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PATTERN DESIGN OF MICRO-PERFORATION ON COMPOSITE PAPERBOARD FOR MODIFIED ATMOSPHERE PACKAGING

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ABSTRACT

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Pattern Design of micro-perforation on composite material for modified atmosphere packaging

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The extrusion-coated paperboard tray packaging which contains a tray container and a piece of lidding film is widely used along with MAP technology in fresh food packaging industry. Much research has been done on perforation onto lidding film. This research is based on the attempt of perforating on the tray materials: uncoated paperboard and paperboard coated with PE polymer or PET polymer. The study was an approach to the perforations on the paperboard and how to design its patterns. The study focused on to which degree does the perforation influences the strength of the paperboard materials. The diameter and the shape of perforations were observed. The GTR and WVTR of the materials were tested.

From the comparison of 25 patterns, it is inferred that the better tensile strength could be achieved when the micro-holes placed with more distance and more uniformly. The less perforation done on horizontal direction of the sample, the better tensile properties it gains. The less destructing rows made on the samples, the better tensile strength the sample gets. More even and straight fraction surfaces appeared in MD samples, while CD samples also have slant and more layered fraction surfaces. Tensile strength in MD is close to two times higher than CD samples. These results are caused by the orientation of the fibers. The appearance differences between micro-holes of the three materials are quite obvious. For manual made perforated hole, the surface is not smooth enough. For laser made perforation, the paperboard got discoloration due to laser, perforation on uncoated board is more flat, outstanding ring circles appeared on PET and PE boards, and a few bubbles could be seen around the ring circle of PET coated board. The perforation could increase the WVTR of three kinds of boards effectively. The design of patterns and the observation of perforations could give the theoretical reference for manufactures or engineers who wants to apply the laser perforation on composite paperboard.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	the tested area [m^2]
Δc	the concentration difference [mol/cm^3]
D	the diffusivity [cm^2/s]
J	the diffusion flux [$mol \cdot cm^{-2} \cdot s^{-1}$]
L	the film thickness [cm]
M_t	the weight loss in the time distance [g]
t	the time distance [s]

BOPP	Biaxially-oriented Polypropylene
CD	Cross Direction
CO_2TR	CO_2 Transmission Rate
ESD	Electrostatic Discharge
GTR	Gas Transmission Rate
LDPE	Low Density Polyethylene
LSM	Laser Scanning Microscopy
MA	Maleic Anhydride
MAP	Modified Atmosphere Packaging
MD	Machine Direction
MFC	Micro Fibrillated Cellulose
OTR	Oxygen Transmission Rate
PE	Polyethylene
PET	Polyethylene Terephthalate
PHBHV	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate)
PP	Polypropylene
PVC	Poly Lactic Acid
RH	Relative Humidity
SEM	Scanning Electron Microscope
WVTR	Water Vapor Transfer Rate

1 INTRODUCTION

Packaging industry is an industry embracing designing, producing, testing and evaluating to commercial operations. Packaging is a bridge between customers and the producers of medicine, food, electrical products, daily products, luxury, engineering products and other industries. Packaging engineering is highly related to mechanical engineering, chemistry and designing.

1.1 Introduction to packaging and food packaging industry

Packaging industry is an industry embracing designing, producing, testing and evaluating to commercial operations. Packaging is a bridge between customers and the producers of medicine, food, electrical products, daily products, luxury, engineering products and other industries. Packaging engineering is highly related to mechanical engineering, chemistry and designing. According to a report of world packaging organization, in 2004, the market value of packaging industry is $485 billion (WPO 2008). According a recent research of Clearwater international, in 2015, the world's packaging volume raised to 3.576 trillion units. The amount is forecasted to increase 12% and thus gain 4.029 trillion units by 2018. In the current market, flexible packaging occupied largest volume (36%); ahead of paper and board 24%; and rigid plastics 20%. The largest packaging markets lies in food (40%), soft drinks (26%) and cigarette (12%). (Clearwater International 2016.)

The protection, transportation and presentation functions of a package are essential for the goods inside. For transportation package, cushion structure such as bubble wrap, plastic and starch-based molded foam are designed to absorb the energy from vibration and shock. Packaging materials are studied to provide suitable properties for the product. Paper, plastic, glass, metal, wood and composite materials are used as raw material for packaging, among which paper, plastic and composite materials weight the most. Composite materials obtained more and more concern on packaging technology to gain multiple and comprehensive effects on the packaging functions. New materials are designed or tried to apply onto packaging industry, to win better results in protect the goods inside.

The three 'R' (Reduce, Reuse and Recycle) catchwords were used as a common rule in sustainable industrial manufacturing. Packaging industry is following this trend aims at a smaller carbon footprint. (Sustainable baby steps 2009.) In recent years, packaging has been concentrating on use relatively less amount material to gain best packaging quality. As less material will reduce material cost, and it will reduce the waste generated after package being used. Packaging machinery and craft can be optimized to reduce the amount of resources used and thereby reduce the amount of waste. This action will not only lighten the burden of the environment, but also reduce the financial coast of the manufactures and consumers. Although methods were taken into practice to call on consumers to save energy, still much waste will be generated. Quite amount of waste can be recycled and reused. Recyclable materials include cardboard, glass, metal, and plastic bottles. Packaging is encouraged to produce reusable products rather than single-use items. Some waste can be recycled after being sort out and after gone through several dispose procedure.

Food packaging industry, as a large sector of packaging industry, has made dramatic improvements in recent decades. The task of a food package is furthest maintaining the characters of the product inside. As food may change its quality by loss of water, the oil inside the food may react the oxidative rancidity, fresh fruit and vegetables may go decay or rot, milk and beverages may spoiled by the connection to oxygen and other medium (Mangaraj, Goswami & Mahajan 2009, p. 133-158). New techniques appeared include: e.g. aseptic packaging, intelligent packaging, vacuum packaging, gas flush packaging and breathable packaging. These formats have been developed to meet the need of protecting the food inside.

Tetra Pak is a major producer of packages for aseptic technique to contented products, packing material and whole packaging processing. The bottles shown in figure 1 are the typical appearance of Tetra-pack package for milk and beverages. These types of packages are the typically used for milk and beverages. This package format represents composite-type approach. The package is composed of many layers including paperboard layer, aluminum foil layer, different plastic layers (component of each layer material is shown in figure 2). The paperboard layer is good for the package to form the shape, and good for printing. The plastic layer makes it easier to prevent water vapor and also provides heat-seal ability. The aluminum foil layers provide an excellent barrier to water, aroma, odor, bacteria and UV light. Other examples of aseptic packages are cans for meat and vegetables. Also in those cases the manufacturing process must be aseptic, and the product must get rid of the bacteria when packed.

Figure 1. Tetra-pack functions at protect milk and juice inside (Eagle 2014).

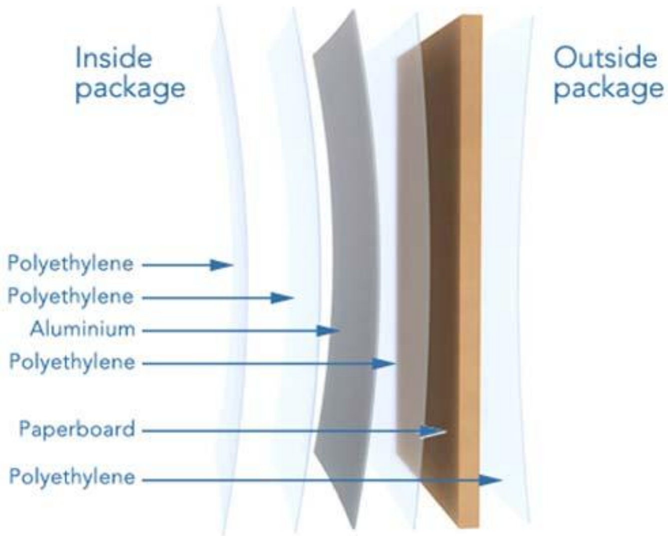


Figure 2. Layer structures of an aseptic beverage package (Tetrapak 2016).

Breathable packaging by perforation technique (shown in figure 3, also called perforation-mediated packaging) can control the level of gases in the package to a certain degree for the sake of extending the shelf life of packed items. Breathable packaging by perforation provides 'air breathing channels' by perforating on the surface of the packaging body. Nowadays, breathable packaging is the most widely used for fresh and fresh-cut food with the packaging form of tray and plastic lid.

Figure 3. Perforation-mediated MAP (Modified Atmosphere Packaging) (Micro laser technology 2016).

1.2 Modified atmosphere packaging technology

The packaging technique of MAP is to modify the atmosphere inside the package, especially for fresh fruit and meat. These packages remain freshness of the product and prolong the shelf life of packed food. Generally MAP refers to the breathable packaging and modified gas flush packaging. Nowadays, breathable packaging is the most widely used for fresh food and fresh-cut food. For the breathable packaging format, perforations were made onto the package to modify the atmosphere inside. The atmosphere in a package can be controlled by modifying the oxygen and carbon dioxide inside to the right amount and being kept in a balanced level, as the respiration of the food inside is a dynamic process.

The MAP for fruit usually gains effect through retarding the respiration rate, browning reaction, softening and decay of fruit. The use rate of MAP package is keep increasing during these years; the MAP technic can achieve a better atmosphere and remain it for longer shelf-life than non-MAP package (McMillin 2008, p. 43-65). As the respiration and permeation of the fresh food are dynamic process happen at the same time (Hussein, Caleb & Opara 2014, p. 7-20). MAP technic has been studied for years on different aspects including temperature, gas composition, packaging film, nature of the product, etc. (Sandhya 2010, p. 381-392).

1.2.1 Fundamentals of MAP Method

In 1927, extremely limited amount of oxygen and suitable amount of CO_2 were combined to be the air atmosphere in the package of fruits thus extending their shelf-life, which is the first usage of MAP technology. This technique expanded to the transportation package of fruits and meat in vessels during 1930s. At the same time, the CO_2 amount in the meat package was improved to adjust the long distance conveying. (Davies 1995, p. 304-320.) During the past years, the MAP technique has grown rapidly on the field of extending the shelf-life of nature product, meat and convenience food. In this field, significant improvements have been made on the breathable package of fresh food.

For better maintenance of the products inside, the O_2 and CO_2 amount and the transmission rate through the material should be studied and thus come out with specific solutions to modify the atmosphere circumstance. The respiration rate of the food should be regarded as the one of the critical factors. When the respiration process absorbs the same amount of oxygen with the amount of came in, and at the same time, the amount of carbon dioxide equals the amount of carbon dioxide came out, the balance could be reached. (Thompson 2003, p. 31-46.)

1.2.2 Water Vapor and Gas permeation theory

Glass and metal packaging materials have quite good barrier function and low permeability. Plastic film and paperboard have different permeability for gas molecules, vapor and aromas and flavor. To study the shelf life and MAP technique for food packaging, it is essential to have the understanding of solution, diffusion and permeation process of these substances transferred through the packaging materials. The permeability is an essential factor of plastic films when choosing the suitable packaging material. The first process of molecules transfer across the film without pinholes or cracks is called diffusion. (Siracusa 2012, p. 1687-2422.) As shown in figure 4, when there are concentration differences between the two surfaces of the material, the molecule dissolves from the higher concentration side and then goes toward the other side under the traction of concentration gradient. The molecule size, shape and solubility will influence the degree of diffusion; the crystalline, molecule chain structure and segmental motion will also influence the diffusion process. According to the research of Kofinas, Cohen & Halasa (1994, p. 1229-1235), gas molecules which are insoluble to crystallites are not able to penetrate through them. When gas molecules are trying to penetrate through semi-crystalline polymers, they can only go through within the amorphous areas. (Kofinas, Cohen & Halasa 1994, p. 1229-1235.)

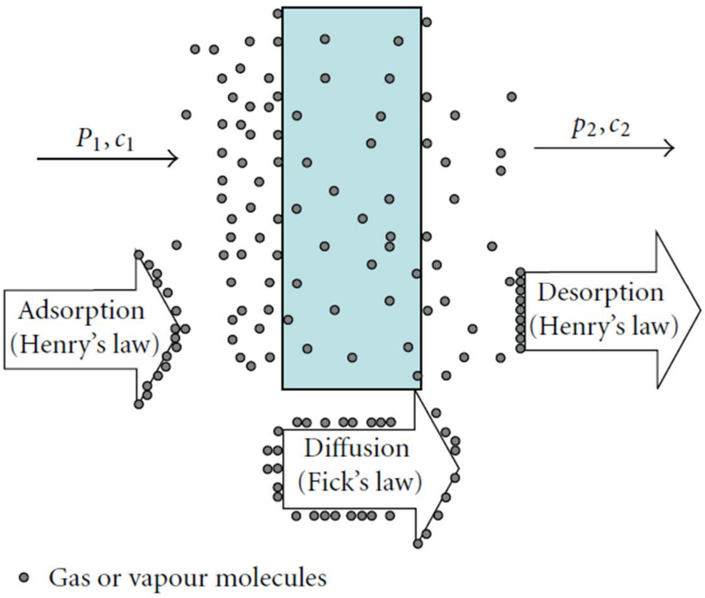


Figure 4. Gas or Vapor permeation through a plastic film (Siracusa 2012, p. 1687-2422).

The permeate flux is represented by Fick's First Law:

$$J = -D \cdot \Delta c \tag{1}$$

When the diffusion is mono-directional through a plastic film, it could be written as:

$$J = -D\,(\Delta c / L) \tag{2}$$

In formula 1 and formula 2, J is the diffusion flux (mol·cm^{-2}·s^{-1}), D is the diffusivity (cm^2/s), Δc is the concentration difference (mol /cm^3), and L is the film thickness (cm). It is only when the penetration happens in mono-direction which is the direction vertical to the film surface that the process can be called diffusion. The polymer category will influence the permeability deeply, but for the same kind of polymer, manufacturing craft will also influence the function of the film. (Siracusa 2012, p. 1687-2422.)

OTR (Oxygen Transmission Rate) is the transmission rate of oxygen molecules through a piece of polymer film. OTR is indicated by the quantity of oxygen molecules that penetrates through a determined area of film in a certain time interval. OTR is heavily influenced by the environment temperature and humidity, as the molecules' activeness and volume are highly influenced by these two factors.

