6 micrometer wavelength, making them processable by laser beam.(5) The laser power is so high that when the beam strikes the surface of the work piece, the plastic is vaporized. It is necessary to use a gas jet to evacuate the vaporized plastic and keep the work piece clean during the perforation.(6) Nylon spray nozzles, mylar boards, and silicone insulator strips are laser perforated.

Glass and Ceramics

Ceramics are perforated either in the fire state or in the green state. One of the problems with ceramics is that excessive heat leads to a thermal shock which damages the work piece. This problem is critical in glass processing, and a lot of precautions must be taken to avoid the bursting of the material. It is therefore necessary to use the enhanced pulse mode which provides a sufficient amount of power to vaporize glass and ceramics without excessively heating the areas surrounding the perforation pattern.(7)

One of the exciting applications of the laser is scribing. Scribe lines consist of a series of small notches on the surface of the material. The minimum penetration depth of the notches is 0.009 inch for ceramics and 0.004 inch for glass. Borosilicate ampules (used as drug containers) and digital watch displays are examples of laser scribing on glass and ceramics.(8)

APPLICATIONS OF THE LASER TO THE PRINTING INDUSTRY

Dieboard Making

The first field of application of lasers to the graphic arts was packaging. After being printed, ganged packages are cut out of a sheet of substrate with a dieboard. Dieboards used to be handmade, and, according to the Handbook of Package Engineering, no less than thirty hours of intensive labor were required of a skilled worker to make a dieboard.(9) The first part of the work consists in determining with accuracy the emplacement of the dies on the board. Then, the board is notched and the base of the dies are inserted and finally tightened into the notch. Apart from the fact that making dieboards by hand is very time consuming and very expensive, accurate positioning of the dies still leaves much to be desired. Thus, laser dieboard-making offers many advantages. First, the production is fully automated. The dieboard is placed on a positioning table controlled by a computer. Any profile can be cut at a rate of up to 14 inches per minute.(10) The precision of the laser cut is far better than the precision of any cut which can be obtained by using traditional processes, and the wood is instantaneously vaporized when it is struck by the beam; Therefore, the edges of the laser cut are clean, and they allow an easy insertion and tightening of the base of the die inside the cutting board.(11)

Paper Cutting

In 1968, Greiner published an article entitled Where Is the Design of Sheeters Going.(12) He predicted that, in the future, lasers would be used in finishing areas to sheet the paper. The biggest advantage of using a laser is the total absence of mechanical contact with the paper. The next advantage is the cleanliness of the edges of the cut piece.

The clean aspect of laser cuts in paper was emphasized in a thesis "The Effect of Laser Beam Cuts on the Strength of Paper Edges" carried out in 1987 by Bernard Pineaux.(13) The purpose of the study was to see whether or not laser-cutting enhanced the strength of the edges of the paper enough to reduce significantly the number of web press breaks. It was demonstrated that laser cut edges are stronger than knife cut edges. Unfortunately, the difference never exceeds 3 per cent. The improvement realized was not considered significant enough to justify the important investment of a laser. In Paper Technology and Industries of September 1978, H.S Ainsworth said that laser technology could bring great improvement in efficiency to cutters.(14) The control of the quality of the cut is better than with mechanical cutting. The laser cutting device does not wear since it is not in contact with the material processed. Changing from one sheet size to another may simply be done by programming a different positioning of the laser beam.

Laser cutting seems to be very promising. However, the application of the laser to the printing industry raises some problems. Cross cutting has already been performed successfully but the technique still has to be enhanced to reach the speed of the presses used in the printing industry.(15) Cutting large thicknesses of paper is still an unsolved problem. The power of the beam required is so high that the paper burns.(16) The cost of a laser is still prohibitive compared to conventional cutting tools.

Paper Perforating

The laser offers great prospects in the field of the paper perforation which is still nearly unexplored. A brief inquiry conducted in the industry showed that the perforations for computer paper are presently effected only mechanically.

However, one surprising application of laser perforation of paper was

reported in the brochure "Everlase: Laser Machine Tools." In this publication, the laser has been found to be the most efficient method of perforating cigarette paper. [17] The holes are perforated just after the filter. These holes regulate the air flow coming from the tip of the cigarette by allowing some air to pass directly through the pattern perforated just after the filter, each time the smoker draws from the cigarette. It also allows part of the nicotine to go out of the cigarette in such a way that the amount of nicotine passing through the filter, and going into the lungs of the smoker decreases. The mechanical perforation process does not work very well in this instance because the paper which is used to make cigarettes is so thin and fragile that the pressure applied by the mechanical perforator damages the perforation pattern. Furthermore, the holes of the mechanical perforations close back after the perforation pins are removed, therefore preventing the air cannot from passing through.[18] The laser successfully solved these problems. Laser holes are clean and remain open, allowing the air to pass through.[19] In addition, the laser process does not apply any pressure and can therefore perforate papers of the highest fragility. From a discussion with Gerald Hertzel, project engineer at Kodak Apparatus Division, it has been found that the smallest diameter of the holes that could be perforated into the paper using the Everlase 150 CO_2 laser, was 0.003 inch.[20] Laser perforations of computer paper should therefore result in a very clean tear of the paper edges by the users and have very good control over the strength of the perforation pattern by the manufacturer.

THE STRENGTH OF THE PERFORATION PATTERN

An exciting study on the strength of perforation patterns on paperboards was carried out in 1987 by Eric Archer on paperboards.[21] Paperboards were

perforated with different bridge widths. The study attempted to establish the relationship between the width of a bridge, the rigidity, the weight, the thickness of the cardboard and the tensile strength of one bridge that has been performed in this cardboard. The relationship between the tensile strength of one bridge and its width was found to be linear. A mathematical model was given. However, the variations of the experimental values versus the theoretical values were pretty broad and not fully satisfying due to the great number of parameters affecting the tensile strength. The relationship between the tensile strength of a multiple bridge structure and its number of bridges per inch was not investigated. A microscopic analysis showed that the pressure which is applied to both sides of a bridge performed in cardboard by the punching pins causes microscopic cracks that are responsible for the weakening of the perforation pattern.

FOOTNOTES FOR CHAPTER II

(1) Coherent General Inc. "Everlase: Laser Machine Tools." Palo Alto, California: Coherent General Inc, 1984.

(2) Society of Manufacturing Engineers. "Nontraditional Machining Processes." Dearborn, Michigan: Society of Manufacturing Engineers, 1984.

(3) Coherent General Inc. Op. Cit.

(4) Coherent General Inc. Op. Cit.

(5) Coherent General Inc. Op. Cit.

(6) Society of Manufacturing Engineers. Op. Cit.

(7) Coherent General Inc. Op. Cit.

(8) Coherent General Inc. Op. Cit.

(9) Hanlon Joseph F. Handbook of Package Engineering. 2nd ed. New York: Hill Book company, 1986.

(10) Coherent General Inc. Op. Cit.

(11) Hanlon Joseph F. Op. Cit.

(12) Greiner T. A."Where Is the Design of Sheeters Going?" Paper Trade Journal. February 26, 1968.

(13) Pineaux Bernard. "The Effect of Laser Beam Cuts on the Strength of Paper Edges". Rochester, New York: Master of Science in Printing Technology, 1988.

(14) Ainsworth H. S. "Paper Technology and Industry." Star Paper Limited. September 1978.

(15) Lambert E. "Cutting by Laser Beam." Lausanne, Switzerland. Ecole Suisse d'ingénieurs des Industries Graphiques et de l'Emballage, 1985.

(16) Lambert E., Op.Cit.

(17) Coherent General Inc. Op. Cit.

(18) Coherent General Inc. Op. Cit.

(19) Coherent General Inc. Op. Cit.

(20) Reference to a discussion with Gerald Hertzel: Project Engineer at Eastman Kodak Apparatus Division.

(21) Archer Eric. "Etude de la Résistance des Points d'Attache." Grenoble, France: Ecole Supérieure d'Ingénieurs des Industries Papetières et Graphiques, 1987.

Chapter III
TECHNICAL BASIS FOR THE STUDY

THE LASER

The Discovery of the Laser Principle

The term laser,as mentioned previously, is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser is a device which produces and amplifies light. The mechanism which accomplishes the stimulated emission was postulated by Albert Einstein in 1917. The first continuously operating helium-neon laser was reported in February 1961 by Javan, Benett, and Herriot on the Bell Telephone Laboratories. Lasers may generate energy in the ultraviolet, or visible infrared spectrum. Helium-neon Lasers produce an intense, coherent, visible light beam.

Different Types of Lasers

Lasers can be classified by their lasing media. These media may be solid state, liquid or gas. The electrical discharge pumped CO_2 gas and the optically pumped solid state are the two types of lasers most commonly used in the manufacturing industry.(1) The CO_2 laser uses a mixture of carbon dioxide (CO_2), helium (He), and nitrogen (N_2) provides the reservoir of active ions needed for the lasing action.(2) The discharge pump CO_2 gas laser is the type of laser that will be used to perform the experiments in this thesis because the wavelength of this type of laser beam is suitable for processing paper.

Operating Principles

The laser effect is due to an atomic reaction. The electrons of an atom are distributed in orbits farther away from the nucleus according to their energy level. When an atom is struck by a photon, the photon transmits to the atom a specific amount or quanta of energy that will make an orbital electron jump to a higher energy level. (See figure 3, page 20) The energy transmitted by the photon is: $E = h \cdot N$, where h is the Planck's constant ($h=6.63 \times 10^{-34}$) and N the frequency of the incident photon. The atom passes from the ground state Eg to the excited energy state Ee. The absorption of a photon obeys the following law.[3]

$$Eg - Ee = h \cdot N_{\text{incident photon}}$$

If there is no "laser effect," the atom spontaneously returns to the ground state and releases the energy gained by reemitting a photon.[4] (See figure 4, page 20)

$$Eg - Ee = h \cdot N_{\text{reemitted photon}}$$

A spontaneous emission is coherent neither in time, nor in space. Each atom emits anytime in any direction, independently of the other atoms.

In the laser principle, the return to the ground state is not spontaneous, but induced by a "stimulating" photon.[5] If, while the atom is at the excited state, it absorbs the energy of another photon, this atom returns to the original level and reemits two photons of same wavelength as the incident photon. The laser is based on this property. In a laser, the gas mixture is enclosed in a glass tube. The laser power supply, nicknamed the "pump," delivers energy that causes glow

discharges in the tube. When electric energy is applied, neon atoms collide with helium atoms and pass from the ground state to the excited state. The atom remains in the energized state a short time, and the electron returns to its original orbit. One photon of light is reemitted. This photon travels through the laser tube and strikes the electron of another atom which is still in the excited state. Then, following the principle that has been previously described, the atom returns to the ground state and two synchronous photons of identical energy and frequency are emitted. [(6)] (See figure 5, page 20) When they are produced in great numbers, these synchronous pairs of photons of identical energy combine to make the electromagnetic wave of the laser beam.

The Laser Design

The laser tube is placed between two highly reflective mirrors facing each other along a central axis. The generated beam bounces back and forth between the two mirrors and is amplified by a factor 1.02 at each pass in the gas. One of the mirrors, called the transmission mirror is designed to allow the escape of less than one percent of the light reflected.[(7)] Thus, the intensity of the beam light is less than one percent of the intensity of the light reflected between the mirrors. The mirrors and the laser tube form an optical resonant cavity. If the mirrors are perfectly aligned, the curve of the flux density obtained is bell shaped and produces a single spot of light. This type of laser is said to be single mode. The others are by opposition called multimode and produce several spots of light, so that they are not very accurate. It is more precise and convenient to perforate a hole using a single spot of laser light than several spots; therefore, the laser which will be used in this study is a single mode laser.[(8)]

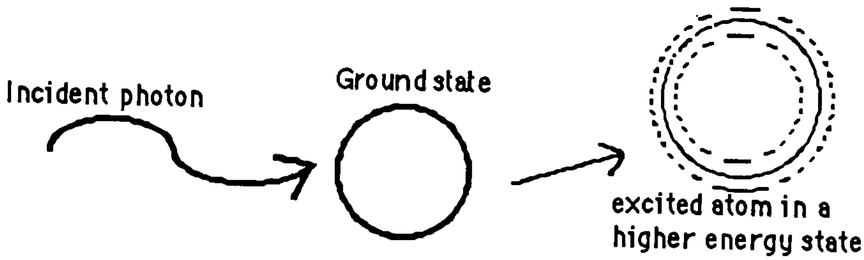


Figure 3. Spontaneous absorption.[9]

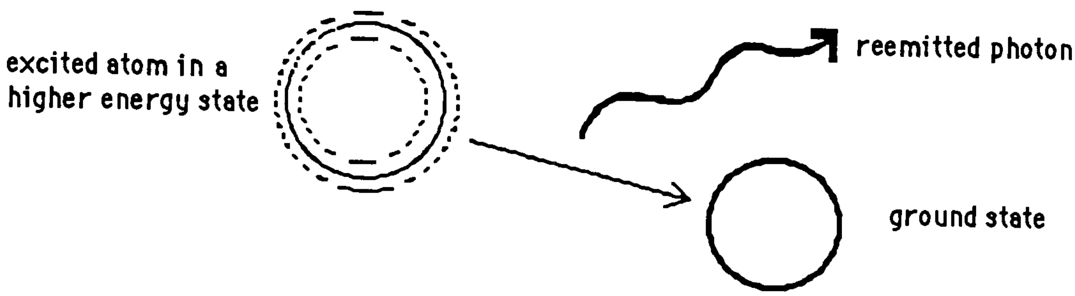


Figure 4. Spontaneous reemission.[10]

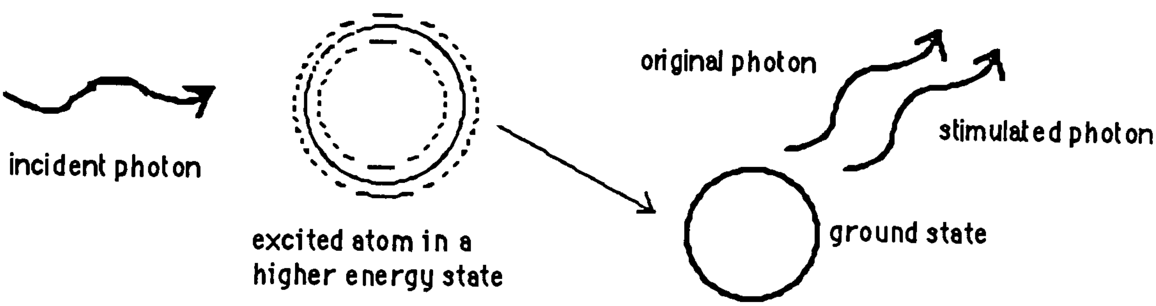


Figure 5. Stimulated emission.[11]

Effects of the Properties of Laser Light on the Perforation of Paper

Directionality

The transmission mirror allows only the light reflected on the axis between the mirrors to escape. The beam emerges well collimated and highly directional. The beam of the 150 CO_2 Everlase laser used in this thesis can create holes in the paper that can be as small as three thousandths of an inch in diameter. Some more recent lasers are able to perforate holes in metal that are as small as one thousandth of an inch in diameter. No mechanical process can produce holes this small and as precisely.