WVTR (Water Vapor Transmission Rate) is the transmission rate of water vapor through a piece of film or material layer. Food packaging requires the package to contain the goods in a suitable humidity environment. When there is humidity difference between the package and the environment, the water vapor will transfer from the high humidity area to the low humidity area under the traction of concentration gradient until a balanced humidity be reached. The water vapor transform properties of films are essential when evaluating their barrier functions to water. Lower WVTR values mean higher barrier function to the humidity variation. Therefore WVTR is a vital index when choosing packaging materials for food packaging industry. Gravimetric devices are able to measure the moisture variation. Some high-accurate instruments are capable of measuring very tiny values. (Froio et al. 2011.)

1.2.3 Research on WVTR and GTR (Gas Transmission Rate)

Mahajan, Rodrigues & Leflaive (2008, p. 555-561) are the first to analyze WVTR with different perforations. The test cup was shown in figure 5. The perforation tube was inserted into the lid film sealing around the top of the cup which contains $CaCl_2$. A piece of metal mesh was placed at the bottom side of the tube, inside the tube placed PVC (Poly Lactic Acid) beads. The weight gain or loss of this system was tested with the variation value of diameter (9, 13 and 17mm), tube length (10, 20 and 30 mm) and storage temperatures (4, 10 and 16 °C). The change of tube length with PVC beads inside is to help gain the result value of different water vapor transfer rate, thus establish the mathematical model. It resulted that as the temperature increases, the WVTR increases. On 7°C condition, the larger diameter samples absorbed more water, the larger tube length samples absorbed less water. Diameter influenced the most on WVTR, followed by length and temperature. (Mahajan, Rodrigues & Leflaive 2008, p. 555-561.)

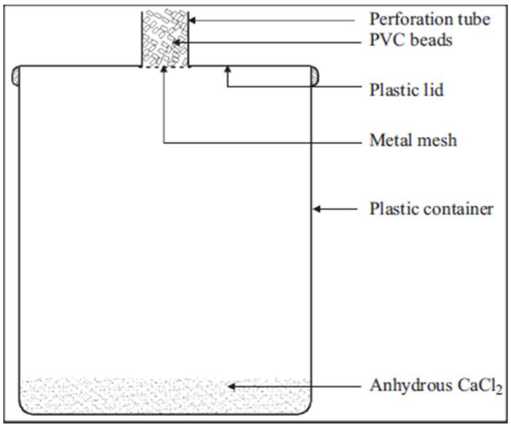


Figure 5. The WVTR testing bottle in Mahajan's research (Mahajan, Rodrigues & Leflaive 2008, p. 555-561).

Lots researchers conducted research on the GTR of the MAP package. Techavises & Hikida (2008, p. 94-104) studied the O_2, CO_2, N_2 and water vapor transmission in perforated MAP with and without produce inside. The permeability of these molecules through the film which thickness is 0.012mm is tested under different temperature (5, 15, 25 °C) and perforation diameter (2, 5, 10, 15mm). In total, the transmission rate of these substances increased as the two factors increased. The O_2, CO_2 and N_2 permeability has no significant difference. The gas concentrations in the LDPE (Low Density Polyethylene) empty packages with 1, 2, 3 perforations was tested separately, and found that the larger perforation area, the more time it need to reach the balanced atmosphere. The gas change situation of the 6, 8 and 10 amount of Tangor fruit package with and without perforations was also tested, and it was found that the more products inside the package, the lower oxygen concentration and higher CO_2 it will gain. (Techavises & Hikida 2008, p. 94-104.)

Numerous researchers have studied the simulation models to present the OTR and WVTR variation dynamic process. In the study of González et al. (2008, p. 194-201), 29 kinds of dimensions (from 40 ×30 μm to 350×110 μm) and thickness (from 29 to 57 μm) of micro-perforated films was tested, a potential equation which can be used when selecting better micro perforation films in MAP method was built.

1.2.4 Essentials of MAP System Design

Paperboard, plastic film, metalized film, can all be used as packaging materials, which could either be used alone or combined together to form a composite material. The designed MAP package could be a single layer or multi-layer plastic bags or metalized, laminated, extrusion-coated, thermoformed trays with peel-able lids either be perforated or non- perforated (Caleb, Opara & Witthuhn 2012, p. 15-30.)

The very essential goal of MAP design is to create an atmosphere with minimizing balancing time to achieve a suitable atmosphere to the product inside for longer time (Mahajan, et al. 2007, p. 84-92). Studying the factors of the inherent characteristics of the packaged product (the most suitable O_2 and CO_2 concentrations and respiration rate) is essential to design an appropriate MAP system. The steps to select packaging materials for the aiming product are the comparing of the inherent attributes of the material, the equilibrium time with product inside, and the balance gas composition with product inside. (Mangaraj, Goswami & Mahajan 2009, p. 133-158.) The unsuccessful designed MAP systems may simulate the spoilage of a product, on condition that O_2 concentration is too high or too low, or if the equilibrium time is too long (Mahajan, Rodrigues & Leflaive 2008, p. 555-561).

1.2.5 MAP Packaging Film

There are many species of polymers films available to apply onto packaging industry. Mostly, the MAP is designed on the plastic films; polypropylene (PP), polyethylene (PE) and polyethylene terephthalate (PET) are the most common used polymers for food packaging industry. The transparency, barrier functions, melting point, sealing characteristics, odor and flavor barrier function, chemical resistance, high temperature performance, need to be considered when choosing suitable materials for a certain product. (Mangaraj et al. 2009, p. 133-158.) Table 1 shows the benefit properties and drawbacks of several typical plastics when used as MAP materials.

Table 1. Comparison of plastic films in food packaging (mod. Kirwan, Plant & Strawbridge 2011, p. 157-212; Blakistone 1999, p. 240-290; Mullan & Mcdowell 2011, p. 263-294).

Polymeric film	MAP use suitability	
	Benefit properties	Drawbacks
Polyvinylidene chloride (PVdC)	Good heat sealabilty that provide peelable feature of MAP Excellent gas, dour and water barrier properties Good resistance to oil, grease and organic solvents Excellent heat sealabilty (able to seal to itself and to other materials)	High barrier to water vapour and gases limit is use for MAP of high respiring produce
Linear low density polyethylene (LLDPE)	Good sealing quality, and therefore its application on the sealing face allows a peelable seal to be made Used as a sealant layer on base trays and lidding films	
Polyvinyl alcohol (PVOH)	Good barrier properties against WV and oxygen (when used properly). It can be copolymerised with ethylene to produce EVOH with improved WV permeability	Barrier properties are moisture-dependent
Bi-axially oriented polypropylene (BOPP)	Rigid and hard plastic material. Being bi-axially oriented, it has improved tensile strength and hence useful as a base tray. Good barrier to water vapour and gases	Higher barrier water vapour limits its suitability to MAP of some fresh produce
Polyamide	Good barrier to gas, flavour, odour loss. High resistance to stress cracking and puncture High water vapour permeability	Not suitable for MAP of high respiring produce Tends to absorb moisture from their environment
Ethyl vinyl alcohol (EVOH)	Excellent barrier to oxygen thus used as a gas barrier layer in MAP applications Barrier to the absorption and permeation of oil, fat and sensitive aromas and flavour Good processing properties	Less sensitive to the presence of moisture Not suitable for MAP of high respiring produce
Polystyrene (PS)	Stiff and brittle material with high gas permeability Foamed PS used as structural layer for preformed MAP base tray applications	Cannot be used alone in MAP application due to high gas permeability, unless combined with EVOH
Polyvinyl chloride (PVC)	Has low softening temperature, good processing properties, thus suitable material for producing thermoformed packaging structures. Excellent oil and grease resistance Common structural material in MAP thermoformed base trays	Unplasticised PVC has moderate gas and water vapour barrier properties, thus not suitable as film for MAP of high respiring produce
Ethylene Vinyl acetate (EVA	Excellent heat-sealing properties Useful as heat seal layer in some MAP applications	
High Density Polyethylene (HDPE)	Tough and stiff material Commonly used for rigid and semi-rigid structures	

There are several factors relevant to the atmosphere, among which the packaging material and the respiration rates are quite essential. Thus it is important to choose the packaging material to be the basis of modified packaging. Sahoo, Bal & Pal (2014, p. 164-170) chose LDPE and PP to conduct a research, to study the shelf life enhancement of bell pepper in MAP packages. Different MAP packages were: LDPE bags, PP bags, perforated LDPE bags and perforated PP bags were used under different storing condition. Among these matched groups, MAP in PP bags in cold storage condition was the best. (Sahoo, Bal & Pal 2014, p. 164-170.)

Bio-based materials can also be used as food packaging material, as it can be recycled and biodegradable. Therefore, it is beneficial to the sustainability of the environment. Aulin, Gällstedt & Lindström (2010, p. 559-574) studied the oxygen and oil permeability of MFC

(Micro Fibrillated Cellulose), which has the possibility to be used as packaging material. Experiments were taken under different RH (Relative Humidity). Resulted that the OTR of the film is very small in low RH, but it increases as the RH increase. The film has great oil barrier properties. The research also tested coating MFC on paperboard. The MFC coating can increase the barrier properties of the paperboard dramatically. The oxygen permeability was lower than that of plasticized starch. (Aulin, Gällstedt & Lindström 2010, p. 559-574.)

1.2.6 Products Protection

After a modified atmosphere system being designed, researchers need to do experiments on testing applying the package onto real products. Manufactures also need the testing data to prove the freshness of their products. So far many researches have been done on MAP applying on exact products, especially fresh fruit and vegetables.

Mushroom is a familiar vegetable in daily life. After being picked, during transportation and displaying on the shelf, the package should keep its quality and prolong its shelf life. Dhalsamant et al. (2015, p. 41-50) studied MAP method for paddy straw mushroom. In normal conditions, the shelf-life of fresh mushroom is usually 1 to 2 days. However, perforation-mediate MAP method made it possible to store the mushrooms for as long as 6 days. The study compared the perforated and un-perforated, treated and untreated MAP samples. The perforated package samples have the least PLW (Physiological Loss in Weight). On the other hand, the differences between the results of treated and untreated products were not so obvious. Oliveira et al. (2011, p. 507-514) conducted a research on the most suitable MAP design for sliced mushrooms, and found that 2 perforations on the package storing at 10°C environment for 3 days could gain a balanced gas composition and the quality of mushrooms was maintained the best.

Berry could grow all over the world. It is one of the most critical fruits in keeping fresh, since its surface is so brittle that is easily broken by the impact of external forces. In addition, once the skin of a berry is broken, bacteria and fungus will grow on it, absorb the nutrient from the berry, and produce pollutions on it. Adobatia et al. (2015, p. 337-342) studied the influence of passive and active MAP on the storage of red raspberries. The berries were put inside the PET trays; these trays were micro-perforated and placed into a master bag. The bag was different in O_2 and CO_2 transmission rate. In active packaging matched group, berries were also put inside the cardboard crate, and placed into a LDPE master bag. In this case, CO_2 emitters were also placed into the bag. The samples were stored in relatively cold and humid conditions (5°C, 70 %RH). Chemical, mechanical and sensory tests were taken. It was found out that both active and passive MAP packaging can significantly extend the storage time of berries. (Adobatia et al. 2015, p. 337-342.)

Jouki & Khazaei (2012, p. 131-140) have taken a study on MAP technique and $CaCl_2$ dipping method on strawberries storage in comparison with the ordinary packaging. Experimental variables were set with 0.5% $CaCl_2$ for 5 min, then stored in 2 atmospheres 5% CO_2 : 10% O_2 : 85% N_2 and 10 % CO_2 : 5% O_2 : 85% N_2 and 4°C. The weight loss, sugar concentrations, fruit firmness, pH and total titratable acidity, fungal decay, firmness, color and sensory quality of strawberries were compared. It was found that MAP kept strawberries changed the least at the weight and appearance, which is superior to the samples packed in the air. $CaCl_2$ dipped strawberries made less change on firmness. The combination of MAP and $CaCl_2$ dipping method stored at 4 °C could extend the shelf life of strawberries to 3 weeks. (Jouki & Khazaei 2012, p. 131-140.) Olías et al. (2000, p. 33-38) studied packaging with different plastic films: LDPE, PVC and PP films, both perforated and non-perforated samples were tested. Evaluation indicators were set as fruit firmness, weight loss, desiccation and decay.

Grapes become also easily rotten. In addition, consumers would prefer to choose grapes which are fresher and have better appearance. Thus study the MAP for grapes is essential. Artés-Hernándeza, Tomás-Barberánb & Artésa (2006, p. 146-154) studied the fresh keeping of superior seedless table grapes with MAP technique with micro-perforation. Grapes were place into micro-perforated and oriented PP films and it was found that the perforation-mediate MAP kept the overall quality of grapes at most.

1.3 Perforation technology

A perforation is a hole made onto the raw material which could be paper or board, plastic film and metal. Electrostatic discharge, pins and needles, dies and laser perforation are most common ways to do perforation.

1.3.1 Introduction to perforation technology

ESD (Electrostatic Discharge) is the charge transfer caused by two objects which have different electrostatic potential getting close or having contact. Sometimes a visible spark could be resulted in. ESD could produce relatively smaller micro-perforations. (Allan-Wojtas et al. 2008, p. 217-229.) This theory could be applied on perforation of electrically non-conductive, thin packaging films. However, the process is so ineffective that is not suitable for perforating large amount of holes (Benedek 2005, p. 110-160).

Pins and needles could be used to do perforating; mostly they are rotating when working to gain the evenness of the hole and the perforating efficiency. The raw material of pins and needles could be plastic, steel and aluminum. Both cold and hot needles are used in manufacturing. Cold perforation may cause the unevenness of the perforate holes, especially when working on more brittle materials. This could have negative effect on the mechanical properties of the material. Nevertheless, hot needles could melt the material when working, thus can cause a more even hole. Hot needle could also improve the efficiency of the work. (Chow 2015, p. 27-31.)

Dies are usually used to make larger holes; the raw materials are more metal working pieces. Dies are working with punches, the punches pressing the raw materials into the dies. The small piece being pressed will be separated with the raw material under the punching pressure. The distance between the die and the punch will influence the evenness of the perforated hole. (Kudla 2003, p. 1581-1587.)

Laser micro-perforation can make smaller holes and even micro-holes on the raw material. When laser beam is focused on the film, part of the energy from the radiated laser light is absorbed by the material, and this energy is enough to melt the film and cause the vaporization of the material and to form a hole. (Robertson 2006, p. 1-550.) The appearance of the laser perforated holes look similar to the hot needles perforated holes. The superiority of laser perforation to other perforation method is the uniform size of the holes. (González et al. 2008, p. 194-201.) When the technology applies on packaging materials for modified atmosphere packaging, the evenness of the hole size is important to evaluate (Winotapun et al. 2015, p. 367-383).

1.3.2 Application of laser perforation on packaging materials

There are three essential elements to form a laser perforation system: a power source that generates laser beam, a medium that radiates laser light, an optical cavity that compress the laser beam to stimulate the emitting of laser radiation (Hussein, Caleb & Opara 2015, p. 7-20). In order to provide suitable WVTR and OTR, especially in applications with modified atmosphere packaging, packaging materials are perforated with holes or micro-holes.

In 1990's the laser drilling technique applied its usage onto paper industry for various perforating and engraving crafts. Laser equipment were relatively expensive than other perforating machinery. In recent years, with the development of laser technology, the price of the laser equipment went down. Therefore, the laser perforating on paper materials have become widely used. (Stepanova, Saukkonen & Piili 2015, p. 138-146.) Paper and board can be perforated by laser equipment accurately and rapidly. Laser perforation made it possible to make relatively even holes. For normal perforation technologies, the damage on fibers and the unevenness of the holes will reduce the mechanical properties of the material. With laser perforation, less reduce of mechanical properties may achieved. (Mommsen & Stürmer 1990, p. 10-14.) The laser perforation will also lead to the discoloration of the paper or paperboard material. The perforated hole gain brown color because of the raise of temperature when laser acting (Stepanova, Saukkonen & Piili 2015, p. 138-146).

Davison and Faskas (Pat. US 0123418 2002, p. 1-8) studied the laser perforation size. In this research, the minimum micro-perforated hole's diameter was 0.025 mm, and the hole size was proved to increase as the laser power increases. Both round perforation and rectangular perforations were studied in this research. Usually, for perforating on polymer films, CO_2 laser equipment was used and operates at the standard speed about 3000 per minute. When exceeded this speed, the consistency of the perforations could not be proved because the perforation might be done partly, and some perforation may be left out. For the laser perforation power, the power source has made its improvement from 20W to 2kW. For the techniques, the beam compression is superior to the previous split beam, plus the polygon mirror, could strongly enhance the uniformity of the perforations. Although the laser perforation equipment and techniques for plastic films both made dramatic improvement, but in the current state, manufactures considers a lot on the production cost. To fully apply laser technique onto packaging materials, further research need to be done to come out more packaging solutions. (Hussein, Caleb & Opara 2015, p. 7-20.)

1.3.3 Laser perforation on paper and paperboard materials

As shown in figure 6, when the resonator generates laser beam, the focused area on the paper material will burned and evaporate, the evaporated paper material vapor will come out from both sides of the paper material.

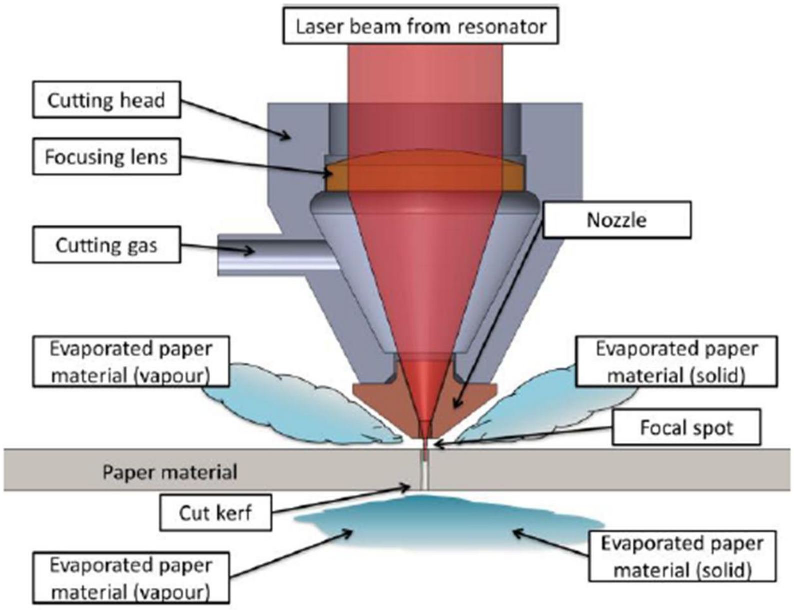


Figure 6. Laser perforating on paper material (Stepanova, Saukkonen & Piili 2015, p. 138-146).

1.3.4 Laser perforation on films

Laser perforation has become a widely used technology in recent years. There are many companies specialized at manufacturing perforated films. Perforation techniques were used in these companies to seek new applications on fresh fruit and vegetables packaging. Perforation on plastic film packaging materials could provide and maintain the positive aspects of the package, the barrier to water loss, moisture, odor, UV light and bacteria, and the seal ability of the films. While the small amount of gas and moisture exchange from the holes could support the respiration reaction of the fresh food inside, consequently delay the decay of the food. (Allan-Wojtas et al. 2008, p. 217-229.) Perforation-mediated MAP made it possible to better maintain of food which is sensitive to the variations of gas proportion.

Geesan et al. (2007, p. 333-347) conducted a research on MAP for Bramley apples, in which simulation method were used to test the shelf life of the product. The micro-perforated LDPE films were proved to be effective to extend the market period of the apples. In the research of Serrano et al. (2006, p. 61-68), micro perforated and non-perforated PP films were formed into MAP packaging and stored at different atmosphere to test the storage of broccoli. The properties changes of the broccolis inside were measured. Found that the perforated films could significantly reduce the weight loss. (Serrano et al. 2006, p. 61-68.)

The main theory of the laser beam affecting the plastic film is that the heat energy from the laser beam makes the area evaporate. For different plastic films, the plastic may be completely evaporated or partly evaporated and part may redeposit around the surface of the perforation (Lazare & Tokarev 2004, p. 221-231). The heat of gasification value could show the burning rates of a material, and to help indicate the danger coefficient of a specific material get in fire. But, the values of this property of polymers are not statistically analyzed (Stoliarov & Walters 2007, p. 135-152).

1.3.5 Appearance of micro-perforations

In the studies on micro-perforations, several researches posted the images of micro-perforated holes. From which the typical appearance of the perforated holes could be seen. In the research of Ellis et al. (2011, p. 2379-2388), the film studied was PHBHV (poly 3-hydroxybutyrate-co-3-hydroxyvalerate) substrate. As shown in figure 7, picture on the left (a) shows the two sides of cell attachment of this film after micro-perforation after four hours, which was taken by relatively lower magnification microscope. Image on the right shows the two sides of cell proliferation five days later, which was taken by SEM (Scanning Electron Microscope) and the scale ruler shows 50µm.

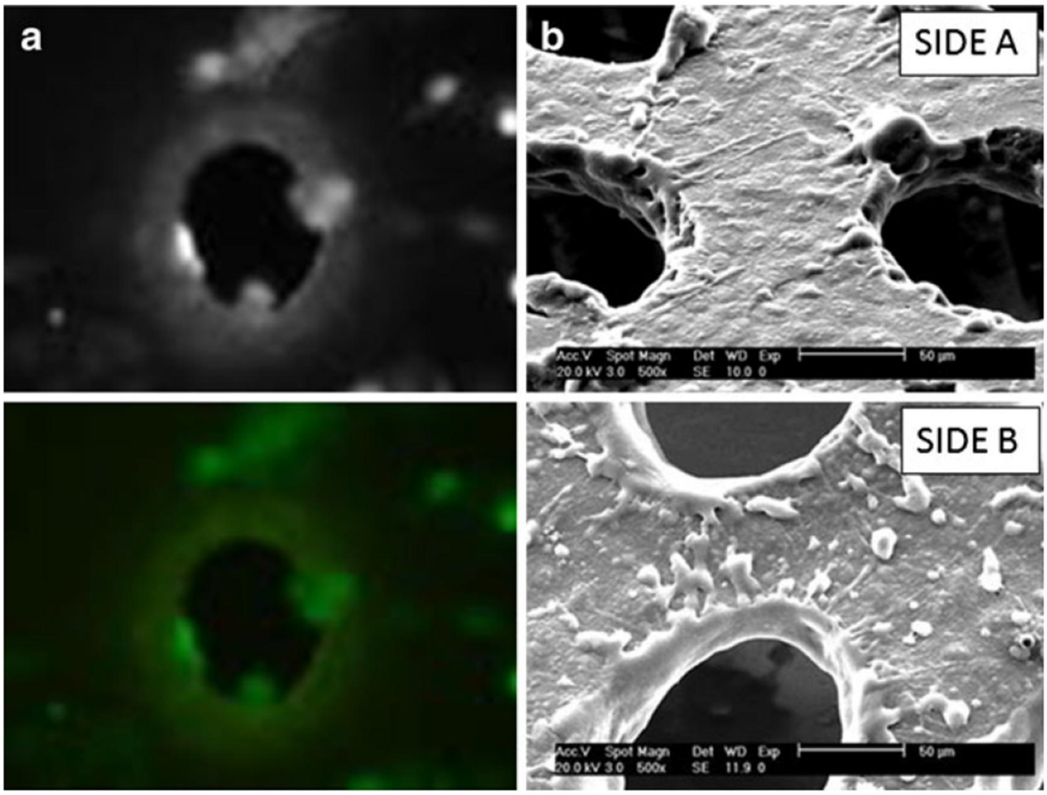


Figure 7. Optical microscopic photographs (a) and scanning electron microscope photographs (b) of perforations on PHBHV substrate film (Ellis et al. 2011, p. 2379-2388).

In the research of Larsen and Liland, the images of laser micro-perforated holes were given. In figure 8, the figure (a) shows a laser micro-perforation on BOPP (Biaxially-oriented Polypropylene) plastic film, the figure (b) shows a laser micro-perforation on PET film, while the figure (c) shows the mechanical perforation on PET film. (Larsen & Liland 2013, p. 271-276.) It is obvious to see that the mechanical perforation on PET film even do not have a round shape, the diameter is not uniform. In comparison, the laser perforation on PET film is much more even and has a clearer round shape. This reflect that laser perforation has more even and consistency than mechanical perforations. A round circle formed around the PET film perforation. A few bubbles could be seen around the PET perforated hole, while fewer bubbles were found around the BOPP perforations.

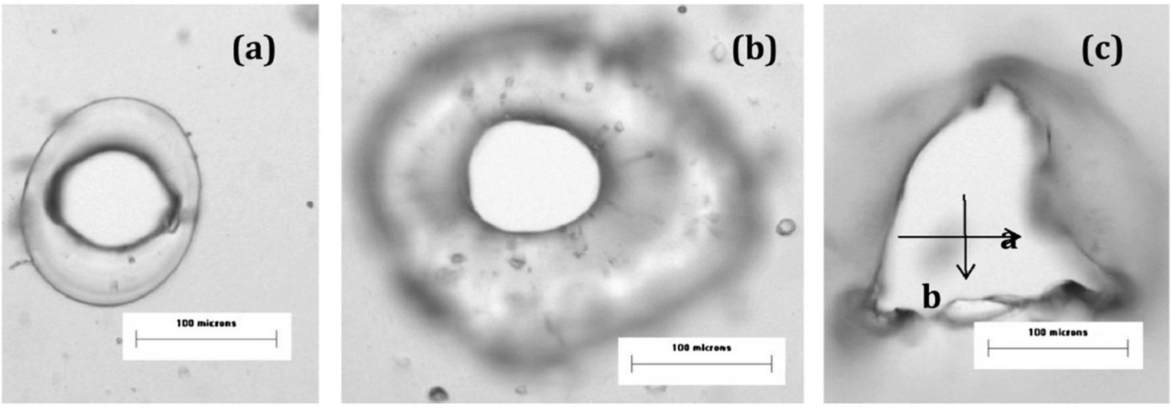


Figure 8. Pictures of different perforations (Larsen & Liland 2013, p. 271-276).

Also in that research of Larsen and Liland, the oxygen and carbon dioxide transmission rate of MAP made by these three materials were measured. The result was shown in table 2. It can be seen that the three films, with the increase of perforations, the OTR (ml.d^{-1}) and CO_2TR (CO_2 Transmission Rate) (ml.d^{-1}) were obviously increased. The perforation can dramatically change the Ratio of CO_2TR/ OTR in the package. The OTR of one mechanical perforation on PET film is similar to the OTR of 3 laser perforations on PET film.

Table 2. O_2 and CO_2 transmission of different testing packages in the research of Larsen& Liland (Larsen & Liland 2013, p. 271-276).

Package	Perforations	Temperature	OTR/pkg (mL d^{-1})	CO_2TR/pkg (mL d^{-1})	Ratio CO_2TR/OTR	OTR/perf. (mL d^{-1})	CO_2TR/perf. (mL d^{-1})	Ratio CO_2TR/OTR/perf.
Mech-PET	1	4	284 ± 20	257 ± 34	0.9	279 ± 19	242 ± 33	0.9
Micro-PET	0	5	5 ± 1	15 ± 3	3.1			
	1	5	103 ± 5	108 ± 5	1.0	98 ± 5	92 ± 5	0.9
	2	5	185 ± 20	172 ± 13	0.9	90 ± 10	78 ± 7	0.9
	3	5	274 ± 17	241 ± 15	0.9	90 ± 6	75 ± 5	0.8
	4	5	366 ± 27	322 ± 26	0.9	90 ± 7	77 ± 7	0.8
Micro-PET	0	10	5 ± 1	19 ± 4	3.7			
	1	10	134 ± 18	124 ± 13	0.9	129 ± 18	105 ± 13	0.8
	2	10	193 ± 7	171 ± 3	0.9	94 ± 4	76 ± 2	0.8
	3	10	279 ± 8	251 ± 7	0.9	91 ± 3	77 ± 2	0.8
	4	10	368 ± 12	329 ± 8	0.9	91 ± 3	77 ± 2	0.9
Micro-PET	0	23	10 ± 1	41 ± 4	4.3			
	1	23	131 ± 22	137 ± 6	1.0	121 ± 22	96 ± 6	0.8
	2	23	224 ± 25	218 ± 28	1.0	107 ± 12	89 ± 14	0.8
	3	23	309 ± 14	295 ± 17	1.0	100 ± 5	85 ± 6	0.8
	4	23	374 ± 21	354 ± 18	0.9	91 ± 5	78 ± 5	0.9
Micro-BOPP	0	4	155 ± 39	267 ± 86	1.7			
	6 or 7	4	745 ± 51	693 ± 84	0.9	88 ±5	63 ± 13	0.7
	11	4	1083 ± 68	1013 ± 22	0.9	84 ± 6	68 ± 2	0.8
	14 or 15	4	1434 ± 137	1229 ± 145	0.9	88 ±6	66 ± 8	0.8

In the research of Allan-Wojtas et al. (2008, p. 217-229), micrographs were captured by LV-SEM (Low-Vacuum Scanning Electron Microscopy). The images in figure 9 are mechanical perforations on polyester film with different areas, from figure (a) to figure (g), the perforation area increases. The proportion bar is 50mm. The O_2 and CO_2 transmission rates of these perforations were tested, and are of obvious differences. (Allan-Wojtas et al. 2008, p. 217-229.)