Coherence

The laser beam stays temporally and spatially coherent during its propagation through gaseous media such as air. This fundamental property is very important since paper perforation can occur with no physical contact.

Intensity

The intensity of the beam is derived from the power of the laser. Because the paper is a material which burns very easily, it must be perforated with a very low intensity. The thermic efficiency of the laser beam is high. Even with a very low intensity (power = 4 Watts), the area of paper struck by the laser beam is completely vaporized.

Monochromaticity

The processability of a material depends on its absorbency to the laser wavelength. For instance, CO_2 lasers can easily perforate the paper because the paper has an excellent absorbency to the 10.6 micrometers wavelength.

THE BREAKING LENGTH AND THE TENSILE STRENGTH OF PAPER

The tensile strength of a paper can be expressed in terms of breaking length which is the physical characteristic used by international standards. This choice is justified because the breaking length is an index which allows us to discard the influence of the paper weight from the tensile strength of the paper.[12] Using the breaking length is therefore required when comparing the tensile strength of paper of different weights. However, since in this thesis all experiments are done on a single paper, the influence of the paper weight does not need to be discarded, and the researcher can therefore work directly with the tensile strength.

The breaking length of paper is the stress divided by the specific mass of the material and by the acceleration of gravity g.[13]

$$BL = \frac{10^6}{g} \cdot \frac{T}{W.R}$$

with:

W = width of the strip of paper.

$g = 9.81\ m / s^2$.

R = weight of the paper, in grams per square meter.

BL = breaking length, in meters.

T = tensile strength of the paper, in kilograms.

The characteristic which is communicated to the printer by the paper manufacturer may be either the tensile strength or the breaking length.[14] However, if needed, the printer can easily derive the tensile strength of the paper from the breaking length by reversing the formula stated above.

FOOTNOTES FOR CHAPTER III

(1) Society of Manufacturing Engineers. Nontraditional Machining Processes. Dearborn, Michigan: Society of Manufacturing Engineers, 1984.

(2) Kallard T. Exploring laser light. New York: Optosonic Press, 1977.

(3) Society of Manufacturing Engineers, Op. Cit.

(4) Society of Manufacturing Engineers, Op. Cit.

(5) Society of Manufacturing Engineers, Op. Cit.

(6) Society of Manufacturing Engineers, Op. Cit.

(7) Society of Manufacturing Engineers, Op. Cit.

(8) Society of Manufacturing Engineers, Op. Cit.

(9) Taken from: Society of Manufacturing Engineers, Op. Cit.

(10) Taken from: Society of Manufacturing Engineers, Op. Cit.

(11) Taken from: Society of Manufacturing Engineers, Op. Cit.

(12) Silvy Jean. "Evaluation de la Qualité des Papiers: Contribution à la Recherche des Critères Optimaux." Revue ATIP, Vol. 36, No. 3, Mars 1982.

(13) Silvy Jean. "Course of Physics of Pulp and Paper." Grenoble, France: Ecole Nationale Supérieure d'Ingénieurs des Industries Papetières et Graphiques, 1985.

(14) In the United States, the characteristic usually reported to the printer by the paper manufacturer is the tensile strength.

Chapter IV
HYPOTHESES

HYPOTHESES

The variability of a perforation process is expressed by the variance of the tensile strength of the perforation patterns which have been done on this process. Statistics are used to demonstrate that the variability of the laser perforation process is significantly lower than the variability of the tensile strength of the mechanical perforation process. The statistical test which is used requires that the hypotheses are stated in "null" form, where it is tested whether or not the difference between the two variables to compare is significant.(1)

1. There is no significant difference between the variance of the tensile strength of the laser microperforation pattern LM (2) and the variance of the tensile strength of the mechanical microperforation pattern MM.(3)

2. There is no significant difference between the variance of the tensile strength of the large-size laser perforation pattern LSL (4) and the variance of the tensile strength of the large-size mechanical perforation pattern LSM.(5)

In order to find a mathematical model describing the variations of the tensile strength, the following hypotheses must be tested:

3. There is a relationship between the tensile strength of a laser perforation pattern and the width of the bridges.

4. There is a relationship between the tensile strength of a laser perforation pattern and the number of bridges per inch.

5. There is a relationship between the tensile strength of a laser perforation pattern and the tensile strength of the paper on which the perforation is done.

FOOTNOTES FOR CHAPTER IV

(1) See Data Analysis, chapter V, page 34.

(2) LM is an abbreviation for the Laser Microperforation pattern reproducing the mechanical microperforation pattern MM.

(3) MM is an abbreviation for the Mechanical Microperforation pattern of which the hole length equals 0.0075 inch, and the bridge width equals 0.0063 inch.

(4) LSL is an abbreviation for the Large-Size Laser perforation pattern reproducing the large-size mechanical perforation pattern MM.

(5) LSM is an abbreviation for the Large-size Mechanical perforation pattern of which the hole length equals 0.190 inch, and the bridge width equals 0.030 inch.

Chapter V
METHODOLOGY

THE THREE DIFFERENT PARTS OF THE STUDY

This study has been divided into three parts. The first part is a comparison of the visual aspect of the perforation patterns which have been obtained by both mechanical and laser processes. All observations are based on the analysis of photographs which have been taken through a microscope. The photographs show the defects which are inherent to each perforation process. The defects are identified and discussed.

The second part compares the variability in tensile strength of the laser perforation patterns to the variability in tensile strength of a mechanical perforation pattern.

The third part provides a mathematical model describing the relationship between the independent and dependent variables.

INDEPENDENT AND DEPENDENT VARIABLES

The independent variable which is studied in this thesis is the tensile strength of the perforation pattern T_{pp}.

The dependent variables are the width of the bridges W, and the number of bridges per inch N.

The tensile strength of the paper, T_{paper}, is a dependent variable which remains constant in all experiments in this thesis since all the experiments are done on the same 20-pound uncoated computer paper.(1)

LIMITATIONS OF THE STUDY

A limited inquiry showed that the paper weight which is the most common for computer papers is 20-pounds. Heavier weight papers are not flexible enough to pass through personal or office computer printers.

The study has been limited to the 20-pound uncoated computer paper manufactured by the printer X for the following reasons:

- It is widely available in adequate quantities.
- It is representative of the type of paper used by offices, computer labs, or personal computers.
- It has the advantage of being supplied with two different sizes of mechanical perforations. Therefore, the comparative study on the quality of the laser and mechanical perforations has been limited to the two sizes of perforations available.

The time of access to the Everlase 150 CO_2 laser at the Eastman Kodak company was limited. Therefore, in the third part, the study on the variation of the tensile strength of the laser perforations has been limited to 16 different patterns. The 16 patterns are obtained by combining four bridge widths to four hole lengths.

MATERIALS

- Ten sheets of 20-pound printer X's uncoated paper, format 8.5" x 11", perforated with the mechanical microperforations.
- Ten sheets of 20-pound printer X's uncoated paper, format 8.5" x 11", perforated with the large-size mechanical perforations.

- One hundred sheets of 20-pound printer X's uncoated paper, format 8.5" x 11".

EQUIPMENT

- A coherent Everlase 150 watts CO_2 laser equipped with a moving 12" x 16" Anorad X-Y table and a stationary laser beam.
- An Inströn tensile strength tester.
- An optical microscope equipped with a micrometer of which the precision of measurement is 0.0001 inch.
- An International Scientific Instruments' electron beam scanning microscope.

EXPERIMENTAL PROCEDURES

Microscopic Study

Pictures showing the front and the back side of the microperforations M will be taken through an electron beam scanning microscope. Some additional pictures will be taken on the same subject through an optical microscope. Close and overall views are respectively obtained using 500 X and 135 X enlargements.

Pictures showing the front and the back side of the large-size mechanical and laser perforations will be taken using an electron beam scanning microscope. Pictures showing the whole perforation hole will be taken using a 15 X enlargement. Close views of the bridges will be taken using a 135 X enlargement.

These pictures will be used to compare the visual aspects of the laser perforation pattern to the visual aspect of the mechanical perforation pattern. The damage and imperfections inherent to each perforation method will be identified

and discussed.

Comparative Study on the Quality of the Mechanical and Laser Perforation Process

Perforation of the Samples

Ten samples of the mechanical microperforation MM and ten samples of the large-size of mechanical perforation LSM made by the printing company X will be collected. These samples are 8.5" x 11" sheets of 20-pound uncoated paper. The mechanical perforation pattern will be situated half of an inch away, parallel to the 11" edge of the sheet.

Ten sheets will be perforated by means of the Everlase 150 CO_2 with a pattern reproducing as closely as possible the mechanical microperforation MM. Then, ten additional sheets will be laser perforated with a pattern reproducing as closely as possible the large-size mechanical perforation pattern LSM.

The bridge width and the perforation hole length which will be used to duplicate by laser the mechanical microperforations MM will be respectively W = 0.00661", and H = 0.00738". The bridge width and the perforation hole length which will be used to duplicate by laser the large-size mechanical perforations LSM will be respectively W = 0.03004", and H = 0.18892".

The position of the perforation pattern across the sample cut for tensile strength testing has a large effect on the results of the tensile strength test.[(2)] Therefore, the laser perforations will be performed half an inch away parallel to the 11" edge of the sheet of paper, so that during the tensile strength test, the position of the mechanical and laser perforation patterns across the samples to be compared will be the same. The sheets of computer paper will therefore be

perforated long grain. This experimental design will allow us to measure and compare the variability of the tensile strength of the laser perforations and mechanical perforations under identical conditions.

Operation of the Laser

All samples to be perforated will be placed on a moving 12" x 16" Anorad X-Y table. The laser beam will be stationary. The samples will be driven by the moving table when perforating. Because of inertia loads associated with the mechanical table, the perforating speed will be very much slower than those which could be obtained on a laser designed to perforate a web of paper on a printing press. The fact that the Everlase 150 CO_2 is too powerful to be applied to the perforation of the paper material will be an additional problem. To avoid burning the paper, the power of the laser has to be set to its very minimum, causing an occasional failure of the beam to turn on at the start of a new perforation hole.(3)

Therefore, the laser microperforation pattern LM will be done in flight, with the positioning table traveling at constant speed. The measurements of the pattern to reproduce will be very small so that stopping the table in order to reset the position reference at each start of hole would cause too much inaccuracy. The laser microperforations LM have been obtained by adjusting the laser beam parameters to the following values.

- Power: 4 Watts.
- Frequency: 41 Hertz.
- Pulse length: 3.02 milliseconds.
- Table speed: 35" / minute.

The measurement of the large-size mechanical perforation pattern LSM will be much larger than the measurements of the mechanical microperforations MM.

Therefore, the large-size laser perforation pattern LSM will be performed using the incremental mode -- the table stops and resets its position reference each time at the start or end of a new hole. The desired hole length and bridge width will be simply entered as parameters in the incremental mode program. Therefore, the large-size laser perforations LSL produced for the current evaluation will be done so by turning on and off the laser beam for specified travel distances to obtain the required hole lengths and bridge width.[4]

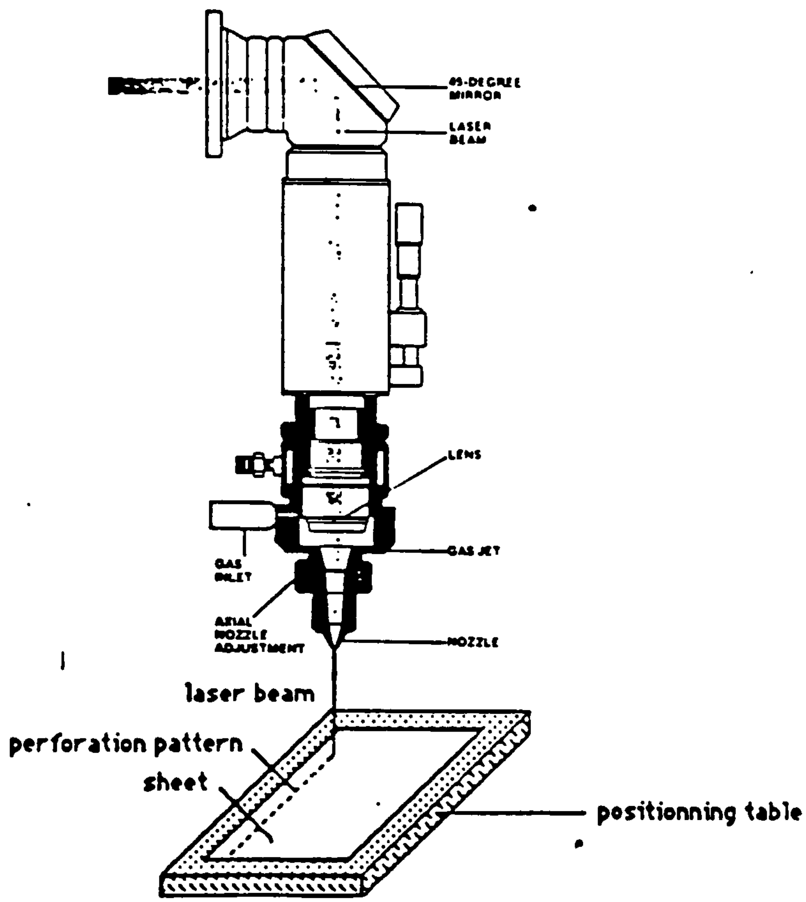


Figure 6. Sample being perforated by the Everlase 150 CO_2 laser.