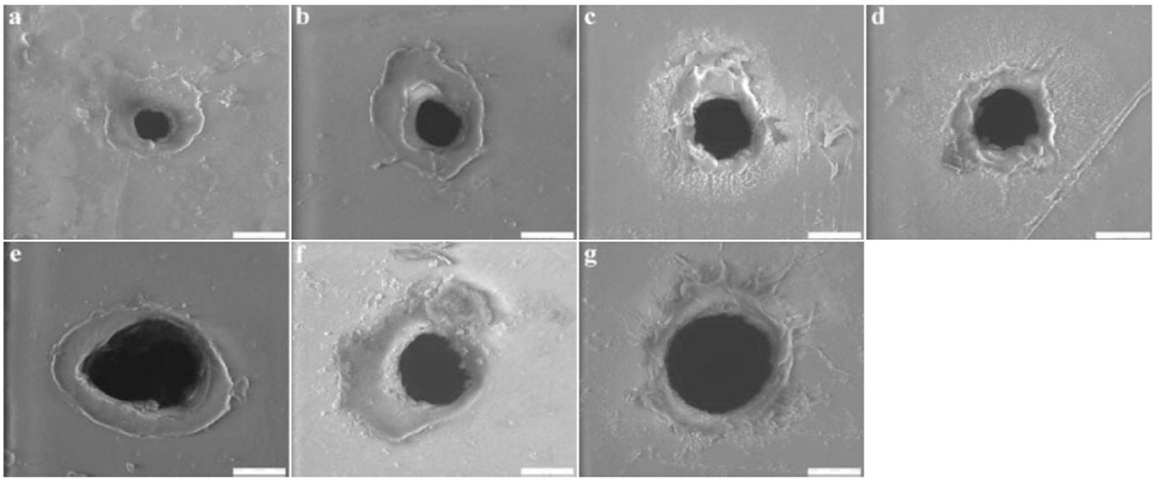


Figure 9. Surfaces of mechanically produced perforations. Bar = 50 mm Images. (Allan-Wojtas et al. 2008, p. 217-229.)

1.4 Introduction to tray packaging

Tray packaging has become a common method for packaging fruit, vegetable, ready -to - eat food, oven use food and cold chain food packaging. In allusion to the specialties of the food inside, shape and materials are designed to form a suitable tray.

1.4.1 Trays made by plastic and metal

Tray packaging for food has been growing promisingly. Plastics, metal and metalized film, fiber-based or starch-based material, paperboard and composite paperboard materials, all could form a packaging tray. The tray body can be pure plastics or paper based composite, lid material is normally plastics as shown in figure 10. The tray body is rigid enough to protect the product from a certain degree of mechanical shock, could make the package stable to place stock, and transport, could support the package to endure the pressure from upper package when stocking. The tray packages could also make the product easy to use than plastic bag packages. The lidding film help the tray to become a relatively sealed space, thus be a barrier to protect the product from gas, vapor, odor and sometimes UV light. The metalized film formed trays have high barriers especially to lights. But it usually laminated with plastics as the metalized film has bad seal ability.

Figure 10. Typical tray containers (Greener Package 2014).

These years, many researches have studied MAP tray systems. For MAP fresh food tray packaging, most fruit and vegetables are packaged in high barrier property trays sealed with a perforated lid film. Several films with high OTR are studied to use as lidding films of the MAP tray packaging, but those films usually have poor seal abilities with the trays (Mangaraj et al. 2009, p. 133-158).

1.4.2 Trays made by composite paperboard material

As shown in figure 11, this kind of package which conventionally contains an extrusion coated tray and the sealed lidding film are now widely used in fresh food packaging technology in Europe, for packaging of fresh food and meat, frozen food and food to be heated in an oven. Typically the tray is a piece of paperboard extrusion-coated with a thin plastic film which is quite effective on preventing gas and moisture transportation. The most common coating polymers are PE and PET. The coated materials can be used as a substrate in tray manufacturing process.

Figure 11. Typical usage of the trays made by composite material (Delight 2016).

Extrusion Coating

The use of multilayer films can achieve higher material properties as it uses several layers of different material and gain multi-function from different properties of material. Plastic films are often gathered with other kind of packaging materials i.e. paper and aluminum. The material can be coated, laminated or metalized.

Extrusion coating is the coating method of which a high temperature melted web of polymer directly coating onto the surface of a moving roller of base material, usually a pressing rubber roller was added to make the surface even, after that the polymer coating was cooled and consolidated. It is a very economical and effective way to improve the surface properties of paperboard. The base material could also be aluminum foils, plastic films, and bio-base materials. The ratio of the running speed of the base material roller and the polymer resin will determine the coating thickness of the polymers. (Wolf & Sparavigna 2010.)

Corona treatment is a high frequency electricity discharge under high electric pressure that increases the adhesion of a plastic surface. Corona discharge is proved effective for strengthen the adhesion of substrates on extrusion coating and to reinforce the print ability of the materials as it increase the wettability of polar molecules. This treatment will not reduce the mechanical properties of the material as it only acts the top surface of the polymers, which is 0.00001 micron thick. (Wolf & Sparavigna 2010.)

1.5 Content and Aim of the study

In recent years, paper-based trays are going to be popularly used in the supermarket for food packaging. MAP technique is used in the tray packaging to control the gas composition and humidity inside the tray to keep the goods inside fresh and to obtain a longer shelf-life. Much research has been done on perforation on the lidding film (described in chapter 1.3.3) of the fresh food tray packaging. With the technology development, bio-based films have been applied to lid for tray package, but certain problems are occurring. First, on the condition that the lidding film is made of biopolymers, laser perforation may harm its mechanical properties strongly. Below are two researches to prove this point.

Figure 12 is made from a research of Zamirian (2013, p. 685-690), which studied the Young’s modulus of LDPE and LDPE and MA (Maleic Anhydride) nano-composites. From the figure, it can be seen that the E modulus of 0% Clay composite LDPE film is around 50 MPa. Table 3 is made from a research of Suyatma et al. (2004, p. 1-6), which studied the mechanical properties of Chitosan and PLA blend. From table 3 it can be seen that the 0% Chit composite PLA film is 384Mpa. The bio-based PLA film (higher Young’s modulus) is stiffer and thus brittle than the LDPE film (lower Young’s modulus).

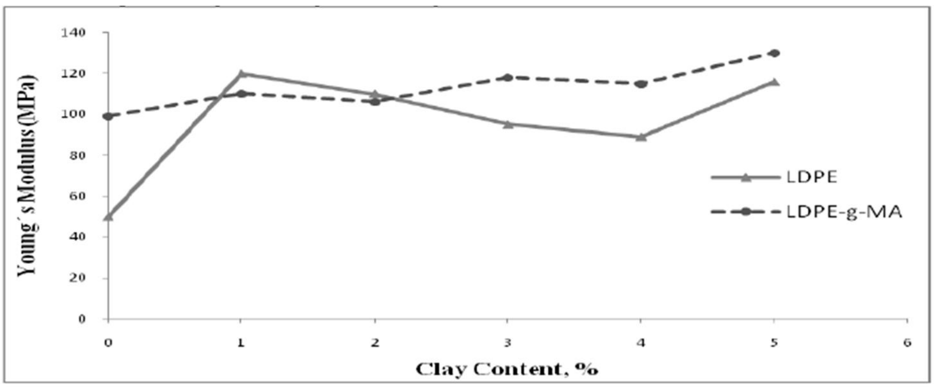


Figure 12. Young's modulus of LDPE and LDPE-g-MA nano-composites (Zamirian 2013, p. 685-690).

Table 3. Mechanical properties of Chitosan. TS, tensile strength; EB, elongation at break; Chit, chitosan. (Standard deviations are given in bracket). (Mod. Suyatma et al. 2004, p. 1-6.)

Composition	TS (MPa)	EB (%)	Young's modulus (MPa)
Chit/PLA: 100/0	82.4 (8.5)	5.2 (0.9)	534 (44)
Chit/PLA: 90/10	72.7 (1.8)	4.9 (0.5)	470 (20)
Chit/PLA: 80/20	64.4 (5.1)	4.2 (0.9)	433 (35)
Chit/PLA: 70/30	54.5 (2.9)	4.1 (0.5)	406 (51)
Chit/PLA: 0/100	52.5 (5.9)	3.6 (0.5)	384 (35)

Second, during stocking process, the trays are stocked together. The upper tray is placed on the lidding film of the lower tray, the gas and water transformation from the perforated holes thus be prevented. This project aims to study the perforation on the tray container part which is composite material based on paperboard. This research is aimed to seek a new approach: the paperboard tray with a plastic coating is perforated and the lidding film will be used without a perforation.

If perforated paperboard will be used instead of un-perforated one, the strength of the paperboard with perforations needs to be verified by research. As paperboard with plastic coating is converted into a tray with four round corners, strength of the tray is related to some factors such as properties of paperboard, properties of plastic coating, converting influence and structure of the tray. Among the factors, strength of the paperboard with and without coating will have primary effect; dimension of the tray and its shape will also have impact. Above the factors, perforation on the board is an external influence to the strength of the tray. Since the plastic coating has some influence on the paperboard, it is important to test the effect of perforation on the strength of uncoated paperboard.

The starting point of this project is to study the laser perforation on composite paperboard as the tensile strength is such an essential mechanical property for package. The general aim of this research was to study the influence of perforation pattern types on the variation of tensile strength with un-coated paperboard and paperboards coated with PE and PET polymer. Firstly, the research questions were determined. The first question was related to the perforation patterns: are there certain designs that impair the strength properties of paperboard more than the other type of patterns. The second question was related to the reliability of perforation techniques, i.e. whether the diameter and the shape of perforations is uniform.

For the research methodologies, four aspects were taken into consideration:

- Mechanical properties: The mechanical properties of the samples should be tested in order to compare the influence of pattern type. Of the mechanical properties, tensile strength is one of the most essential one for paperboard based materials.
- Realization of micro-perforation: Laser micro-perforation should be done to test the reliability of perforation, the micro-holes coming out should be observed carefully.
- The perforation on packaging material will influence the water vapor transmission rate of the package system. Thus the WVTR test should take place to test the water absorption condition of the samples.
- Function of the perforation on packaged items will not be studied in this thesis project. However, the water vapor transmission rate of the laser-perforated boards was measured, as it is one of the key properties of the perforated material and a critical indicator of the applicability of the perforated material.

2 MATERIALS AND METHODS

Based on the considerations described above, to study the influence of different ways of perforation on the physical properties of fiber based materials, the research materials and methods in this project were settled.

2.1 Materials and samples

The materials chosen in this research are uncoated, PE polymer coated and PET polymer coated paperboard. The materials are prepared into samples with designed shapes and the perforating was done after that.

2.1.1 Testing samples

Types of materials and samples used in this study are listed in table 4. All samples tested in the experiment were 240 g/m^2 paperboard made from bleached kraft pulp. Uncoated samples with 250µm thickness is processed with pigments on one side (side 2) of paperboard of 240 g/m^2; PE coated samples use the same kind of paperboard by applying extrusion coating of 20 g/m^2 PE plastic to side 1 of the board to form its thickness around 262 µm, and by extrusion coating of 35 g/m^2 PET plastic to side 1 of the board to make thickness around 267 µm PET coated samples.

Table 4. Samples and their specifications.

			side 1		side 2	
Sample names	Thickness around	Paperboard base	Coating Material	Coating Gram mage	Coating Material	Coating Thickness
	(µm)	Grammage (g/m^2)		(g/m^2)		
Uncoated	250	240	non	0	Pigment	very thin
PE coated	262	240	PE	20	Pigment	very thin
PET coated	267	240	PET	35	Pigment	very thin

2.1.2 Preparation of Testing Samples

The chosen coated and uncoated paperboard materials were prepared into samples for different sample shapes and different perforation patterns on them. Both manual perforation and laser perforations were used in this research.

Shape of testing samples

For tensile properties testing, the paperboard was first cut into 160mm*160mm square by a manual cutting machine. After their exact thickness was measured, they were precisely cut into 160 mm in length and 15mm in width by the cutting machine. During tensile strength testing, the effective area of 100 mm*15 mm rectangle was shown as the shadow area on figure 13. The samples of the paperboard were grouped into MD (Machine Direction) and CD (Cross Direction) and marked for tensile strength tests. For WVTR tests, the samples were cut in to 50mm*50mm squares. The samples were also prepared for making perforation on them with different patterns.

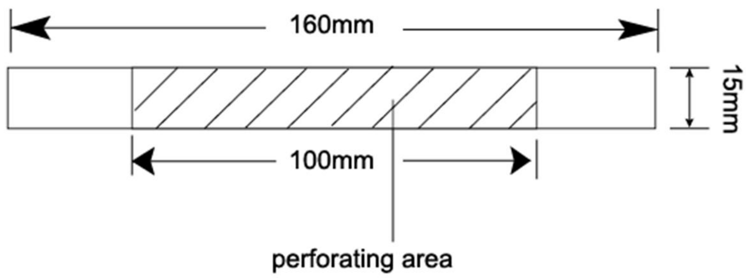


Figure 13. Schematic view of perforating area on the paperboard.

Design of perforation patterns on samples

Samples with perforations were prepared to test their mechanical strength on tensile in two directions. The tests will verify the descent in mechanical strength because of the perforation. To better illustrate the perforation on different samples, definition of horizontal and vertical direction along stripe of samples is shown in figure 14. For better understanding of perforation location, density and influence to mechanical properties, samples of different patterns were designed and prepared for testing.