The large-size laser perforation LSL has been obtained by adjusting the parameters to the following values:

- Power: 5 Watts.
- Frequency: 495 Hertz.
- Pulse length: 0.1 Millisecond.
- Table speed: 6" / minute.

Tensile Strength Test Procedures

The tensile strength of each sample will be measured by means of an Inströn tensile strength tester.

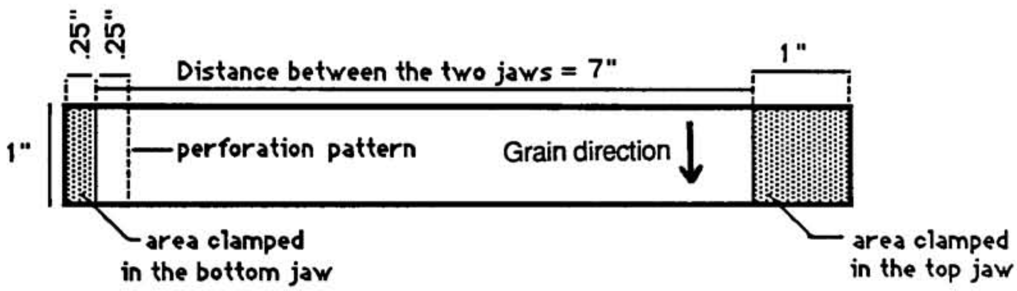


Figure 7. Cut out of the tensile strength test samples for the comparison of the laser perforations to the mechanical perforations.

On the 20-pound uncoated paper , the mechanical perforations have been performed half an inch away from the edge of the sheet. Therefore, during the tensile strength test, the perforation pattern will be situated one quarter of an inch away from the bottom jaw. The tensile strength test will be performed on the mechanical microperforation pattern, laser microperforation pattern, large-size mechanical perforation pattern, and large-size laser perforation pattern with the following parameters:

- Crosshead speed: 10 millimeters per minute.

- Paper speed on the plotting table: 1,000 millimeters per minute.
- Initial distance between the jaws: 7 inches.
- Load scale. Microperforation pattern: 10 Kilograms.
- Load scale. Large-size perforation pattern: 2 Kilograms.

Number of Samples

Thirty samples will be tested per method of perforation and per size (See table 1, below), because this is the minimum number necessary to do a significant statistical analysis.

Table 1. Number of samples for the comparison of the variability of the laser perforation process to the variability of the mechanical perforation process.

		Perforation size	
		1	2
Treatments	Laser perforation	30	30
	Mechanical perforation	30	30

Data Analysis

Comparison of the variances is done only within the perforations of same size. Hypothesis tests about S_1^2, variance of the mechanical perforation population, and about S_2^2, variance of the laser perforation population, are based on the value $F = S_1^2 / S_2^2$. The decision rule for accepting or rejecting the hypotheses is based on the F value.(5) For each one of the two perforation sizes, one sample of size $N_1 = 30$ is selected from the mechanical perforation

population, and one sample of size $N_2 = 30$ is selected from the laser perforation population. If the two samples have equal variance the ratio $F = S_1^2 / S_2^2$ has a distribution with $N_1 - 1 = 29$ degrees of freedom at the numerator, and $N_2 - 1 = 29$ degrees of freedom at the denominator, where S_1^2 is the mechanical perforation sample variance and S_2^2 the laser perforation sample variance. The null hypothesis No 1 is tested using an F test at a level of confidence of 95 % ($\alpha = 0.05$).

Therefore, the null hypotheses 1 and 2 will be accepted if: (6)

$$0.537 \leq (F = S_1^2 / S_2^2) \leq 1.86$$

Study on the Relationship between Independent and Dependent Variables

Perforation of the Samples

In order to study the variation of the tensile strength test versus the bridge width W and the number of bridges per inch N, 16 different patterns will be perforated. The 16 patterns will be obtained by a combination of four different bridge width values and four hole lengths. The number of bridges per inch of the 16 laser perforation patterns appear in table 2, page 36.

Table 2. The number of bridges per inch of the 16 patterns of laser perforations. (The bridge width and the hole length are expressed in thousandths of an inch)

Number of bridges per inch				
Bridge Width	20	40	80	160
Hole length				
20	25	16	10	5
40	16	12	8	4
80	10	8	6	4
160	5	5	4	3

Each one of the 16 patterns will be produced on five 8.5" x 11" sheets. Since one will not have to copy any already existing mechanical perforation pattern, the laser perforation patterns will be performed in the center of the sheet, parallel to the 11" edge (See figure 8, page 37). The sheets of computer paper will therefore be perforated long grain. Also, during the tensile strength test, the perforation pattern will be placed at equal distances between the jaws of the tensile stength tester in order to avoid dissimetry in the sample.

Operation of the Laser

The laser is operated in the same incremental mode which will be used to do the large-size laser perforations (See Operation of the Laser, chapter V, page 32). The operational parameters of the laser will be:

- Power: 5 Watts.
- Frequency: 495 Hertz.

- Pulse length: 0.1 millisecond.
- Table speed: 6" / minute.

The new bridge width W and hole length H operational parameters are programmed each time a new pattern is perforated.

Tensile Strength Test Procedures

The laser perforation samples to be tested will be cut out as shown below, in figure 8.

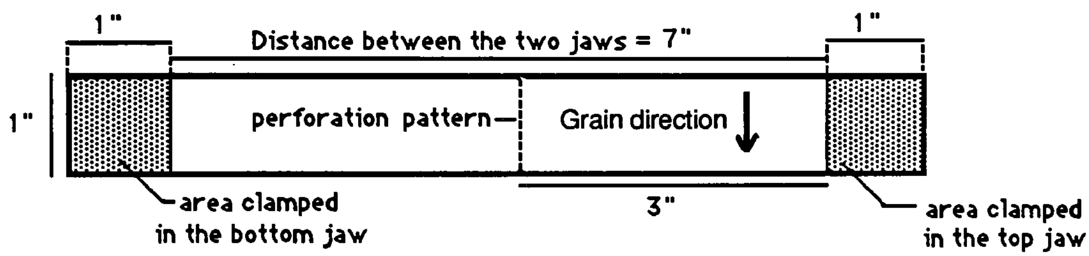


Figure 8. Cut out of the tensile strength test samples for the study on the relationship between dependent and independent variables.

The tensile strength tests will be performed using an Instron tensile strength tester with the following operational parameters.

- Crosshead speed: 10 millimeters / minute.
- Paper speed on the plotting table: 1,000 millimeters per minute.
- Initial distance between the jaws: 7 inches.
- Load scale: 2, 5 or 10 Kilograms / inch depending on the strength of the pattern tested.

Number of Samples

Ten samples will be tested for each one of the 16 patterns of perforation. Ten

samples is the number of measurements recommended by the TAPPI official standard T494 om- 81 to get a good average value of the tensile strength of the product tested. [7]

Data Analysis

The purpose of this analysis will be to find a mathematical model which describes the variations of the tensile strength of the 16 pattern of perforations versus the bridge width W and the number of bridges per inch N. The method of the least squares will be used to find the mathematical model which gives the highest correlation to the experimental tensile strength values.

FOOTNOTES FOR CHAPTER V

(1) Some of the characteristics of the computer paper used for the experiments of this thesis are described in Appendix E, page 85.

(2) Some preliminary tensile strength trials have shown that changing the position of the perforation pattern between the jaws of the tensile strength tester during the test affects the tensile strength. Changing the position of the perforation pattern affects the length of paper between the perforation pattern and the jaw, and the stretch of a strip of paper varies versus its length. The tensile strength is a physical characteristic related to the stretch and is therefore affected by the length of paper which is present between the perforation pattern and the jaw. It has been observed that the closer the perforation pattern to the jaw, the lower the tensile strength.

(3) This problem occurred sometimes during the laser perforation of the samples at the Eastman Kodak Company.

(4) Discussion with Gerald Hertzel, Project engineer at Eastman Kodak Apparatus Division.

(5) Anderson David R., Sweeney Denis J., Williams Thomas A. Statistics Concepts and Applications. Saint Paul, Minnesota: West Publishing Company, 1986, pp. 411-438.

(6) These values have been found in table 26, appendix D, page 82, for a degree of freedom at the numerator equal to equal to 29, and a degree of freedom at the denominator equal to 29.

(7) TAPPI Standards. "Tensile Breaking Properties of Paper and Paperboard (Using constant rate of elongation apparatus)." TAPPI Standards. T494 om-81, 1981.

Chapter VI
RESULTS

MICROSCOPIC STUDY ON THE CHARACTERISTICS AND DEFECTS OF THE LASER AND MECHANICAL PERFORATIONS

Photograph 1. (Optical microscope)

The laser microperforation holes (at the top of the photograph) have a rounded shape. The holes remain open and free of any paper dust coming from the perforation. The spacing and the size of the the holes remain very even along the pattern, that is to say that the accuracy of the laser perforation process can compete with the accuracy of the mechanical perforation process. In contrast, the mechanical microperforation holes (at the bottom of the photograph) are rectangular and closed. It can be seen on the picture that the light cannot pass through.

Photograph 2. (Optical microscope)

It can be seen on this close view, that the edges of the laser perforated holes (at the top of the photograph) are very clean and smooth. Since the holes are rounded, the bridges are arc-shaped and longer than the bridges of the mechanical perforation pattern. The shape and length of the bridges certainly affects the elasticity of the bridges and therefore the tensile strength.(1) The edges of the mechanical perforation holes (at the bottom of the photograph) are jagged. The bridges are rectangular and short. The holes are closed. The laser microperforations do not match exactly the size of the mechanical microperforations, but are however a very close reproduction which fully satisfies the requirements for this thesis.(2)

Photograph 3. (Electron beam scanning microscope)

Photograph 3 shows an exciting overall view of the laser perforation pattern. The heat dissipated by the laser beam has melted slightly the fibers around the hole. Some dust coming from the melting of the fibers has been scattered around the holes.

Photograph 4. (Electron beam scanning microscope)

Photograph 4 shows a close view of the front side of a laser perforation hole. The diameter of the holes is decreasing from the front side towards the back side. The tridimensional shape of a laser perforated hole is a truncated cone.[3] All the different layers of fibers belonging to the paper seems to have been cleanly cut off, without any bridge damage. The fact that no paper residue is visible added to the fact that the tips of the fibers seem to have melted shows that the laser beam has vaporized the cellulose and the filler.

Photograph 5. (Electron beam scanning microscope)

This close view of the front side of a mechanical perforation hole shows how much the perforation pins damage the areas surrounding the hole. Fibers are smashed and twisted back toward the bottom of the hole. The fibers are not cleanly cut off as the case is in the laser process but they are stretched and finally torn off by the perforation pins, therefore producing jagged hole edges. The picture shows that all the fibers which have been trapped under the perforation pin are smashed at the bottom of the hole. Some of the smashed fibers are cut off into two parts by a crack. However, most of them remain linked to the back side of the sheet of computer paper, and seal the perforation hole.

Photographs 6 and 7. (Electron beam scanning microscope)

It can be appreciated on both photographs how much the bridges are

damaged. The layer of smashed fibers at the back side of the holes is pushed away when the perforation pins pass through the paper. The bridges are pushed away and deformed by the pressure applied on both sides by the pins. Note that a big fiber which is on the bridge on the right hand side of the photograph has been ruptured by the pressure applied.

Photographs 8 and 9.

Here again, it can be appreciated the large difference between the quality of the holes that can be obtained by both processes. The back side of the hole microperforated by laser has a very smooth and clean rounded shape and is wide open. What could be melted cellulose and filler can be seen around the hole. In contrast, the back side of the hole microperforated mechanically is closed by the layer of smashed fibers. This layer is most of the time partially cracked and increases the variability of the mechanical perforation tensile strength.

Photograph 10. (Electron beam scanning microscope)

The large-size laser perforations (at the top of the photograph) have the same properties as the laser microperforations. The perforation hole is wide open whereas the hole perforated mechanically (at the bottom of the photograph) remains closed. However, the hole perforated by laser is much wider. The width can be changed by varying the power of the laser. It can barely be distinguished some jagged edges on the sides of the laser-perforated holes due to the pulsing of the laser beam.

Photograph 11. (Electron beam scanning microscope)

Photograph 11 shows that the bridge width of the large-size laser perforation pattern (at the top of the photograph) reproduces very closely the bridge width of the large-size mechanical perforation pattern (at the bottom of the photograph). It

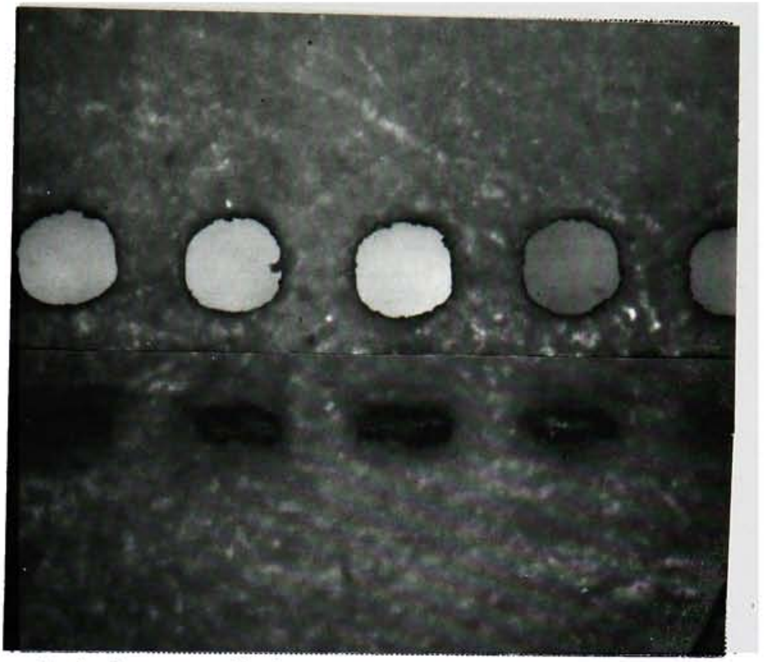
is interesting to notice that the bridge of the large-size mechanical perforation pattern looks somewhat stretched. However, in contrast to the mechanical microperforations, no cracks or major deformation can be seen on the laser microperforations. This is one of the reasons why the tensile strength of the microperforation patterns is so variable while the large-size mechanical perforation pattern does not seem to have any particular problems. The positioning table of the laser used for the experiment stops at every beginning and ending of each perforation holes. The tips of the perforation holes are therefore exposed slightly longer to the laser beam and are wider than the average width of the hole. This effect is only due to the equipment used in the experiment and would not be present with a laser designed for perforating a web of paper on a printing press.

Photograph 12. (Electron beam scanning microscope)

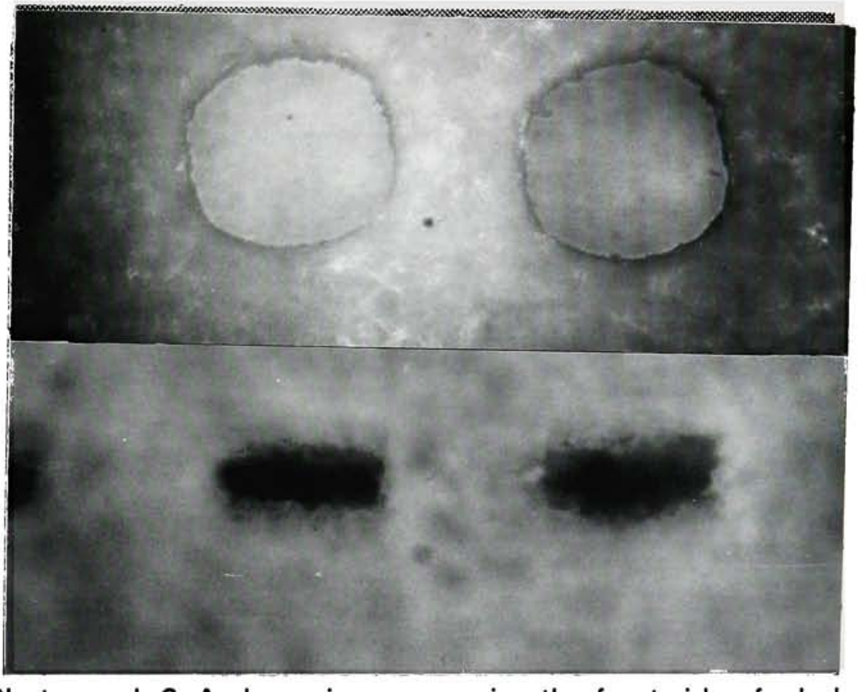
Photograph 12 shows that the back side of large-size laser perforation hole remains wide open whereas the back side of the mechanical perforation hole remains closed by a thin layer of fibers. This property may find some useful applications in the future.

Photographs 13 and 14. (Electron beam scanning microscope)

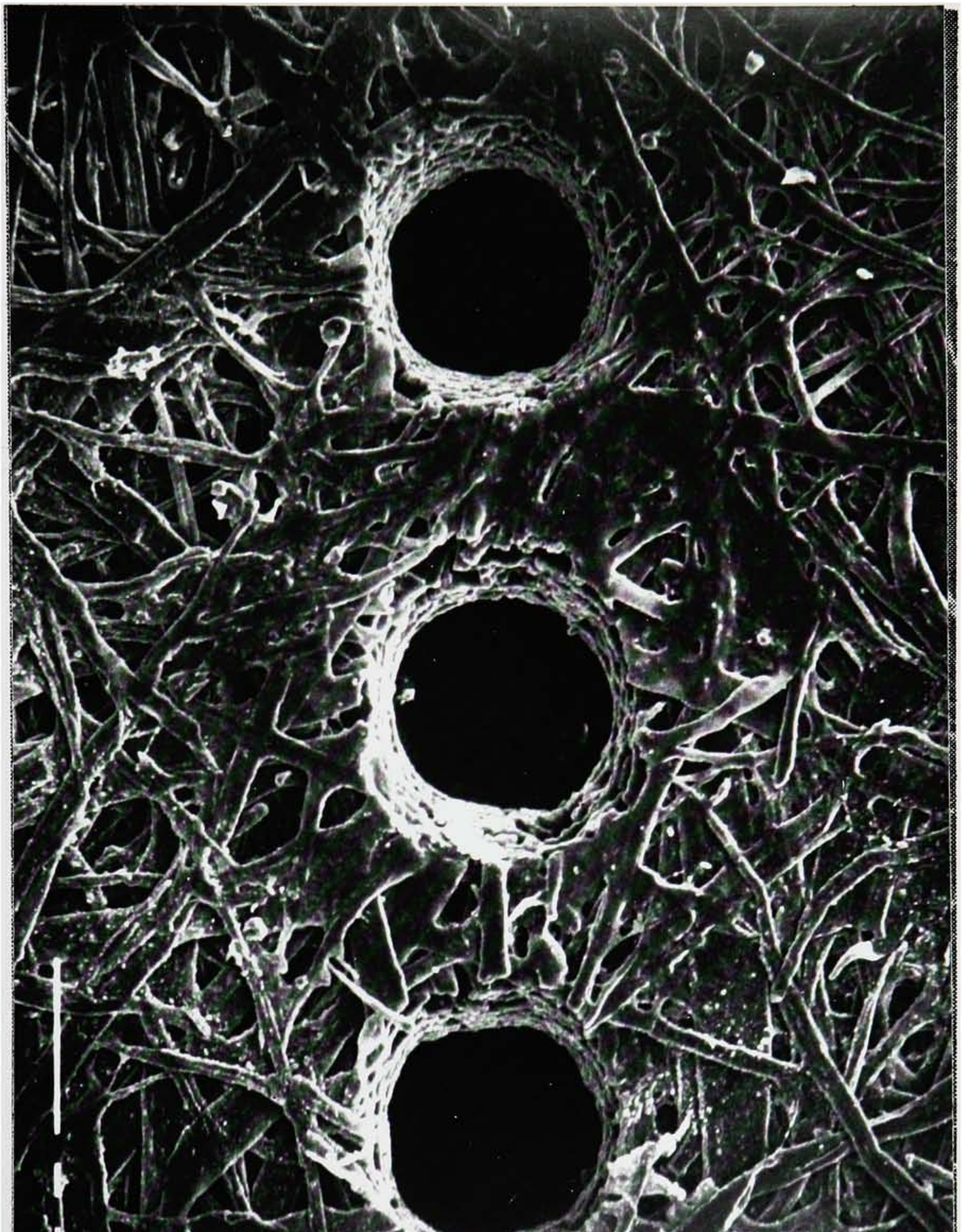
No defects can be seen in the back side of the bridge of the large-size laser perforation pattern on photograph 13. Photograph 14 shows a tilted view of the junction between the perforated hole and the bridge in the large-size perforation pattern. As it has been already said, no major crack or deformation affects the bridges. However, the tilted view shows that the bridge is somewhat subject to stretching and folding due to the pressure applied by the perforating blade.



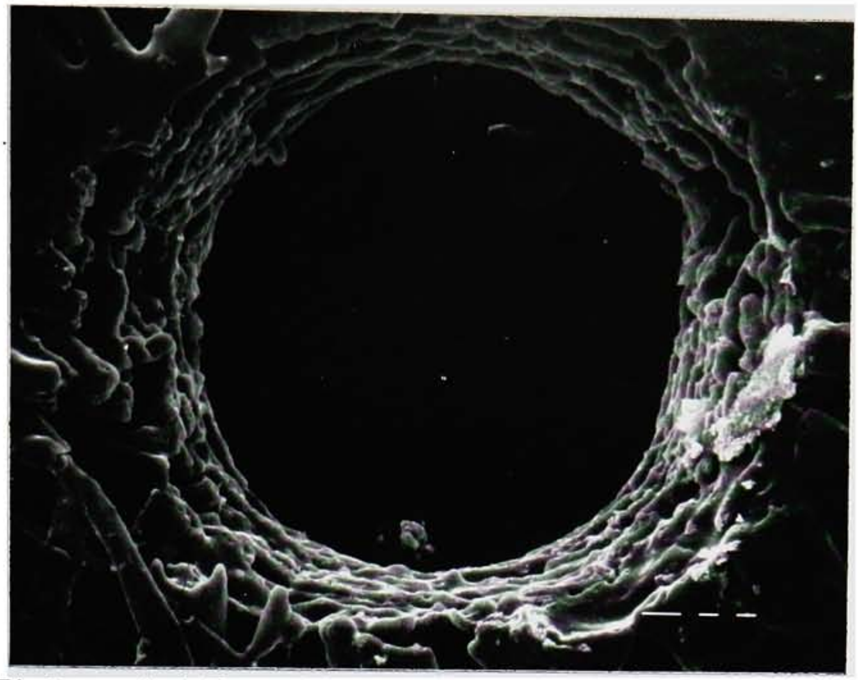
Photograph 1. An overall view comparing the front side of the laser microperforation pattern (top) to the front side of the mechanical microperforation pattern (bottom). Enlargement 65 X



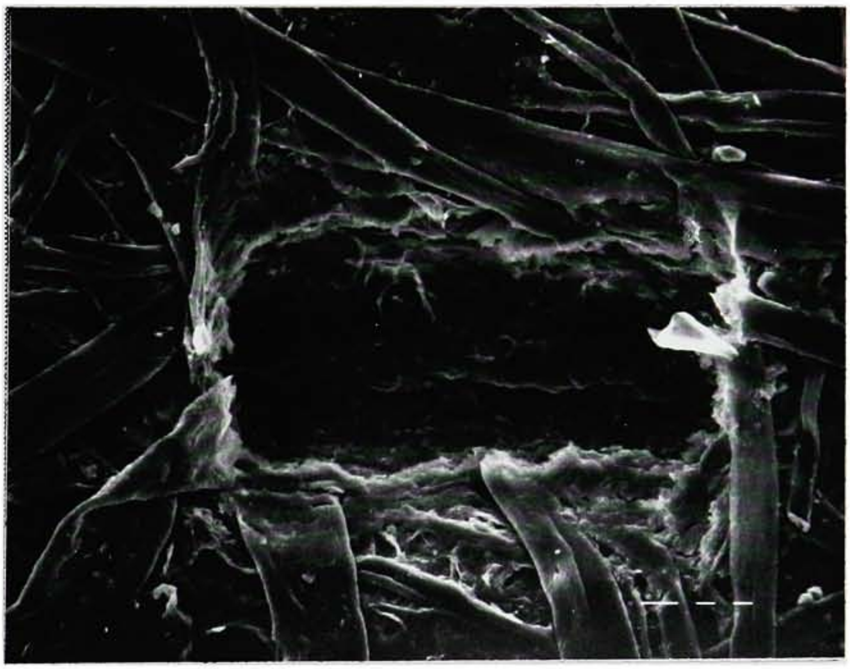
Photograph 2. A close view comparing the front side of a hole microperforated by laser (top) to the front side of a hole microperforated mechanically (bottom).Enlargement 129X



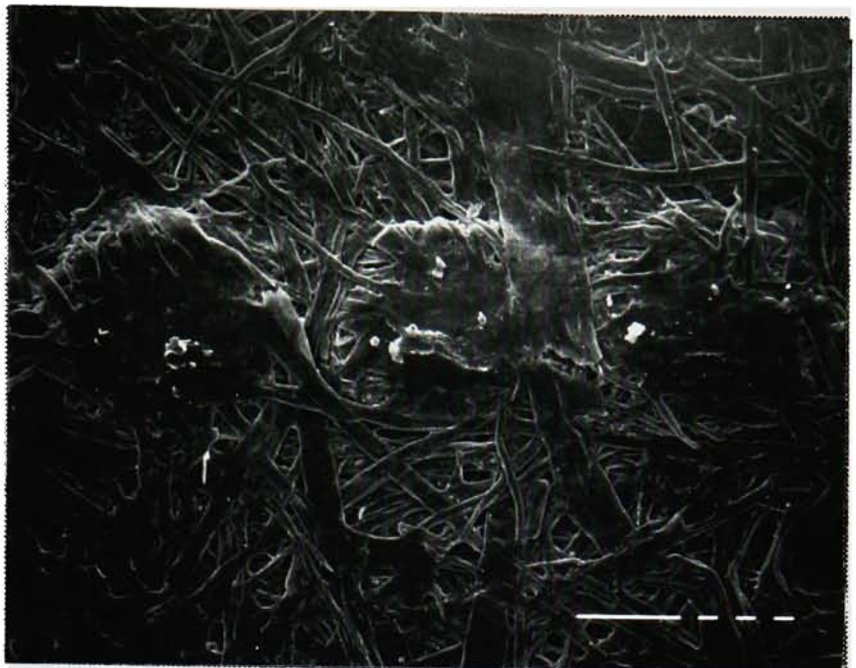
Photograph 3. Overall view of the front side of the laser microperforation pattern. Enlargement:270X



Photograph 4. Front side of a hole of a laser microperforation.
Enlargement: 500X