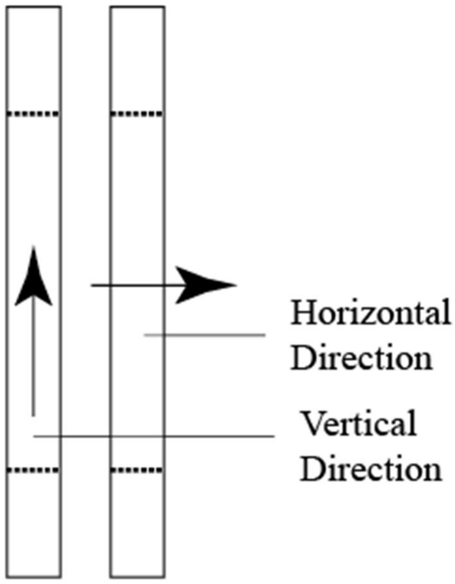


Figure 14. Schematic map of the horizontal and vertical direction of test samples along the stripes.

Uncoated, PET coated and PE coated samples of paperboard were prepared according to the perforation of different sample types. The perforation method, perforation pattern and sample grouping information are shown in table 5 below.

Table 5. Sample types and their labels.

Testing Type	Perforation Method	Perforation Specifies	paperboard and group amounts	Samples in each group
Tensile tests	manual	0-8 perforations in horizontal direction	Uncoated (9), coded U0 to U8 PET coated(9), coded H0 to H8	10MD 10CD
		25 patterns	PET coated (25), coded T1 to T25	10MD 10CD
	by laser	2,4,6 and 8 perforations in vertical direction	Uncoated (4), coded LN2,LN4,LN6,LN8 PET coated(4), coded L2,L4,L6,L8 PE coated (4), coded L2’,L4’,L6’,L8’	10MD
WVTR tests	non	non-perforated	Uncoated (3), coded WN1,WN2,WN3 PE coated (3), coded W1,W2,W3 PET coated (3), coded W1’,W2’,W3’	3
	by laser	4 perforations on each sample	Uncoated (3), coded WN4,WN5,WN6 PE coated (3), coded W4,W5,W6 PET coated (3), coded W4’,W5’,W6’	3

0 to 8 perforations along the horizontal directions of the samples were prepared (schematic view show in figure 15).

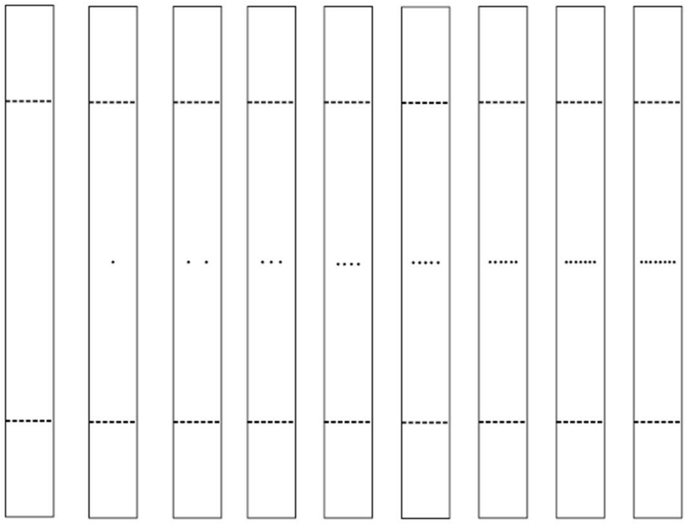


Figure 15. Schematic view of 0-8 manual perforation holes on horizontal direction.

25 different types of perforating patterns were designed on a stripe of paperboard for the testing (patterns are shown as figure 16). The perforation number on each stripe was 8. Among these 25 patterns, for each pattern, there are 4 to 8 rows of holes along the sample's vertical direction and less than 4 perforation rows along horizontal direction. During the testing process, the pattern types were coded from T1 to T25. Sample without perforation for comparison purpose is coded as H0. In the Master's thesis of Genesis (2015, p.1-80), it is found that the perforation density of 4000 holes per square meter is suitable for his study. In this research, according to previous study of perforation on paperboard, distribution of perforations was decided to be 5333 perforations per square meter. Thus 8 holes were perforated on each 15mm*100mm diameter samples.

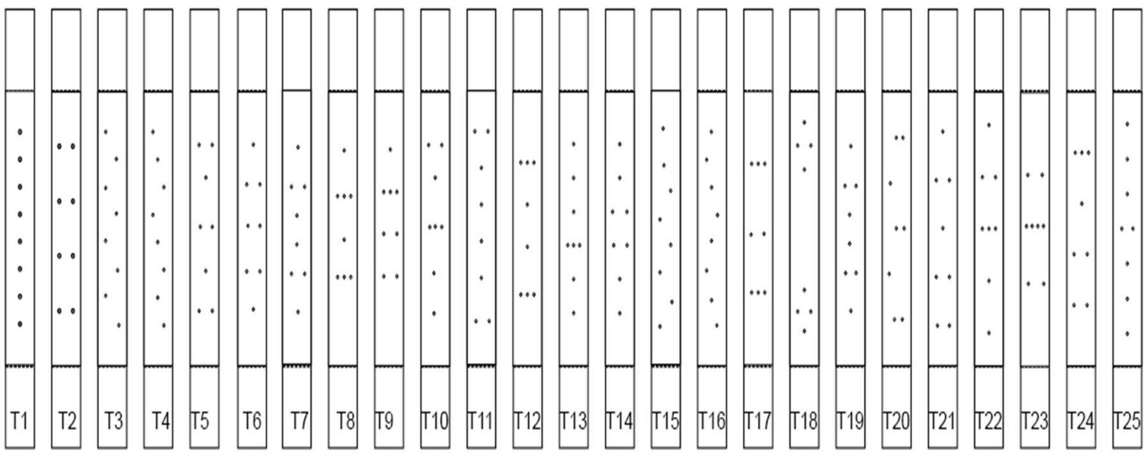


Figure 16. Schematic view of 25 different patterns.

The 0, 2, 4, 6 and 8 perforations along horizontal direction of the samples were prepared by laser machine. The schematic view was shown in figure 17. The perforations were made along the midcourt line of the testing samples in vertical direction. The perforation was made by laser machine. In each sample, the distance between two adjacent perforations is the same.

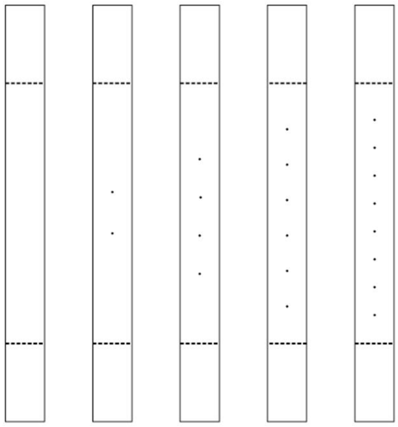


Figure 17. Schematic view of 0, 2, 4, 6 and 8 laser perforations along horizontal direction of the samples.

The GTR testing samples were cut into 70mm*70mm square samples. Only non-perforated GTR samples were tested in this research. The WVTR test samples used had four perforations onto a 50 mm*50 mm square sample (as shown in figure 18). The distance between each two perforations was 10mm. The ring circle in the figure shows the track which was adhesive to the bottle top. The samples were used to place onto the top of the 50ml flask for testing water vapor transmission rate influenced by the perforations.

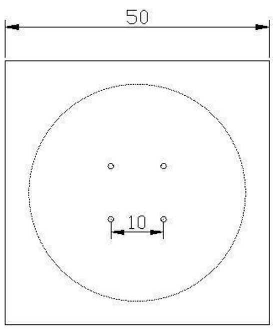


Figure 18. Perforation position of WVTR samples (unit: mm).

Perforation making on samples

Two methods were used for perforation on the samples. One was manual perforation and the other was made by a laser machine. Tools for hand-made perforation were a hammer, a perforating metal punching pin, a metal pad, a thin cushion pad (a piece of cloth), a piece of very thin and transparent plastic film. Figure 19 shows the tools used to make the manual perforation. The metal pad was put on a flat surface, and then the cushion pad is placed on the metal pad. The sample stripe was laid on the cushion and covered by the plastic film with drawings representing designed pattern, and fixed by using the magnet stone to make the sample's position stable. Perforation was carried out by using punching pin with the small hammer. To have the perforations as consistent as possible, the punching pin should be vertical to the surface of the sample in each action. Drawing the patterns on the film helps to make sure the perforation of the 10MD and 10CD samples stripes at the right position.

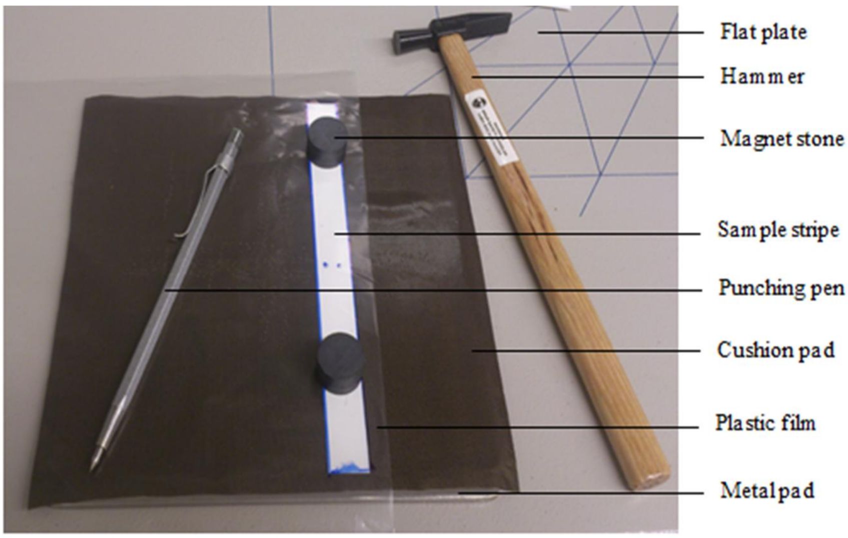


Figure 19. The tools used to do hand-made perforation.

The Bodor CO_2 laser machine was used for perforation. The pattern need to be drawn on the software on the computer connected to the machine, then the paperboard sample was placed on the working platform, and the suitable distance from the laser gun to the material was set. Then the suitable set up on the computer was made and the perforation program was started. The perforation by laser beams was also used to prepare samples for both tensile strength tests and barrier property evaluation. The perforation position and patterns were made much easier by equipment using laser technology.

2.2 Testing Methods

Methods for testing samples include mechanical strength, micro structure observation and barrier properties. Main devices used in the thesis are listed below in table 6.

Table 6. Main devices and equipment used in the study.

Machine type	Company	Model	Country
Tensile tester	Lorentzen & Wettre	SE 064	Sweden
Thickness tester	Lorentzen & Wettre	51D2	Sweden
Cutting machine1	EBA	1043	Germany
Cutting machine2	DAHLE	565	Germany
Climate chamber	JEIO technology	TH-KE 100	Korea
CO_2 Laser machine	Bodor	BCI 1309XU	Switzerland
Pocket microscope	BYK-Gardner	DPM100	USA
Pocket microscope 2	milite Precise instrument	WYSX-80X	China
Confocal microscope	ZEISS	LSM710	Germany
Analytical scale	Precisa	290	Switzerland
GTR tester	Labthink	VAC-VBS	China

2.2.1 Conditioning and dimension measurement of the samples

The testing conditions followed the standard ISO 187-1990. All samples (except for GTR testing samples which have no demand on relative humidity) were pretreated according with ISO 187-1990 in the laboratory for at the least 6 hours under 23 °C and R.H. 50%. The air conditional chamber was used in the tests. The thickness of the 160mm*160mm samples was measured according to the standard ISO 534-2005. The thickness of 5 pieces of paperboard samples was recorded at the same time, thickness of each sample then calculated by divided by the sample number in the thickness test.

2.2.2 Tensile strength testing

A tensile tester was used for tensile strength of each sample. The tensile strength testing followed strictly with the standard dimension of ISO 192-3_2005 (15mm*100mm). The L&W tensile tester was used in this research, for the test of each pattern type, the thickness, testing codes and gram-mage should be put into the machine. It could test the 10MD sample stripes and 10 CD sample stripes continuously in one program. After each sample stripe was tested, the tensile strength and strain at break will show on the screen, and this value was recorded in this research. After each testing program finished, the machine calculates and prints out the results automatically. The report includes the tensile strength, tensile index, E modulus, breaking length, tensile energy absorption (TEA), TEA index, tensile stiffness and the standard deviation of each data.

2.2.3 Microscope observation

Different types of microscopes were used to check the appearance and diameter of the micro holes. Different types of microscopes were used to check the appearance and diameter of the micro holes. First, pocket microscope DPM100 and WYSX-80X were used to test the appearance and diameter of the micro-holes. Then the LSM (Laser Confocal Microscope) 710 was used to observe the perforations in details.

Pocket microscope observation and dimension measurement

Pocket microscope DPM100 was used to capture the appearance picture of the micro-holes on both sides of the sample and to determine the diameters of the perforations. Although the more even and more round the better micro hole it gets, but in real practice , as the limitation of the device and time, the resulted hole in this research is not so even and round. Therefore, on measuring of the shape of the micro holes, both diameter and area of the holes were measured, and area was used to compare the shape of the holes. The area was estimated by using the software as shown in figure 20 and figure 21.

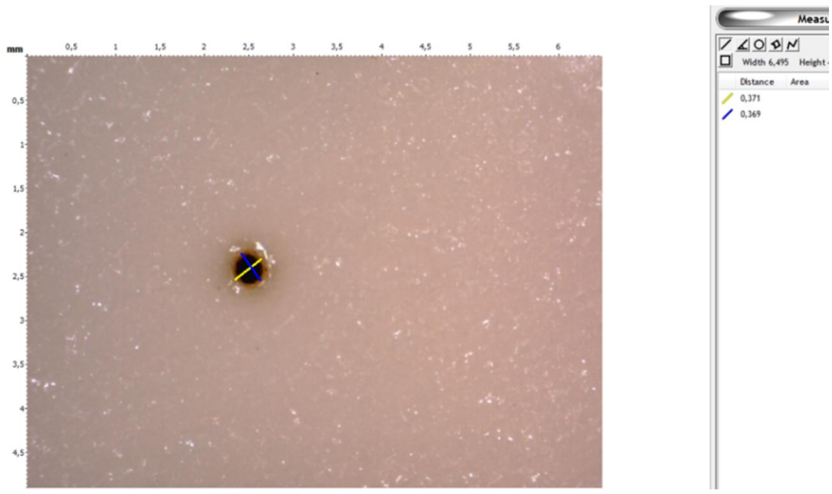


Figure 20. An example of diameter measurement of the micro-hole.

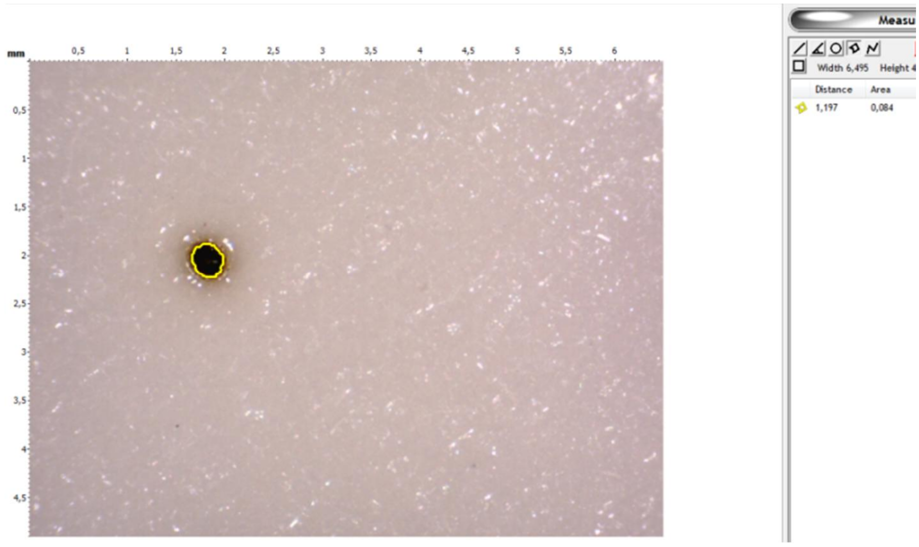


Figure 21. An example of area measurement of the micro-hole.

LSM Microscope measurement

Some samples were also imaged with LSM710 (ZEISS, Germany), to get a much better image of the micro-hole. The LSM710 microscope was used to observe the appearance of the holes in detail. The micro-hole on both sides of uncoated and PE, PET coated samples were observed during the tests. The appearance of perforations on three boards under laser power of 10.80W, 11.16W, 11.52W, 12.00W, 12.60W, 13.20W, 14.40W and 18.00W was measured.

2.2.4 GTR tests and WVTR tests

The GTR of PET coated paperboard was tested using differential pressure method, and was tested by VAC-VBS GTR testing machine by Labthink company. The testing condition was 23°C and 0%RH, the testing gas was the air. The GTR tests method was following the international standard ISO 2556:1974, which specified a method to test the GTR through plastic films using differential pressure method.

The WVTR of micro-perforated uncoated and PE, PET coated paperboard were tested. The water absorbent material used was finely ground calcium chloride ($CaCl_2$) (VWR, Germany). The micro-perforated samples (50mm*50mm, with four micro-holes on it) were sealed on the top of the glass bottles with a hot-melt glue gun. There was around 30 grams of calcium chloride inside each bottle. The samples were put into the chamber for 4 hours before sealing. The weight of the empty bottle, the bottle with calcium chloride and the bottle after sealing were measured using an analytical balance which had an accuracy of four decimals. The calcium chloride was put into the oven for 110°C for 24 hours before the test in order to remove the moisture.

After weighting, the samples were put into the climate chamber, for 48 hours. The weight of the bottles was checked twice, one was after 24 hours the other one was after 48 hours. The water absorbed was calculated by the data. Figure 22 shows the bottles after sealing. The WVTR testing method is based on ISO 2528: 1995-09-01, which specified a method to determine water vapor transmission rate across polymeric film sheets by the conditioning chamber.

Figure 22. The bottles after sealing.

The inner diameter of the 50ml Scott Duran flask used for this WVTR test is 0.001017876 m^2. Thus the perforation density of WVTR test samples are 3930 micro-holes per square meter and the WVTR could be calculated by equation (3) below:

$$WVTR = M_t / t \cdot A \qquad (3)$$

In equation 3, M_t mean the weight loss in the time distance (g), t means the time distance(s), A means the tested area (m^2).

3 RESULTS AND ANALYSIS

After 25 pattern types of perforation were tested, the results were compared, patterns which have major effects to the mechanical properties were found. The variation trends of samples' tensile properties as the perforation number increases from 0 to 8 in horizontal and vertical directions were obtained. The most suitable laser power for laser perforation in this research was studied. The appearance and diameter of the micro-holes were measured and compared. The WVTR of the samples were tested and the results have been analyzed.

3.1 Results of tensile properties testing

After the tensile properties of the samples were tested, the data was compared according to different perforation patterns, types of sample breaking surfaces and the breaking position of the sample stripes.

3.1.1 Tensile properties of 0 to 8 perforation in horizontal direction

After testing the tensile properties including the tensile strength, tensile index, strain at break of the 0 to 8 holes perforating in horizontal direction on samples under the testing method demonstrated in earlier chapter, the results data were gathered. The tensile index, tensile strength has a trend of decrease as the amount of perforation on board increased.

Uncoated samples perforated along horizontal direction (MD and CD stripes)

Figure 23 shows the charts of the tensile properties of the tested uncoated samples in MD. Decent of tensile strength indicates numbers of the perforation affects tensile strength of the samples. The results show that one and two holes on the samples have limited impact to the tensile strength; the average of tensile strength is around 19 N which has equally result compared with the sample tested without perforation. These three types of samples can be put into as the first group. Perforations of 3, 4, 5 and 6 on the samples have minor effects to the tensile strength; the tensile strength of the samples reduces within a narrow band with difference less than 2.5-7.5%. The samples have clear reduction in the tensile strength when perforations on the samples more than 7. The tests show that tensile strength of the samples more than 7 holes possesses only 80% tensile strength of those with the perforations less than 2. Tensile strength of the uncoated samples without perforations can reach19.31 kN/m in MD and the strength reduced to 14.86 kN/m when the perforation amount increased to eight. Mechanical strength of the paperboard samples with perforations on them can, to some extent, reflect strength of the tray body made of paperboard.

Strain at break to the samples with designed perforations is nearly the same which demonstrates that the holes affect the strength of the board but has less effect to the material's elongation in the tensile state. But the results of test on samples with 8 holes showed higher strain at break, this might be caused by weaken material connecting holes. The paperboard material in this group actually already losses its resistance at the tensile around 60 N while the connecting parts are still functioning showing the higher elongation.

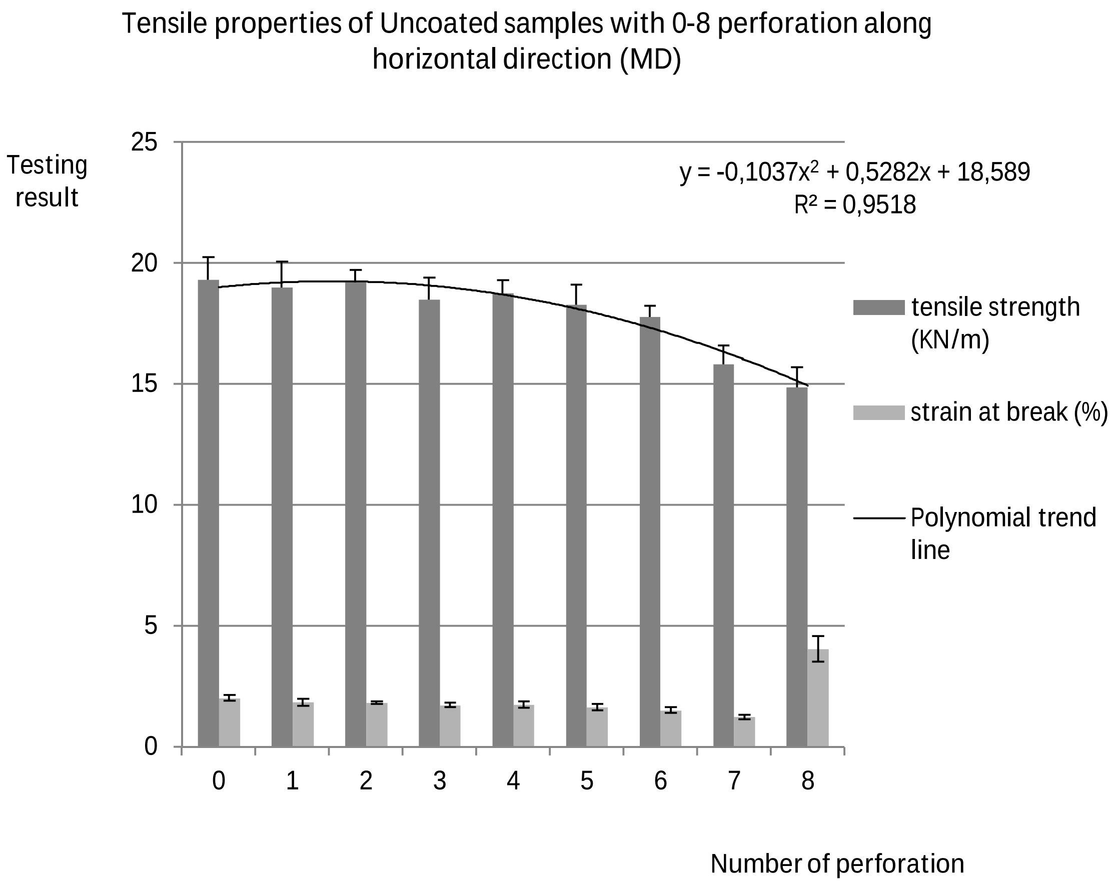


Figure 23. Tensile properties of uncoated samples with 0-8 perforation along horizontal direction (MD).

Figure 24 shows the tensile properties of uncoated samples with 0-8 perforation along horizontal direction of the CD samples. For 1-6 perforations, the impact on tensile strength and strain at break is not so heavy, but for 7 and 8 perforation samples, perforation have remarkable reduce effect on tensile properties. In total, the variation trend of CD uncoated samples are not as clear as MD samples. The R^2 for the polynomial trend line of tensile strength is 0.8581. As perforation located along width of the samples, which are also along fiber orientation, this can cause direct damages to the strength of the testing stripes. For perforation of 0-4 holes, compared to the tensile strength around 18kN/m, the result in CD is lower, around 10kN/m. As the holes are along orientation of the fibers, the strain at break is much higher compared to those tested along MD.

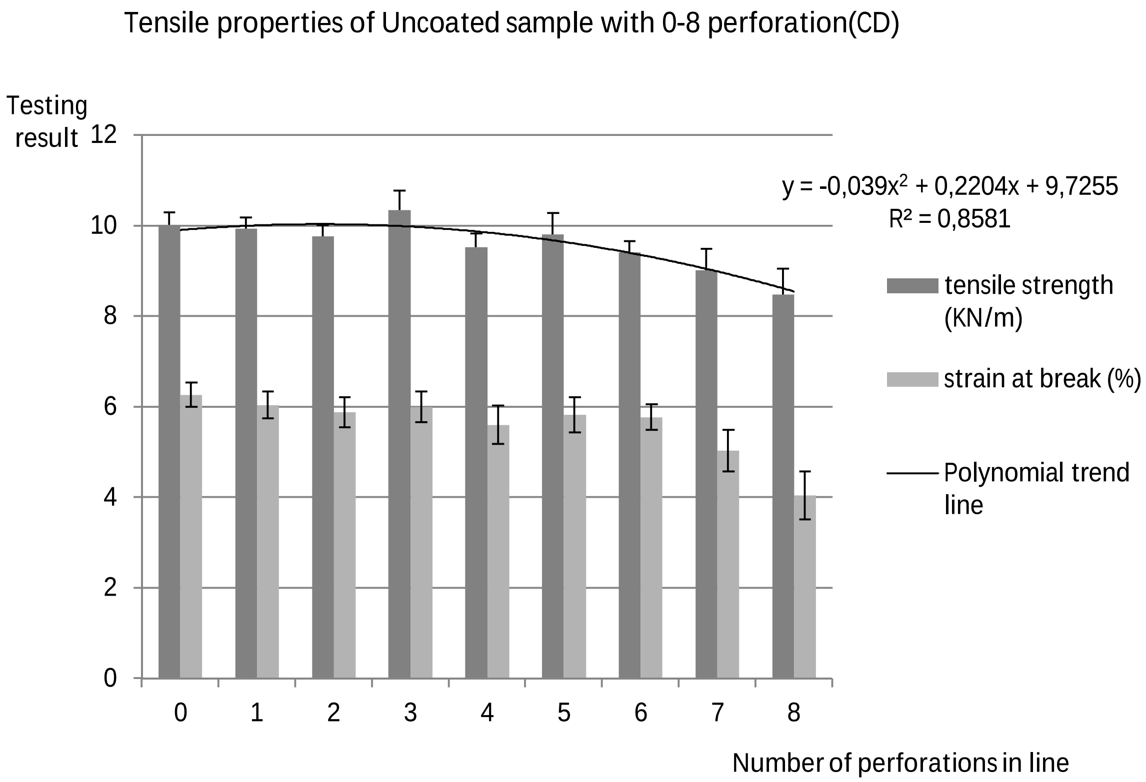


Figure 24. Tensile properties of uncoated samples with 0-8 perforation along the horizontal direction (CD).

PET coated samples perforated along horizontal direction (MD and CD stripes)

Figure 25 shows the tensile properties of PET coated samples with 0 to 8 perforations in horizontal direction. From the Figures below, it can be seen that as the number of perforated holes increase from 0 to 8, the tensile strength and the strain at break of the PET coated samples decrease, which variation trend is quite obvious. Tensile strength of PET coated samples without perforations can reach 21.5 kN/m in MD and the strength reduced to 13.3 kN/m when the perforation amount increased to eight. The tensile strength of the PET coated board is relatively higher than the uncoated samples, indicating that the coated material played a role in increasing strength and also the coated PET strengthened the surface of the board fiber in its melting state. The standard deviations are quite small and the R^2 of the polynomial trend line for tensile strength is 0.9985 so that the results can definitely be considered reliable.