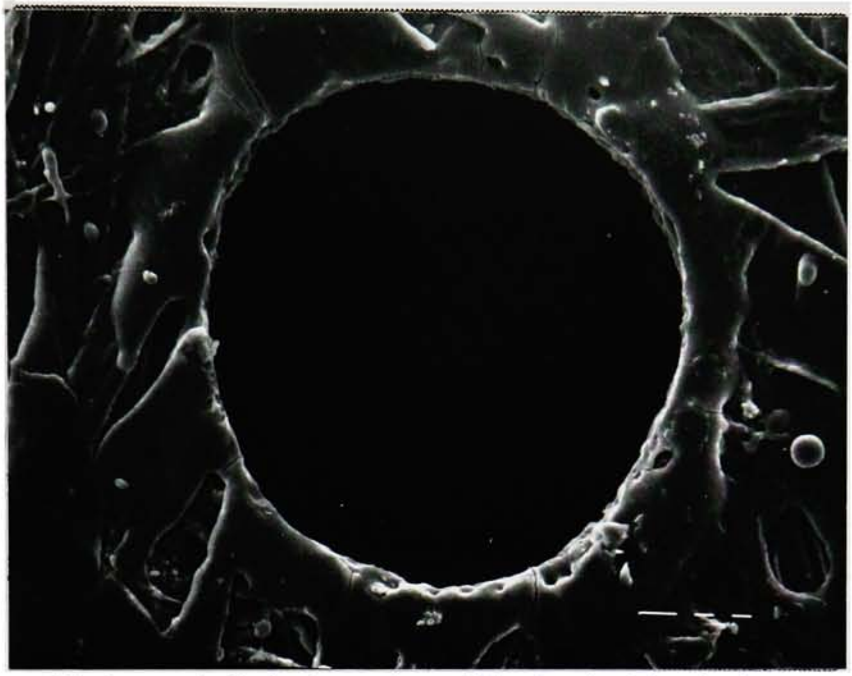


Photograph 5. Front side of a hole of a mechanical microperforation.
Enlargement: 500X

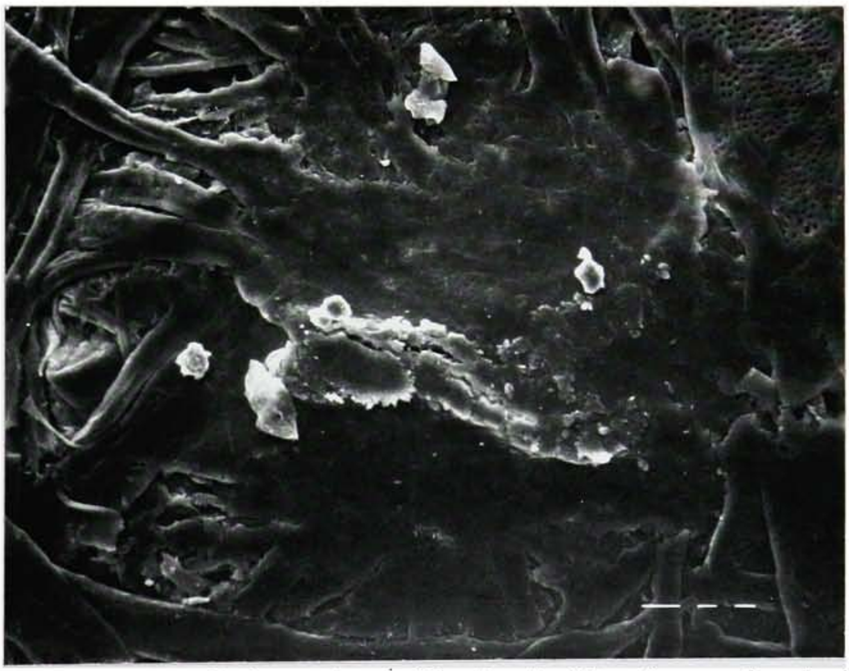


Photograph 6. A vertical view of the back side of a mechanical microperforation pattern. Enlargement: 135X

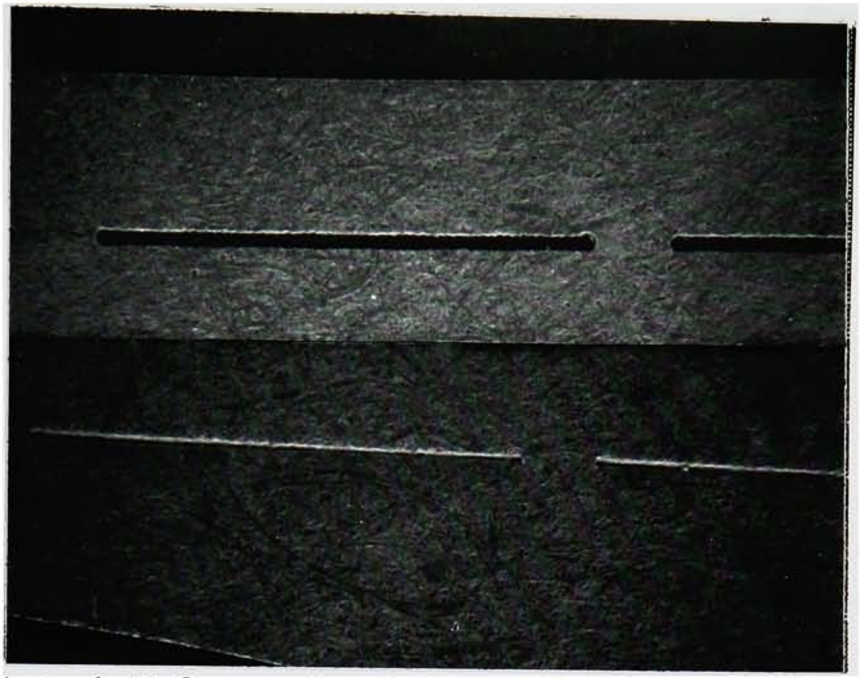
Photograph 7. A tilted view (angle 60^{o}) of the back side of a mechanical microperforation pattern. Enlargement: 135X



Photograph 8. A close view of the back side of a laser microperforation. Enlargement : 500X



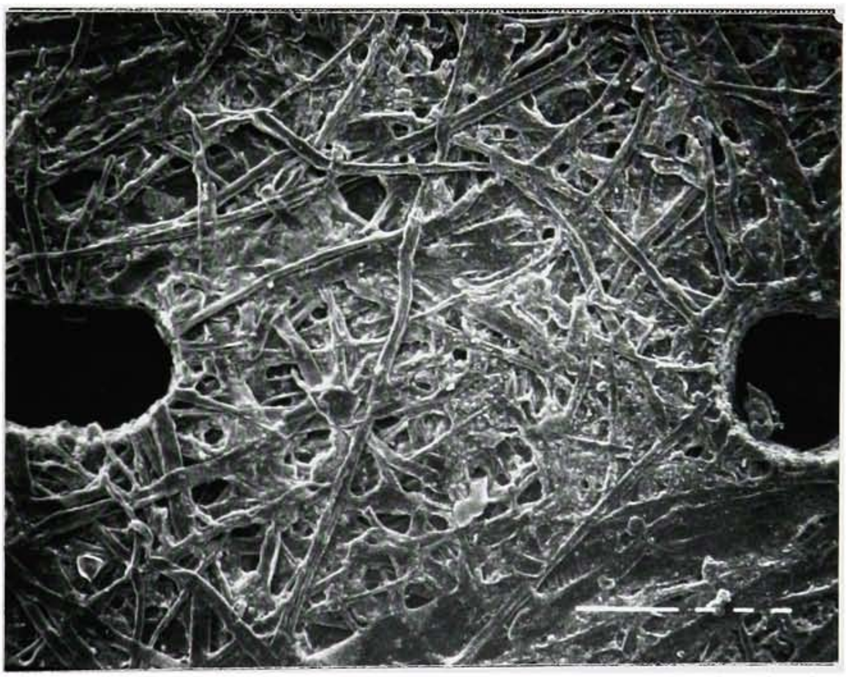
Photograph 9. A close view of the back side of a mechanical microperforation. Enlargement : 500X



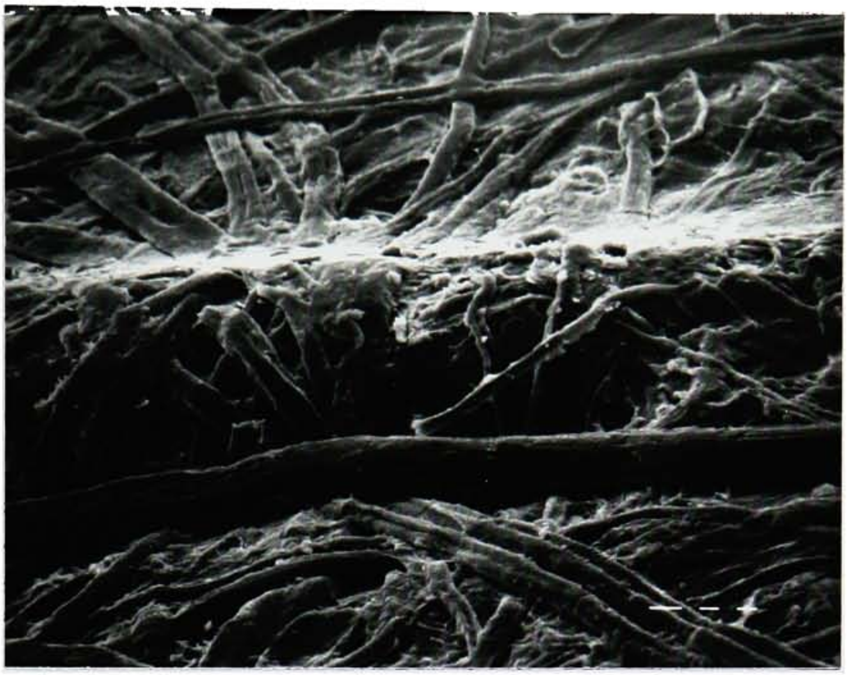
Photograph 10. Comparative view of the front side of the large-size laser perforations (top) to the front side of the large-size mechanical perforations (bottom). Enlargement: 15X

Photograph 11. A close view comparing the front side of a bridge in the large-size laser perforation pattern (top) to the front side of a bridge in the large-size mechanical perforation pattern (bottom). Enlargement: 135X

Photograph 12. Comparative view of the back side of the large-size laser perforation pattern (top) to the back side of the large-size mechanical perforation pattern (bottom). Enlargement: 15X



Photograph 13. Close view of the back side of a bridge in the large-size laser perforation pattern. Enlargement: 135X



Photograph 14. A tilted view (angle 60°) of the junction between a bridge and a hole on the back side of the large-size mechanical perforation pattern. Enlargement: 420X

COMPARISON OF THE VARIABILITY OF THE LASER PERFORATION PROCESS TO THE VARIABILITY OF THE MECHANICAL PERFORATION PROCESS

Control of the Actual Size of the Microperforation Pattern and Large-Size Perforation Pattern for the Comparative Study

Table 3. Mean and standard deviation of the size of the mechanical and laser perforation patterns for the comparative study (In thousandths of an inch).(1)

	Bridge width		Hole length		Bridge + Hole	
	mean	standard deviation	mean	Standard deviation	mean	standard deviation
Mechanical Microperf.	6.611	0.247	7.382	0.265	13.993	0.340
Laser Microperf. front side	6.251	0.447	7.583	0.292	13.835	0.358
Laser Microperf. back side	6.463	0.422	7.323	0.258	13.786	0.359
Large-Size Mechanical perf.	30.040	0.944	188.920	1.666	218.961	1.405
Large-Size Laser perf.	29.899	0.307	190.412	0.336	220.311	0.339

The standard deviation of the measurement of the large-size mechanical perforation pattern is significantly higher than the standard deviation of the size of the microperforation pattern. Therefore, the bigger the size the less accurate the mechanical perforation pattern.

In contrast, the standard deviation of the measurement of the laser perforated pattern is independent from the size of the perforation. This result is confirmed by the measurement of the size of the 16 different laser perforation patterns shown in table 6, page 48. Inaccuracy in laser perforations are due to three factors: the error of positioning of the table, the variations in the laser beam power, and especially the fact that the paper areas surrounding the holes are burned back after the laser beam has been turned off. The standard deviation figures show that the precision of the laser perforation pattern process can compete with the mechanical

perforation process when doing microperforation. When doing large-size perforations, the laser perforation process offers much more precision. The size of the laser perforation patterns do not match exactly the size of the mechanical perforation patterns, but are, seemingly, however, a very close copy. It is observed that the variable used for the comparison of both processes, the variance of the tensile strength, is independent from the size of the laser perforation pattern. Thus, the slight difference in size between the laser perforation patterns and the mechanical perforation pattern does not affect the validity of the comparative study.

Results of the tensile strength test

The tensile strengths and the variance of the tensile strengths which have been found for the four pattern of perforation follow.

Table 4. Tensile strength values of the perforation patterns for the comparison of the laser perforation process to the mechanical perforation process.[(2)]

Tensile strength (Kg/Inch)		Perforation pattern	
		Microperforation	Large Size
perforation process	Mechanical	3.298	1.524
	Laser	3.432	1.417

As it can be seen in the photographs 6 and 7, page 43D, and photograph 11, page 43F, the fibers are smashed at the bottom of the perforated holes. This layer of smashed fibers is an additional link between both sides of the perforation pattern, which creates additional tensile strength. On the other hand, as it can be seen in photographs 8 and 9, page 43E, the mechanical perforation process damages the bridges.

The tensile strength of the laser microperforation pattern is higher than the tensile strength of the mechanical microperforation pattern. It can be explained by the fact that the loss of strength caused by the damaged bridges of the mechanical perforation pattern is higher than the additional tensile strength brought by the layer of fibers smashed at the bottom of the hole. The tensile strength of the large-size laser perforation pattern is lower than the tensile strength of the large-size mechanical perforation pattern. In this case, the tensile strength added by the fibers smashed at the back side of the holes seems to be higher than the decrease of tensile strength caused by the damage to the bridges.