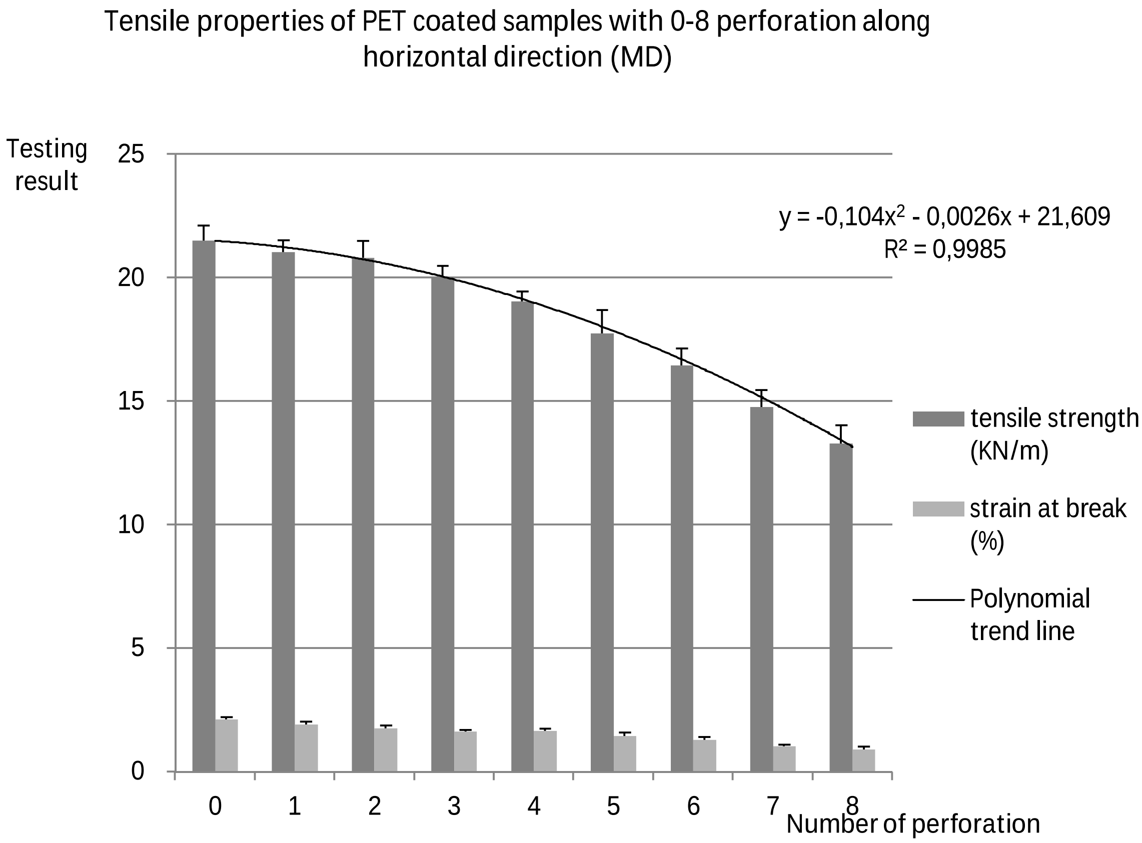


Figure 25. Tensile properties of PET coated samples with 0-8 perforation in horizontal direction (MD).

As shown in figure 26, for CD samples, when perforation amount is larger than 5, the decrease in tensile properties is obvious. However, the situation of CD samples is more complicated and that the results variation trend is not as good as MD samples.

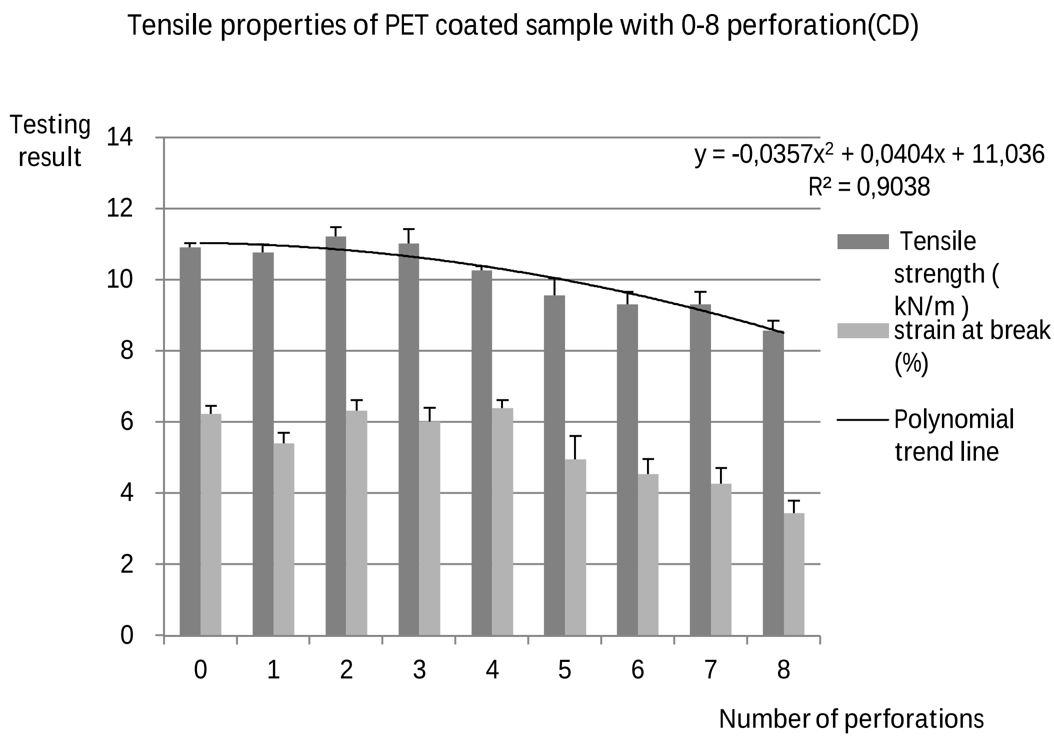


Figure 26. Tensile properties of PET coated samples with 0-8 perforation in horizontal direction (CD).

During the tensile strength testing, it was found that the tensile strength in the machine direction is about two times higher than in the cross direction. This is because when the paper was produced, most fibers follow the way which machine operates. In machine direction, the fiber's orientation made the paper gains the better physical properties than in cross direction. (Stepanov 2015, p.1-119.) Most fibers' length orientation is following the machine direction, and the diameter direction of the fibers crossed together. Fiber orientation gives raise to higher increased bounding force along this direction and thus the higher strength of the board. It is harder to break long fibers into two parts than to strain two fibers to be separated. And the time of operation on each MD stripe is about 2 to 3 seconds, but the time operating on each CD stripe is about 4 to 5 seconds. This is because in CD fibers crossed more heavily than in MD direction, thus fibers get rid of each other much slower than in MD. More even and straight fraction surfaces appeared in MD samples, while CD samples also have slant and more layered fraction surfaces. The strain at break of one CD samples is about triple of the MD samples. The changes of tensile strength in MD are clearer than in CD. These experimental phenomena are caused by the fibers orientation.

3.1.2 Tensile properties of 25 types of designed patterns

25 pattern types of PET coated samples were designed and tested. The resulting data were compared according to the data of tensile strength, strain at break, appearances of breaking surface, whether the breaking gone through the location of perforation, and the amount of destruction rows along the vertical direction of the samples stripes. For the tensile strength testing of the 25 different kinds of patterns, from the testing results, the type which had the best tensile index is T19 (20.01 kN/m), the lowest tensile strength among 25 patterns was the MD of T17(16.76 kN/m), the pattern type which has the best strain at break is T 1, The best two on the condition that tensile index weights 50% and strain at break weights 50% are T1 and T16, and the worst one is T23. Figure 27 shows the tensile strength properties of 25patterns (MD and CD). Figure 28 shows the strain at break of 25 patterns (MD and CD). Among the test results of T23 was the worst, which might be due to pattern that had four holes in one line in the middle. T1 and T16 possess higher value of tensile strength this might due to the perforation pattern of the samples which there are no two holes in one line along horizontal direction of the samples, and the arrangement of the perforation location was quite dispersed. The results of 0 to 8 lines in the horizontal direction show that the more perforations consecutively along one line, the lower tensile strength present. Therefore, the suggestion by the results of this research is that in order to get better mechanical properties of the plastic-coated paperboard, it is preferable to design the locations as dispersed as possible.

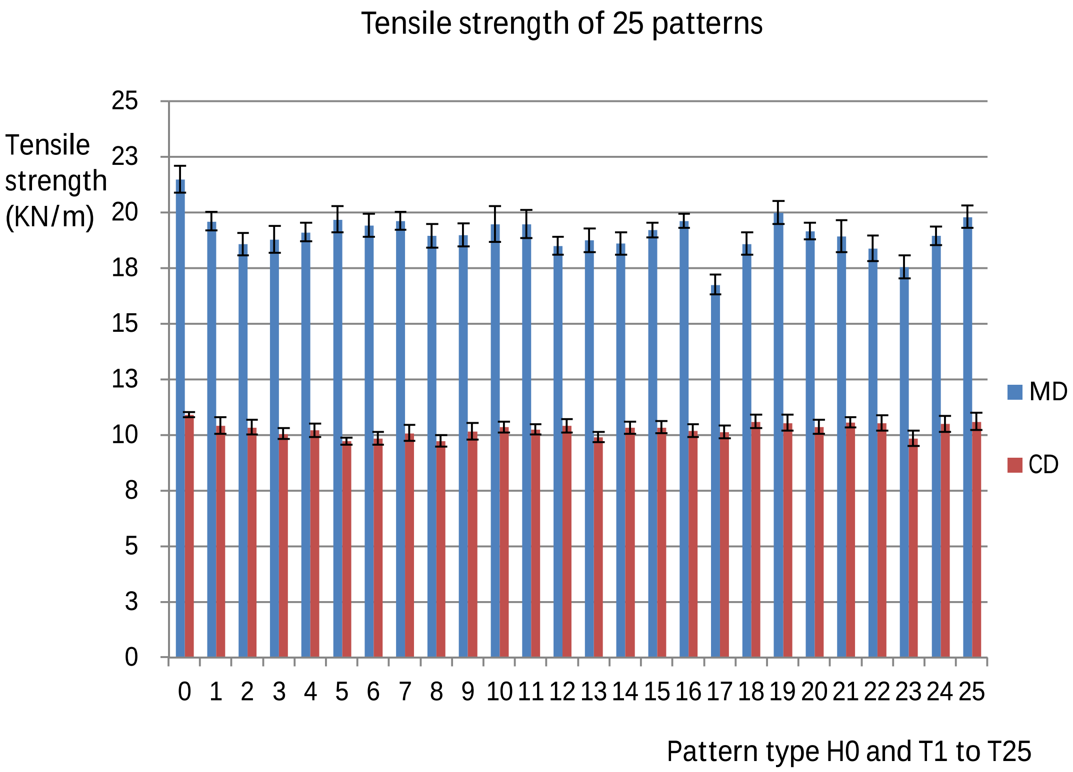


Figure 27. The tensile index properties of the 25 different types of pattern design (MD and CD).

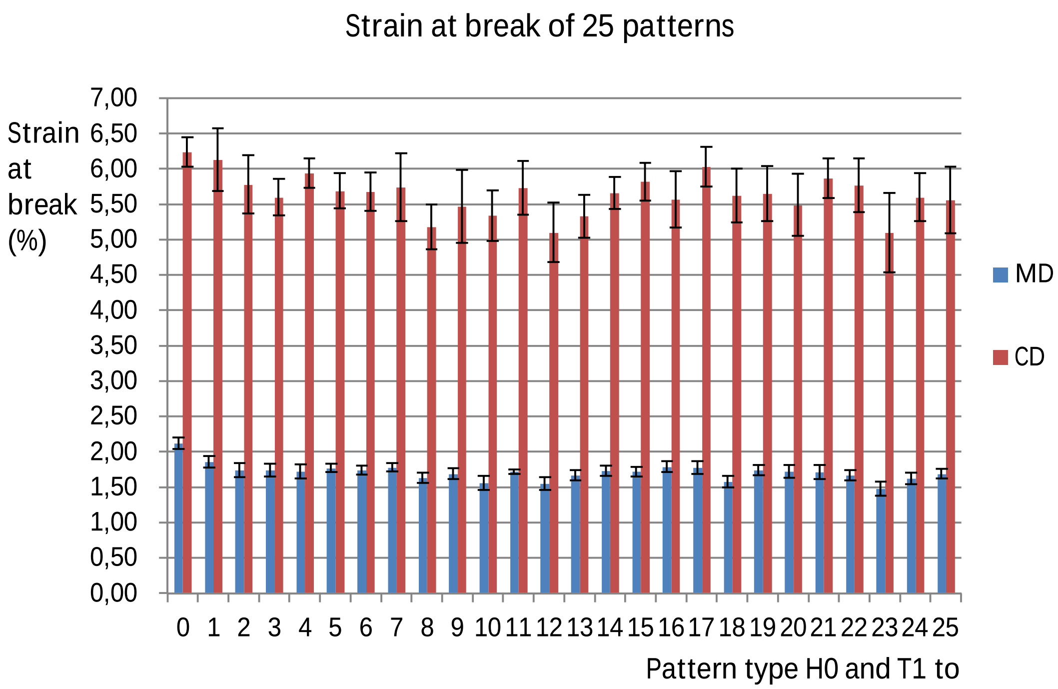


Figure 28. The strain at break properties of the 25 different types of pattern design (MD and CD).

Among the 25patterns, the minimum tensile strength is T 17, 16.76kN/m. Compared to the non-perforated PET board, of which tensile strength is 21.5 kN/m, the decrease in tensile strength is 22%. T6 and T7 have similar patterns; their tensile strength values in MD are similar. When the pattern has 1 hole lines, 2 hole line or even 3 hole lines along the horizontal direction of the stripe, the break tend to happen at the line which have more holes. Pattern T7 has 1 hole lines and 2 hole lines along horizontal direction of the stripe, but more stripes break at the 2 hole lines.T8 breaks more stripes at 3 holes lines and T 12 breaks at 3 hole lines. For patterns of T 3, T 4, T 15 and T 16, the configuration of the hole lines are slant, but the tensile strength are close to the similar pattern which has straight hole lines.

Four groups of 25 patterns

In a single line of the material, as the number of destruction increase, the tensile properties decreased. On each sample, the destruction area is the same, as they all were perforated by with 8 holes. However, the break point in testing direction was different. In this study, a hypothesis came out, that the tensile properties of the perforated samples are influenced by the number of destruction rows in the testing direction (as illustrated in figure 29, each red rectangle show one row, and the numbers in red show the amount of rows). That is, for T1 to T5, the amounts of destruction rows respectively are 1, 2, 2, 3 and 3. In this way, the 25 pattern types are divided into 4 groups (as shown in table 7).