Table 5. Variance of the tensile strength of perforation patterns for both laser perforation process and mechanical perforation process.[3]

Tensile strength variance (Kg / inch)		Perforation pattern	
		Microperforation	Large Size
perforation process	Mechanical	0.694	0.0421
	Laser	0.0751	0.0338

From the above table, it can be seen that using a laser instead of a mechanical perforator to do microperforations drastically cuts down the variability in tensile strength by 89.2 percent. Using a laser instead of a mechanical perforator to do large-size perforation patterns cuts down the variability in tensile strength by 7.65 per cent.

It is interesting to notice that the variability in tensile strength is much higher for the mechanical microperforation pattern than for the large-size perforation pattern. This result confirms that the mechanical microperforations have a problem of stability in tensile strength whereas the mechanical large-size

perforations are working fine.

Results of the statistical analysis

As it is explained in Data Analysis, chapter V, page 32, the difference between the variance of the tensile strength of the mechanical perforation pattern and the variance of the tensile strength of the same size laser perforation pattern is not significant if:

$$0.537 \leq \frac{\text{Variance (Mechanical)}}{\text{Variance (Laser)}} \leq 1.86$$

- In the case of the microperforations, calculated from the values shown in table 5, page 46, that:

$$\frac{\text{Variance (Mechanical)}}{\text{Variance (Laser)}} = 0.694 / 0.0751 = 9.244$$

Since 3.040 is greater than 1.86, it can be concluded that the difference between the variance of the tensile strength of the laser microperforation pattern LM and the variance of the tensile strength of the mechanical microperforation pattern MM is significant. Therefore, the null hypothesis 1, "there is no significant difference between the variance of the tensile strength of the laser microperforation pattern LM and the variance of the tensile strength of the mechanical microperforation pattern MM" is rejected.

- In the case of the large-size perforations, it is calculated from the values shown in table 5, page 46, that:

$$\frac{\text{Variance (Mechanical)}}{\text{Variance (Laser)}} = 0.042 / 0.0388 = 1.082$$

Since $0.537 \leq 1.041 \leq 1.86$, the difference between the variance of the large-size laser perforation pattern LSL and the variance of the large-size perforation pattern LSM is not significant. Therefore, the null hypothesis 2, "There is no significant difference between the variance of the tensile strength of the large-size

laser perforation pattern LSL and the variance of the tensile strength of the large-size mechanical perforation pattern LSM" is accepted.

THE RESEARCH ON A MATHEMATICAL MODEL EXPRESSING THE VARIATIONS IN TENSILE STRENGTH OF THE LASER PERFORATION PATTERNS

Control of the Actual Size of the 16 Patterns of Perforation

Table 6 shows the actual size of the 16 patterns of perforation done versus the size which was programmed on the laser.

Table 6. Mean and standard deviation of the size of the 16 laser perforation patterns for the study on the relationship between independent and dependent variables.(4)

Laser perforation size programmed		Bridge width mean	Bridge width standard deviation	Hole length mean	Hole length Standard deviation	Bridge + Hole mean	Bridge + Hole standard deviation
W=20	H=20	19.751	0.372	21.488	0.404	41.239	0.371
W=20	H=40	20.824	0.761	39.205	0.639	60.029	0.698
W=20	H=80	20.203	0.803	79.967	0.794	100.171	0.815
W=20	H=160	20.729	0.763	159.54	0.769	180.269	0.708
W=40	H=20	41.033	0.577	21.169	0.623	62.203	0.527
W=40	H=40	40.101	0.578	40.067	0.741	80.167	0.664
W=40	H=80	38.996	0.534	81.201	0.447	120.197	0.532
W=40	H=160	38.773	0.218	161.524	0.310	200.297	0.258
W=80	H=20	80.693	0.347	21.414	0.300	102.107	0.382
W=80	H=40	79.655	0.310	40.567	0.316	120.221	0.288
W=80	H=80	79.477	0.521	80.771	0.517	160.249	0.432
W=80	H=160	79.286	0.336	161.056	0.295	240.343	0.249
W=160	H=20	161.18	0.289	21.059	0.319	182.39	0.078
W=160	H=40	161.47	0.342	38.829	0.359	200.299	0.230
W=160	H=80	160.70	0.347	79.65	0.363	240.37	0.484
W=160	H=160	160.619	0.481	159.83	0.420	320.44	0.329

Table 6 shows that the precision of the laser perforation process is independent from the size of the perforation pattern. The actual bridge width and hole length values obtained are close to the values programmed. These actual

measurements of the 16 perforation patterns are used to compute the mathematical model.

Some Considerations in the Attempt to Find a Mathematical Model for the Tensile Strength of Laser Perforations

Prior to finding the model, the following considerations are made:

- A theoretical perforation pattern of which the bridge width W or the number of bridges per inch N equals zero has a tensile strength equal to zero.

- The tensile strength of a single one inch wide bridge (N=1, W=1) equals the tensile strength of the non-perforated paper.

Results of the Tensile Strength Test

Table 7. Experimental tensile strength values of the 16 laser perforation patterns versus bridge width values and number of bridges per inch values.[5]

Actual Bridge Width W (1/1000 ")	Number of bridges per inch N	Experimental tensile strength (in Kg / inch)	Standard deviation
1000	1	6.437	0.198
19.751	25	4.513	0.268
20.824	16	3.303	0.243
20.203	10	2.040	0.354
20.729	5	0.957	0.099
41.033	16	5.568	0.529
40.101	12	4.492	0.335
38.996	8	2.865	0.277
38.773	5	2.029	0.165
80.693	10	6.166	0.185
76.655	8	5.016	0.239
79.477	6	4.192	0.374
79.286	4	2.722	0.182
161.180	5	5.174	0.517
161.470	4	4.324	0.212
160.700	4	4.942	0.153
160.619	3	3.643	0.326
0	0	0	0

Table 7 shows the tensile strength of a perforation pattern versus the number

of bridges per inch N and versus the bridge width W. The standard deviation of the tensile strength of the laser perforation pattern is independent of the bridge width and the number of bridges per inch. The standard deviation expresses how much in control the perforation process is.

Preliminary Analysis of the Relationship between the Tensile Strength of a Perforation Pattern and the Number of Bridges per Inch

The variations of the tensile strength versus the number of bridges per inch N at constant bridge width W are shown below in figure 9.

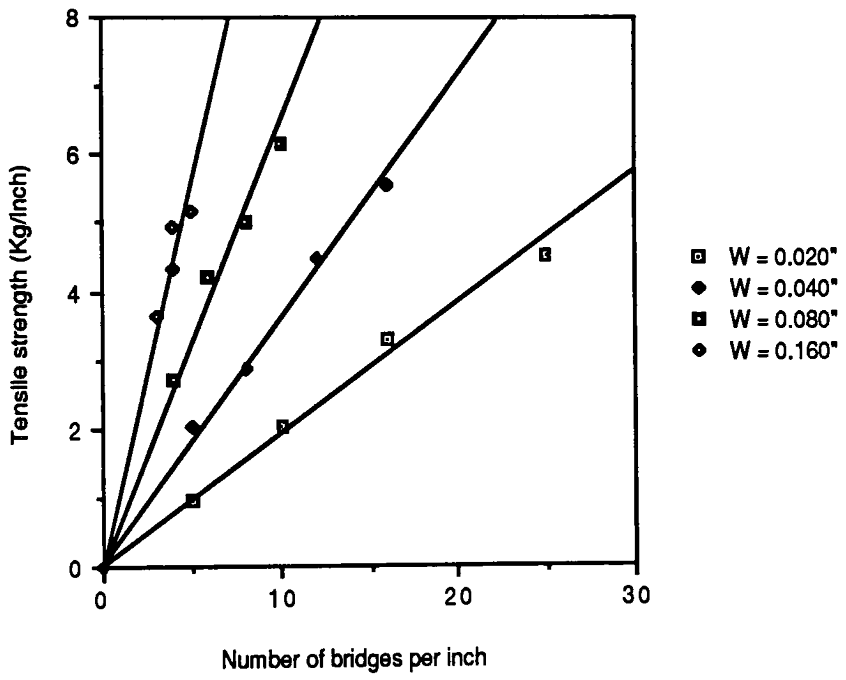


Figure 9. The linear variations of the tensile strength of the sixteen laser perforation patterns versus number of bridges per inch N at constant bridge width W.

Figure 9 shows clearly that the tensile strength varies linearly versus the

number of bridges per inch N. Therefore, the relationship between the tensile strength of the perforation pattern T_{pp} and the number of bridges per inch N can be expressed for each one of the four constant bridge widths tested by the following linear equation:

$$T_{pp} = a_w \times N + b_w$$

where a_w and b_w are parameters which are varying as a function of the bridge width W.

The a_w and b_w values found for each one of the four constant bridge width are shown below, in table 8.

Table 8. a_w and b_w values for the four bridge widths W=20, 40, 80, and 160 thousandths of an inch.

	$T_{pp} = a_w \times N + b_w$	
W = cste	a_w	b_w
20	0.198	0
40	0.351	0
80	0.651	0
160	1.154	0

The Complete Mathematical Model Expressing the Variations of the Tensile Strength of the Perforation Pattern as a Function of Bridge Width, Number of Bridges per Inch, and Tensile Strength of Paper

In order to determine the complete mathematical model, the variations of the parameter a_w as a function of the bridge width W must be studied. The tensile strength of the paper is a constant parameter that must appear in the model.

It can be derived from the considerations made in page 49 that:

- Tensile strength (Bridge Width = 0) = 0 Kg/inch.

Therefore, function (Bridge Width = 0) = 0.

- Tensile strength (Bridge Width = 1) = Tensile strength of the paper.

Therefore, function (Bridge Width = 1) = Tensile strength of the paper.

Modeling the parameter a_w using the first degree polynomial $a_w = W$ has been tried but the results are not satisfying because the maximum (1.319 kg) and the average deviation (0.708 kg) between the mathematical model found (model 1: $T_{pp} = T_{paper} \times N \times W$) and the experimental tensile strength values are too large. The tensile strength and its deviation from the experimental values obtained when modeling the parameter a_w by the first degree polynomial mentioned above are shown in table 9, model 1, page 53.The closest model found for the variation of the parameter a_w as a function of bridge width is the first degree polynomial $a_w = 0.01067 + 1.04080 \times W$. Therefore, the complete mathematical model expressing the relationship between the tensile strength of the laser perforation pattern and the dependent variables studied is the following model 2.

$$\mathbf{T_{pp} = T_{paper} \times N \times (0.01067 + 1.04080 \times W)}$$

Where:

- T_{pp} is the tensile strength of the perforated pattern in Kilograms per inch.
- T_{paper} is the tensile strength of the paper in Kilogram per inch (6.467 Kg/inch).
- W is the width of the bridges in inches.
- N is the number of bridges per inch.

The deviation between the tensile strength computed using the model 2 and the experimental tensile strength values has a maximum of 0.568 kilograms, and a typical value of 0.264 kilograms. Those values are shown in table 9, model 2, page 53. Therefore, the mathematical model found allows the printer to predict

with an average error of 0.264 kilograms the tensile strength from the tensile strength of the paper, the number of bridges per inch, and the width of the bridges. It is observed that the value 0.01067 is close to 0, and the value 1.04080 is close to 1. Therefore, the model 2 is close to the model 1, but as it has been demonstrated above, model 2 gives much better results. Moreover, model 2 shows that the tensile strength of a perforation pattern varies linearly versus bridge width and number of bridges per inch.

The variations of the experimental tensile strength values versus the tensile strength values calculated using the mathematical model 2 are shown in figure 10, page 54.

Table 9. Comparison of the tensile strength values calculated by the mathematical models to the experimental tensile strength values.

			Model 1		Model 2	
Bridge width W (1/1000th of an inch)	Number of Bridges per inch N	Experimental tensile strength (in Kg / inch)	Calculated tensile strength Model	Deviation model - Exper.	Calculated tensile strength Model	Deviation Model - Exper.
1000	1	6.467	6.467	0	6.800	0.333
19.751	25	4.513	3.194	1.319	5.050	0.536
20.824	16	3.303	2.155	1.148	3.347	0.044
20.203	10	2.040	1.307	0.733	2.050	0.010
20.729	5	0.957	0.671	0.286	1.042	0.086
41.033	16	5.568	4.276	1.292	5.523	0.047
40.101	12	4.492	3.111	1.381	4.067	0.425
38.996	8	2.865	2.017	0.848	2.652	0.213
38.773	5	2.029	2.507	0.478	1.650	0.379
80.693	10	6.166	5.218	0.947	6.122	0.044
76.655	8	5.016	3.965	1.05	4.680	0.336
79.477	6	4.192	3.083	1.108	3.624	0.568
79.286	4	2.722	2.051	0.671	2.411	0.311
161.180	5	5.174	5.211	0.037	5.769	0.595
161.470	4	4.324	4.176	0.149	4.623	0.299
160.700	4	4.942	4.156	0.782	4.603	0.339
160.619	3	3.643	3.116	0.526	3.450	0.193
0	0	0	0	0	0	0
	Correlation coefficient =		0.95	-	0.98	-
	Mean =		-	0.708	-	0.264

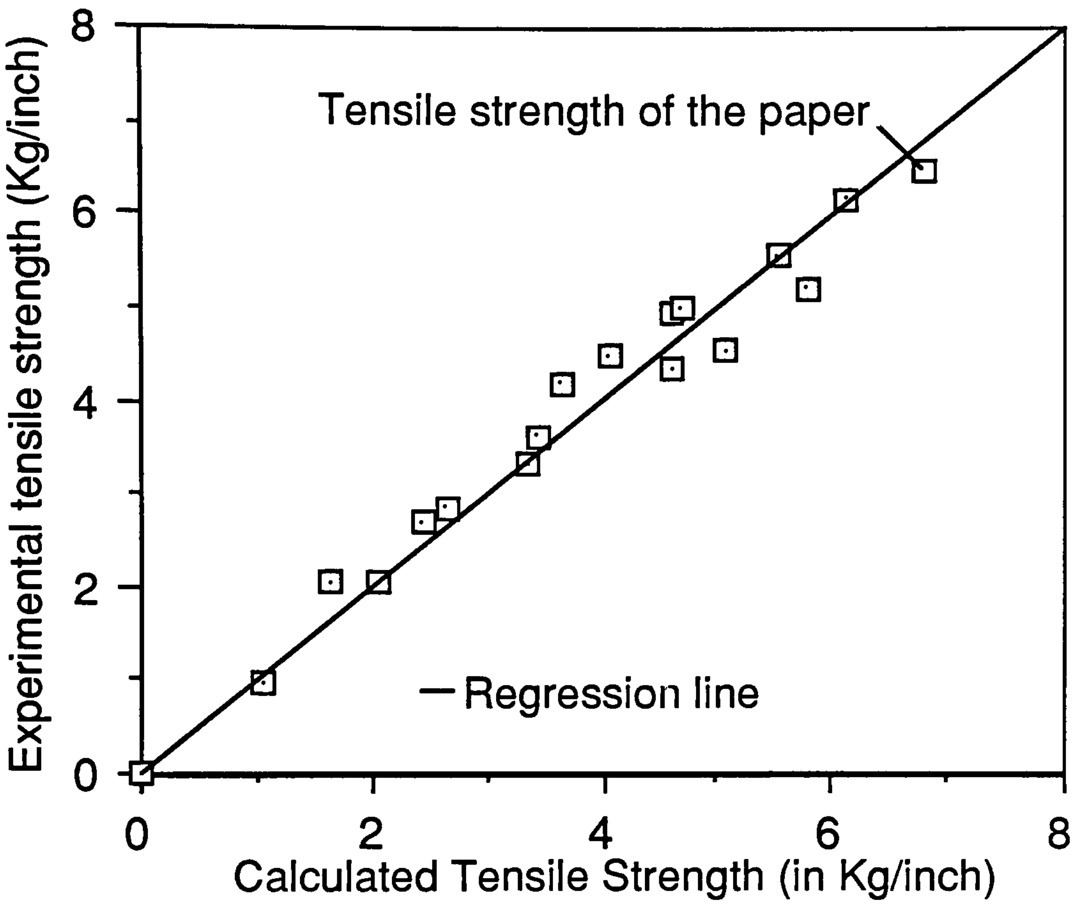


Figure 10. Correlation of the tensile strength values calculated using the mathematical model 2 to the experimental tensile strength values.

The coefficient of the correlation of the tensile strength computed by the mathematical model to the tensile strength values found experimentally is very high: r = 0.98. The regression line has been computed and drawn in figure 10.

The mathematical model describing the variations of the tensile strength of a perforation pattern as a function of the bridge width, the number of bridges per inch, and the tensile strength of the paper has been found with a very high coefficient of correlation (r = 0.98), therefore, the mathematical model provides a

good fit for the data and there is a significant relationship between the dependent and independent variables studied. Therefore:

- Hypothesis 3, "There is a relationship between the tensile strength of a laser perforation pattern and the width of the bridges W" is accepted.

- Hypothesis 4, "There is a relationship between the tensile strength of a laser perforation pattern and the number of bridges per inch" is accepted.

- Hypothesis 5, "There is a relationship between the tensile strength of a laser perforation pattern and the tensile strength of the paper on which the perforation is done" is accepted.

FOOTNOTES FOR CHAPTER VI

(1) Table 3 summarizes the results of the measurements that are shown in the tables 10 to 12, Appendix B, page 60.

(2) Table 4 summarizes the results of the measurements that are shown in the table 21, Appendix C, page 72.

(3) The tensile strength variance values shown in table 5 are obtained by squaring the standard deviation values found in table 21, Appendix C, page 72.

(4) Table 6 summarizes the results of the measurements of the actual size of the 16 laser perforation patterns that are shown in the tables 13 to 20, Appendix B, page 60.

(5) Table 7 summarizes the results of the tensile strength tests that are shown in the tables 22 to 26, Appendix C, page 72.

Chapter VII
CONCLUSIONS AND RECOMMENDATIONS

The defects affecting the mechanical microperforation patterns have been identified. The pressure applied by the perforation pins stretches, deforms, and damages the bridges. The fibers of the perforated area are not removed but smashed and piled up at the back side of the perforated hole. In addition to closing the hole, this layer of smashed fibers is often partially cracked and adds an uncontrollable amount of tensile strength to the perforation pattern. Microperforations are reaching the limits of what can be accomplished on a mechanical perforator.

No major problem affects the large-size mechanical perforation pattern. However, it has been noticed on the photographs that the bridges seem to have been slightly stretched.

Since the laser perforation process is a contactless process, the perforation pattern is free of all the defects mentioned above. The bridges are not deformed and no crack is visible. The perforated holes are round-shaped, clean and remain wide open.

Consequently, using a laser instead of using a mechanical perforator to do microperforations drastically cuts down the variability in tensile strength from 0.694 kilograms to 0.0751 kilograms. This difference is significant. Therefore, it can be concluded that the laser perforation process is a very valuable process for doing high quality microperforations. However, using a laser instead of a mechanical perforator to do large-size perforations cuts down the variability in tensile strength only from 0.0421 kilograms to 0.0338 kilograms. This difference is not significant. Therefore, it is not worth investing money in a laser to do large-size perforations in paper, unless the application requires that the holes are

very clean and smooth.

The laser perforation process should be applied to the printing industry to microperforate high quality computer paper and business forms. Due to burning problems, the laser perforating speed that can be reached on paper is limited. The laser is therefore too slow to replace effectively high speed mechanical perforators which are used on web presses for long-run commercial printing and other similar applications. However, the speed of the laser perforation process is high enough for the laser to be used on the special short-run presses used to print computer paper and business forms. Despite the high cost investment required, the application of a computer-controlled laser perforation unit could seemingly be profitable because of its very low operating cost, and also because of the versatility and ability to changeover the position of the perforation patterns while running at full speed, without stopping the press.

The laser perforation process can also find an application anywhere open perorated holes are required, since open holes are a feature that mechanical perforators cannot offer. This is the reason why the laser perforation process has been applied to the perforation of cigarette filter paper.

Adjusting the tensile strength of a mechanical perforation pattern is usually done by guess, based on past experience, whereas adjusting the tensile strength of a laser perforation pattern can be done simply and precisely by using the mathematical model established in this thesis. The average precision offered by the model for the particular 20-pound uncoated paper is 0.248 kilogram.

Much research remains to be done on laser perforations. It would be interesting to see how the laser perforation affects the tearing strength or the folding of the perforation pattern. It would be also helpful for printers to know how to relate the tensile strength, the folding, and the tearing strength to some paper physical characteristics such as rigidity, weight, or thickness. Studying whether or not the open holes of the laser perforation pattern can enhance high speed

folding and piling would be interesting. The speed of the laser perforation process is limited, due to burning problems. Research needs to be done on a special coating that would prevent the paper from burning back when it is struck by the laser beam. It would then be possible, using a very high power, to perforate the paper at very high speed without burning the areas situated around the perforation holes.

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APPENDIX A

Samples of the laser and mechanical perforation patterns produced for the comparison of the variability of the laser perforation process to the variability of the mechanical perforation process

1

2

1

2

Microperforation patterns

1. Laser

2. Mechanical

Sample of bad quality

Mechanical microperforation

Large size perforation pattern

1. Laser

2. Mechanical

APPENDIX B

The actual size values of the perforation patterns

Table 10. Measurement of the actual bridge width and hole length of the laser microperforation pattern LM. (All values are expressed in thousandths of an inch)

	Front side			Back side		
	Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
	5.870	7.85	13.72	5.85	7.44	13.29
	6.200	7.63	13.83	6.76	7.68	14.44
	5.990	7.73	13.72	6.40	7.21	13.69
	6.450	7.86	14.31	6.22	7.28	13.50
	6.170	7.57	13.74	6.19	7.71	13.90
	5.830	7.77	13.60	5.99	7.76	13.75
	6.270	7.77	14.04	6.69	7.33	14.02
	5.540	8.13	13.67	7.03	7.07	14.10
	6.620	7.59	14.21	6.13	7.18	13.31
	6.620	7.30	13.92	6.82	7.40	14.22
	5.570	7.63	13.20	7.0	6.93	13.96
	7.200	7.47	14.67	6.5	7.13	13.72
	6.520	7.14	13.66	7.03	7.09	14.12
	6.630	7.12	13.75	6.29	7.09	13.38
	6.290	7.19	13.48	5.85	7.54	13.39
Mean	6.251	7.58	13.83	6.46	7.32	13.78
Standard deviation	0.447	0.292	0.358	0.422	0.258	0.359

Table 11. Measurement of the actual bridge width and hole length of the large size laser perforation pattern LSL. (All values are expressed in thousandths of an inch)

	Bridge width	Hole length	Bridge width
	29.900	190.60	220.50
	29.390	190.60	219.99
	30.340	190.30	220.64
	29.780	190.42	220.20
	30.110	190.20	220.31
	29.710	190.58	220.29
	30.000	190.90	220.90
	29.850	190.50	220.35
	29.710	190.94	220.65
	30.600	189.70	220.30
	29.600	189.90	219.50
	29.790	190.44	200.23
	29.860	190.65	220.51
	30.170	190.25	220.42
	29.670	190.20	219.87
Mean	29.90	190.41	220.31
Standard deviation	0.307	0.336	0.339

Table 12. Measurement of the actual bridge width and hole length of the mechanical microperforation pattern MM and large-size mechanical perforation pattern LSM.
(All values are expressed in thousandths of an inch)

	Microperforations			Large size perforations		
	Bridge width	Hole length	Bridge + Hole	Bridge width	Hole length	Bridge + hole
	6.580	7.390	13.970	19.460	201.180	220.640
	6.480	7.090	13.570	29.880	190.460	220.340
	6.830	7.190	14.020	30.770	188.800	219.570
	6.510	7.670	14.180	29.480	188.580	218.060
	6.720	7.220	13.940	30.170	190.170	220.340
	6.180	7.450	13.630	29.960	191.210	221.170
	6.990	7.850	14.840	31.000	187.400	218.400
	6.140	7.600	13.740	29.250	188.070	217.320
	6.540	7.630	14.170	30.450	188.670	219.120
	6.490	7.630	14.120	29.890	188.260	218.150
	6.810	7.040	13.850	29.690	188.200	217.890
	6.810	7.570	14.380	28.870	188.740	217.610
	6.460	7.070	13.530	30.900	189.760	220.660
	6.890	7.260	14.150	32.340	186.120	218.460
	6.740	7.070	13.810	28.480	188.210	216.690
Mean	6.611	7.382	13.993	29.373	189.587	218.961
Standard deviation	0.247	0.265	0.340	2.901	3.444	1.405

Table 13. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 20, and H = 20 and 40.
(All values are expressed in thousandths of an inch)

	W = 20 - H = 20			W = 20 - H = 40		
	Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
	20.260	22.32	42.58	20.800	40.14	60.94
	19.360	21.99	41.35	20.100	39.27	59.37
	19.130	21.93	41.06	20.950	39.47	60.42
	19.590	21.98	41.57	21.020	38.34	59.36
	19.850	21.36	41.21	21.220	39.48	60.70
	19.830	21.28	41.11	20.790	38.51	59.30
	19.460	21.44	40.90	21.240	39.56	60.80
	19.760	21.34	41.10	21.970	38.58	60.55
	20.540	21.31	41.85	21.220	38.33	59.55
	19.790	21.17	40.96	21.710	38.27	59.98
	19.400	21.02	40.42	19.190	39.93	59.12
	20.010	21.41	41.42	20.650	39.98	60.63
	20.110	21.78	41.89	20.680	39.57	60.25
	19.660	20.82	40.48	21.380	39.21	60.59
	19.510	21.17	40.68	19.440	39.43	58.87
Mean	19.751	21.488	41.239	20.824	39.205	60.029
Standard deviation	0.372	0.404	0.371	0.761	0.639	0.698

Table 14. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 20, H = 80 and 160.
(All values are expressed in thousandths of an inch)

	W = 20 - H = 80			W = 20 - H = 160		
	Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
	21.520	80.10	101.62	21.370	158.91	180.28
	21.190	79.22	100.41	19.980	159.33	179.31
	20.460	78.85	99.31	20.630	160.99	181.62
	20.110	79.92	100.03	21.350	159.16	180.51
	20.580	79.36	99.94	21.310	159.18	180.49
	20.470	79.84	100.31	20.280	159.09	179.37
	20.720	78.84	99.56	21.070	158.87	179.94
	20.220	78.90	99.12	19.830	160.37	180.20
	19.920	80.06	99.98	21.930	159.30	181.23
	19.340	80.46	99.80	20.280	159.32	179.60
	19.860	80.66	100.52	19.980	160.78	180.76
	20.220	80.26	100.48	21.100	159.04	180.14
	19.040	81.05	100.09	20.080	160.72	180.80
	18.480	80.83	99.31	21.990	158.63	180.62
	20.910	81.18	102.09	19.750	159.42	179.17
Mean	20.203	79.967	100.171	20.729	159.54	180.269
Standard deviation	0.803	0.794	0.815	0.763	0.769	0.708

Table 15. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 40, and H = 20 and 40.
(All values are expressed in thousandths of an inch)

	W = 40 - H = 20			W = 40 - H = 40		
	Bridge width	Hole length	Bridge + Hole	Bridge width	Hole length	Bridge + hole
	41.530	20.140	61.67	40.22	41.02	81.24
	41.240	21.810	63.05	39.36	39.84	79.20
	41.630	19.880	61.51	39.42	40.01	79.43
	40.550	21.380	61.93	40.37	41.21	81.58
	41.150	21.560	62.71	40.80	39.56	80.36
	40.380	21.060	61.44	41.41	38.20	79.61
	41.100	21.120	62.22	40.73	39.41	80.14
	41.100	20.810	61.91	39.64	40.08	79.72
	40.130	21.980	62.11	39.75	40.65	80.40
	41.260	21.220	62.48	39.39	40.30	79.69
	42.380	20.600	62.98	40.12	40.74	80.86
	40.280	21.760	62.04	39.91	40.04	79.95
	40.830	21.770	62.60	40.36	39.50	79.86
	40.820	20.860	61.68	40.11	40.35	80.46
	41.120	21.590	62.71	39.92	40.09	80.01
Mean	41.033	21.169	62.203	40.101	40.067	80.167
Standard deviation	0.577	0.623	0.527	0.578	0.741	0.664

Table 16. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 40, H = 80 and 160.
(All values are expressed in thousandths of an inch)

W = 40 - H = 80			W = 40 - 160		
Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
39.000	82.05	121.05	38.870	160.99	199.86
37.920	81.31	119.23	38.470	161.93	200.40
38.770	81.97	120.74	38.290	162.14	200.43
39.780	81.06	120.84	38.980	161.70	200.68
39.610	80.58	120.19	38.840	161.38	200.22
39.280	80.82	120.10	38.640	161.58	200.22
38.880	80.97	119.85	39.040	161.55	200.59
38.930	81.42	120.35	38.810	160.95	199.76
38.960	81.35	120.31	39.030	161.27	200.30
38.680	80.88	119.56	38.840	161.40	200.24
39.420	81.46	120.88	38.940	161.61	200.55
39.050	80.74	119.79	38.470	161.58	200.05
38.250	81.54	119.79	38.840	161.65	200.49
39.830	80.65	120.48	38.790	161.46	200.25
38.590	81.21	119.80	38.740	161.68	200.42
38.996	81.201	120.197	38.773	161.524	200.297
0.534	0.447	0.532	0.218	0.310	0.258

Table 17. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 80, H = 20 and 40.
(All values are expressed in thousandths of an inch)

	W = 80 - H = 20			W = 80 - H = 40		
	Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
	80.940	21.13	102.07	80.270	39.86	120.13
	80.690	21.71	102.40	79.510	40.73	120.24
	80.840	21.40	102.24	79.890	40.59	120.48
	80.870	21.28	102.15	79.870	40.72	120.59
	80.130	21.27	101.40	79.230	40.88	120.11
	80.860	22.07	102.93	79.710	41.02	120.73
	80.590	21.10	101.69	79.930	40.16	120.09
	81.160	21.44	102.60	79.910	40.39	120.30
	80.750	21.04	101.79	79.330	40.85	120.18
	80.600	21.59	102.19	79.610	40.56	120.17
	79.800	21.91	101.71	79.710	40.23	119.94
	80.980	21.14	102.12	79.340	40.74	120.08
	80.900	21.25	102.15	79.100	40.50	119.60
	80.480	21.40	101.88	79.740	40.87	120.61
	80.810	21.48	102.29	79.670	40.40	120.07
Mean	80.693	21.414	102.107	79.655	40567	120.221
Standard deviation	0.347	0.300	0.382	0.310	0.316	0.288

Table 18. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 80, H = 80 and 160.
(All values are expressed in thousandths of an inch)

	W = 80 - H = 80			**W = 80 - H = 160**		
	Bridge width	**Hole length**	**Bridge + Hole**	**Bridge width**	**Hole length**	**Bridge + hole**
	79.520	81.24	160.76	79.300	161.44	240.74
	79.040	80.73	159.77	79.160	160.98	240.14
	79.300	81.09	160.39	79.130	160.93	240.06
	79.220	80.63	159.85	79.290	160.91	240.20
	78.650	81.47	160.12	79.320	161.33	240.65
	79.410	81.47	160.88	78.870	161.37	240.24
	79.590	80.58	160.17	79.740	160.72	240.46
	80.070	80.87	160.94	79.410	160.94	240.35
	78.950	80.63	159.58	78.690	161.51	240.20
	79.030	81.06	160.09	79.100	161.08	240.18
	78.990	81.28	160.27	78.930	161.05	239.98
	80.150	80.60	160.75	79.280	161.31	240.59
	80.240	80.15	160.39	79.610	161.11	240.72
	80.290	79.75	160.04	79.980	160.52	240.50
	79.710	80.02	159.73	79.480	160.65	240.13
Mean	79.477	80.771	160.249	79.286	161.056	240.343
Standard deviation	0.521	0.517	0.432	0.336	0.295	0.249

Table 19. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 160, and H = 20 and 40.
(All values are expressed in thousandths of an inch)

	W = 160 - H = 20			W = 160 - H = 40		
	Bridge width	Hole length	Bridge + Hole	Bridge width	Hole length	Bridge + hole
	161.290	21.17	182.46	161.230	39.08	200.31
	161.470	20.53	182.00	160.740	39.13	199.87
	161.650	20.89	182.54	161.370	39.21	200.58
	161.070	20.86	181.93	161.590	38.89	200.48
	161.170	21.15	182.32	161.920	38.38	200.30
	161.300	20.99	182.29	161.790	38.40	200.19
	161.190	20.97	182.16	161.400	38.67	200.07
	161.610	21.14	182.75	161.530	38.78	200.31
	161.200	20.72	181.92	160.800	39.63	200.43
	161.170	21.02	182.19	161.650	39.18	200.83
	161.350	21.03	182.38	161.860	38.35	200.21
	160.870	21.12	181.99	161.550	38.60	200.15
	160.610	21.79	182.40	161.590	38.70	200.29
	160.890	20.86	181.75	161.360	38.73	200.09
	160.860	21.65	182.51	161.670	38.71	200.38
Mean	161.180	21.059	182.239	161.470	38.829	200.299
Standard deviation	0.289	0.319	0.279	0.342	0.359	0.230

Table 20. Measurement of the actual bridge width and hole length obtained when programming the laser with the parameters W = 160, and H = 80 and 160.
(All values are expressed in thousandths of an inch)

	W = 160 - H = 80			W = 160 - H = 160		
	Bridge width	Hole length	Bridge + Hole	Bridge width	Hole length	Bridge + hole
	160.360	79.18	239.54	160.620	159.73	320.35
	160.320	80.28	240.60	160.090	160.12	320.21
	161.120	79.98	241.10	160.100	160.30	320.40
	161.020	79.10	240.12	161.050	160.08	321.13
	161.200	79.50	240.70	160.240	160.32	320.56
	160.380	79.42	239.80	160.070	160.12	320.19
	160.380	79.54	239.92	160.100	159.91	320.01
	160.250	79.97	240.22	160.030	160.22	320.25
	160.920	80.05	240.97	160.610	160.25	320.86
	160.790	79.41	240.20	161.320	159.54	320.86
	160.460	79.53	239.99	160.610	159.69	320.30
	160.470	80.10	240.57	161.010	159.18	320.19
	161.220	79.99	241.21	161.010	159.66	320.67
	160.760	79.53	240.29	160.910	159.34	320.25
	160.920	79.40	240.32	161.370	159.03	320.40
Mean	160.705	79.653	240.37	160.609	159.833	320.44
Standard deviation	0.347	0.363	0.484	0.481	0.420	0.329

APPENDIX C

The tensile strength values

Table 21. Tensile strengths of the mechanical microperforation pattern MM, laser microperforation pattern LM, large-size mechanical perforation pattern LSM, and large-size laser perforation pattern LSL.
(The tensile strength values are expressed in kilograms per inch)

	Microperforations		Large-size perforations	
	Mechanical	**Laser**	**Mechanical**	**Laser**
	2.78	3.18	1.47	1.55
	2.15	3.05	1.26	1.53
	2.14	3.27	1.99	1.70
	2.98	3.43	1.27	1.33
	3.21	3.35	1.84	1.68
	4.55	3.58	1.33	1.24
	4.82	3.22	1.63	1.47
	4.96	3.90	1.60	1.24
	3.13	2.80	1.38	1.51
	2.00	3.28	1.29	1.08
	2.22	3.42	1.32	1.29
	3.64	3.45	1.66	1.41
	2.77	3.30	1.69	1.19
	4.02	3.60	1.28	1.47
	4.18	3.45	1.71	1.24
	2.33	3.44	1.96	1.38
	2.62	3.87	1.64	1.65
	2.72	3.35	1.51	1.43
	3.93	3.35	1.44	1.39
	4.32	3.19	1.46	1.45
	3.45	3.17	1.45	1.73
	3.94	3.39	1.60	1.40
	4.51	3.25	1.49	1.15
	2.94	3.73	1.86	1.61
	3.51	3.92	1.46	1.73
	3.43	3.87	1.35	1.15
	3.05	3.95	1.64	1.71
	3.02	3.40	1.41	1.48
	2.75	3.29	1.39	1.20
	2.88	3.51	1.34	1.14
Mean	3.298	3.432	1.524	1.417
Standard deviation	0.833	0.274	0.205	0.197

Table 22. Tensile strength of the paper.

(The tensile strength values are expressed in kilograms force per inch)

	6.57
	6.30
	6.22
	6.39
	6.64
	6.76
	6.23
	6.48
	6.72
	6.36
Mean	6.467
Standard deviation	0.198

Table 23. Tensile strength of the laser perforation patterns of which the bridge width equals 20, and the hole length equals 20, 40, 80, and 160 thousandths of an inch.
(The tensile strength values are expressed in kilograms per inch)

	H = 20	H= 40	H = 80	H = 160
	3.95	3.27	2.10	1.12
	4.67	3.27	1.72	1.14
	4.28	3.51	1.95	0.85
	4.56	3.29	1.55	0.90
	4.43	2.83	2.15	0.91
	4.85	3.33	2.66	0.90
	4.45	3.66	2.48	0.92
	4.76	3.57	2.15	0.91
	4.43	3.24	2.02	1.01
	4.75	3.06	1.62	0.91
Mean	4.513	3.303	2.040	0.957
Standard deviation	0.268	0.243	0.354	0.099

Table 24. Tensile strength of the laser perforation patterns of which the bridge width equals 40, and the hole length equals 20, 40, 80, and 160 thousandths of an inch.
(The tensile strength values are expressed in kilograms per inch)

	H = 20	**H= 40**	**H = 80**	**H = 160**
	5.84	4.58	3.08	2.07
	5.99	5.01	2.95	1.72
	6.34	5.04	3.09	2.01
	5.31	4.66	3.00	2.18
	4.79	4.28	2.57	1.95
	5.60	4.32	2.95	1.81
	5.82	4.37	3.10	2.13
	4.65	4.35	2.67	2.02
	5.48	4.34	2.98	2.23
	5.86	3.97	2.26	2.17
Mean	5.568	4.492	2.865	2.029
Standard deviation	0.529	0.335	0.277	0.165

Table 25. Tensile strength of the laser perforation patterns of which the bridge width equals 80, and the hole length equals 20, 40, 80, and 160 thousandths of an inch.
(The tensile strength values are expressed in kilograms per inch)

	H = 20	H= 40	H = 80	H = 160
	6.17	5.03	3.95	2.82
	6.24	5.19	3.78	2.55
	6.12	5.34	4.55	2.87
	6.26	5.19	3.88	2.99
	6.38	5.01	3.92	2.71
	5.84	4.82	3.90	2.84
	6.39	5.12	4.49	2.86
	6.30	5.10	4.32	2.51
	6.01	4.50	4.20	2.63
	5.95	4.86	4.93	2.44
Mean	6.166	5.016	4.192	2.722
Standard deviation	0.185	0.239	0.374	0.182

Table 26. Tensile strength of the laser perforation patterns of which the bridge width equals 160, and the hole length equals 20, 40, 80, and 160 thousandths of an inch.
(The tensile strength values are expressed in kilograms per inch)

	H = 20"	H= 40"	H = 80"	H = 160"
	5.75	4.32	4.82	3.64
	5.90	4.38	5.25	3.69
	5.60	4.62	4.75	4.25
	5.61	4.10	4.83	3.37
	5.02	4.07	4.86	3.69
	4.98	4.00	5.10	3.95
	5.07	4.40	5.04	3.87
	4.70	4.28	4.87	3.50
	4.79	4.53	5.00	3.17
	4.32	4.54	4.90	3.30
Mean	5.174	4.324	4.942	3.643
Standard deviation	0.517	0.212	0.153	0.326

APPENDIX D

Table of the values of $F_{.05}$ for the F distribution

Table 27. Values of $F_{.05}$ for the F distribution

Denominator Degrees of Freedom	Numerator Degrees of Freedom 1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40
1	161.4	199 5	215 7	224 6	230 2	234 0	236.8	238.9	240.5	241.9	243.9	245.9	248 0	249.1	250.1	251 1
2	18.51	19 00	19 16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19 47
3	10 13	9.55	9 28	9 12	[illegible]	8 94	8.89	8.85	8 81	8.79	8.74	8 70	8.66	8 64	[illegible]	[illegible]
4	7.71	6.94	6 59	[illegible]	[illegible]	[illegible]	6.09	6.04	6.00	5.96	5.91	5.86	5 80	5.77	[illegible]	5.72
5	6 61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4 68	4.62	4.56	4.53	4.50	4 46
6	5.99	5 14	4 76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77
7	5.59	4.74	4 35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.28	3.22	3.15	3.12	3.08	3 04
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83
10	4.96	4 10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2 80	2.75	2.69	2.62	2.54	2.51	2.47	2.43
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20
16	4 49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03
20	4 35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79
40	4.08	3.23	2 84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59
120	3.92	3.07	2.68	2.45	2.29	2.17	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.50
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39

APPENDIX E

Some of the characteristics of the computer paper used for the experiments of the thesis

Characteristics of the paper

- White uncoated paper
- Startch surface sizing
- Free sheet: no groundwood
- Actual weight: 19.25 pounds (17" x 22" - 500 sheets)
  or 72.4 grams / square meters
- Caliper: 0.00363 inch or 92.4 microns
- Ash content: 4.1 percent.