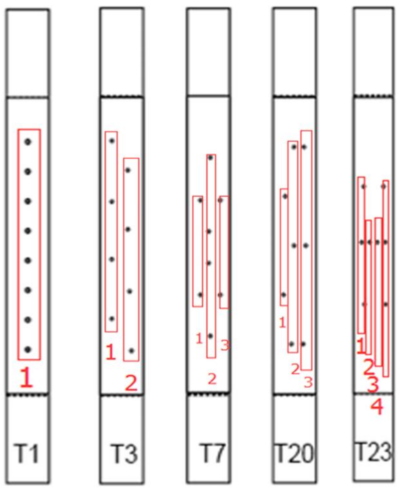


Figure 29. Examples to explain the four group according to the destruction rows, the numbers in red means the amount of destruction rows.

Table 7. Four groups of 25patterns

Group code	Containing patterns	Amount of destruction rows	Tensile strength (average) MD (kN /m)	Tensile strength (average) CD (kN /m)
1	T1	1	19.61	10.42
2	T2, T3 ,T15, T25	2	19.17	10.32
3	T4,T5,T6,T7,T8,T9,T10,T12,T13,T14,T15, T16,T17,T18,T19,T20,T21,T22,T24,	3	18.99	10.26
4	T23	4	17.55	9.84

3.1.3 Types of breaking surfaces of manual perforated stripes

The testing material for 25 pattern types is PET coated paperboard, after each kind of pattern test, the broken testing stripes were placed in order and was taken photo, in order to analyze the results on at which place did the sample broken and the relationship on broken place and tensile properties of the sample. Figure 30 shows an example of the photo taken after test.

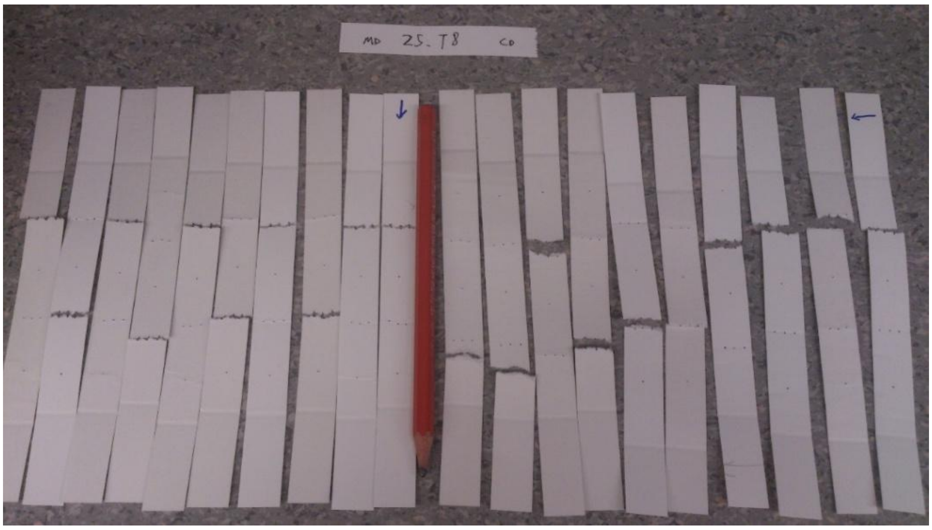


Figure 30. An example of the photo taken after test.

After one sample stripe broke into two parts, different shapes of fracture surface were formed among manual perforated samples. Figure 31 shows the three typical ways of the section surfaces. The surfaces in type (a) are quite straight and even. The surfaces in type (b) are slant and curving. While in type (c), the fiber layer and the plastic layer did not break at the same place, and thus clear board interface and plastic interface can be seen at the breaking surface. When analyzing the photos taken after tests, it is obvious to find that type (a) surface is typical to find in MD samples. While for CD sample stripes, the breaking surfaces might be one of the three types. This might because that in MD samples, more fibers are arranged along the stretch direction. While in CD samples, the fibers are arranged in more complicated ways.

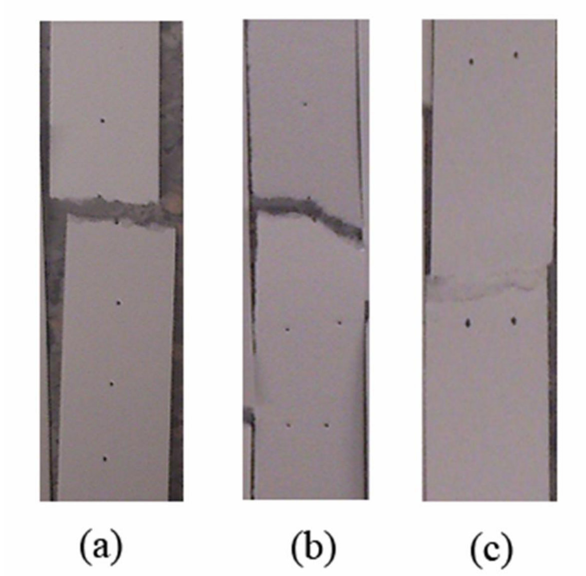


Figure 31. Three typical breaking ways in tensile tests.

3.1.4 Tensile properties of the laser perforated samples

The paperboards were micro-perforated by laser under the methodology described in earlier chapter. The amount of perforations for each kind of board was 2, 4, 6 and 8 in MD. Figure 32 and figure 33 show the tensile strength and strain at break of the three boards. From the testing results, the variation trend of tensile strength and strain at break is not so clear. This might because the laser perforations are so small that the differences between the results is small, also laser perforation can make more smooth holes than manual perforation thus gain less regions of stress concentration. The differences between the adjacent results for all three materials are small and the variation trend is not clear enough. The difference between the best and worst tensile strength is about 1-2 kN/m, the difference between the largest and least strain at break is about 0.25%.

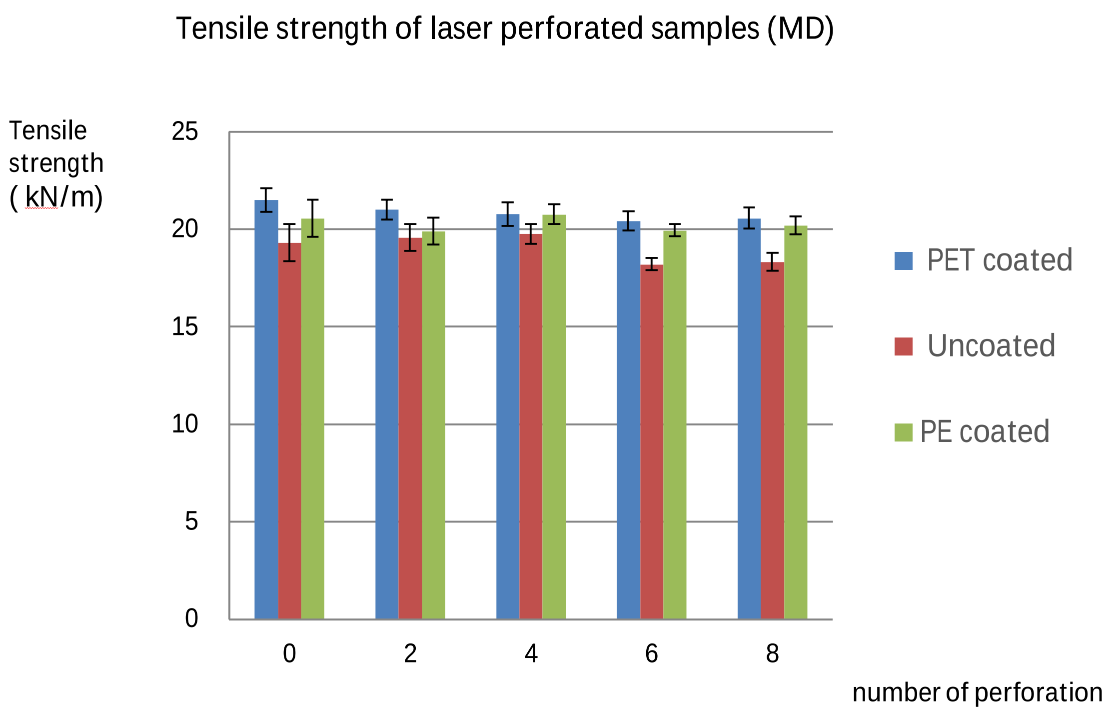


Figure 32. The tensile properties of 0, 2, 4, 6 and 8 perforations on uncoated samples in vertical direction (MD)

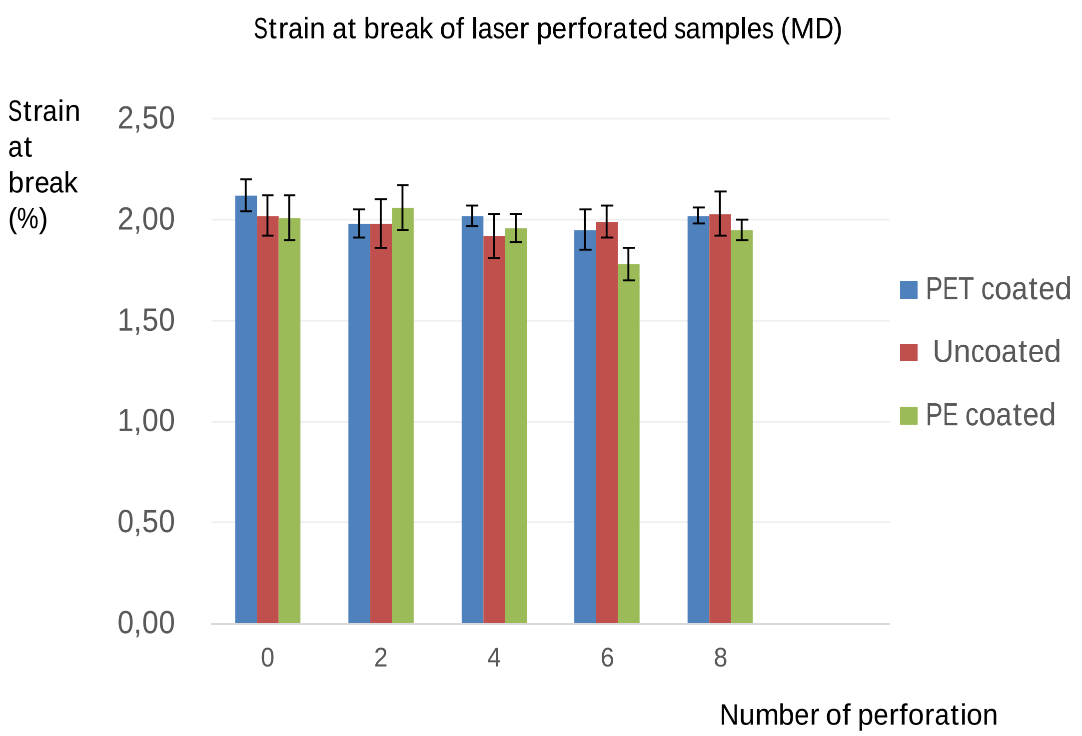
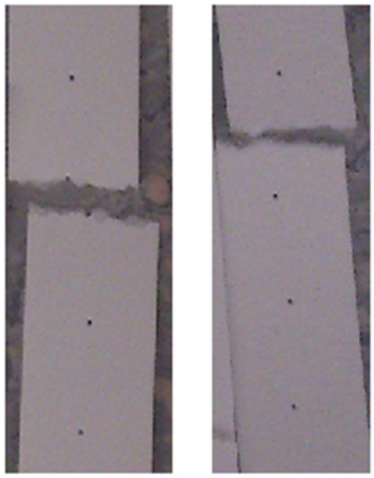


Figure 33. The strain at break properties of 0, 2, 4, 6 and 8 perforation on uncoated and PET coated samples in vertical directions (MD).

3.1.5 Breaking position of sample stripes

The tensile testing sample stripes are counted for the breaking positions. The breaking are classified into two kinds, as show in figure 34, (1) is an example that the break happened through the location of the perforation, while (2) is an example to express the break did not went through the location of the perforation.



(1) (2)

Figure 34. Schematic map of the sample stripe breaking surface. (1): breaking through the position of perforation. (2): did not break through the position of perforation.

Table 8. Amount of samples break through the hole's position in 10 parallel samples (1 to 8 perforations in horizontal direction, H1 to H8).

Perforation amount		1	2	3	4	5	6	7	8
Uncoated	MD	8	10	10	9	10	10	10	10
	CD	3	3	2	7	3	4	10	10
PET coated	MD	9	10	10	10	10	10	10	10
	CD	1	4	7	6	7	9	10	10

From table 8, it could be seen that, for both uncoated and PET coated samples, the amount of samples break through the location of the hole in 10 MD samples is about 9 to 10. While the number in CD samples have a trend to increase from 1 to 8 perforations along horizontal direction.

Table 9. Amount of samples break through the hole's position in 10 samples (pattern T1 to T25).

Code	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19'	T20'	T21'	T22'	T23	T24	T25
MD	10	10	10	10	10	10	10	10	10	10	10	10	9	10	10	10	10	10	10	10	9	10	10	10	10
CD	10	7	9	9	10	8	10	8	9	8	8	9	8	8	10	10	8	9	5	7	8	6	10	8	8

From table 9 above, it is clear to see that the amount of samples break through the position of the hole in 10 parallel samples for samples coded T1 to T25 is almost 10 in MD and less in CD.

Table 10. Amount of samples break through the position of the hole in 10 samples (laser perforation of 2, 4, 6 and 8 holes along vertical direction of the samples).

Coating	2 perforations	4 perforations	6 perforations	8 perforations
Uncoated	5	9	6	5
PET	7	5	8	5
PE	9	7	8	9

From the table 10 above, the amount of samples break through the position of the hole in 10 parallel samples in MD has randomness, which is less than the amount of samples H1 to H8 and T1 to T25.

3.2 Results of microscope observation

Figures were captured in this research to analyze the appearance of the perforations. The figures got by WYSX-80X shows the shape of the manual perforation and the differences of fibers orientation in MD and CD of the samples. From figures got by DPM100, the diameter and the area of the laser perforations were analyzed. From figures got by LSM710 the appearances of the laser perforation of the three kinds of paperboard were observed.

3.2.1 Microscopic image analysis

Manual perforated holes

The manual perforated holes are observed by reading microscope WYSX-80X (Shanghai milite Precise instrument, China); Figure 35 and 36 shows the appearance of the two sides of a perforation. The diameter of the hole in side 1 is around 0.25mm, the diameter of side 2 is around 0.5mm.This is caused by the tip of the punching pen is not a cylinder but a cone, and the materials on the two sides also made differences. The blue color in figure 37 and figure 38 is gained by the marking pen which used to draw the pattern on the plastic film. It also can be tell that the surface of the perforation is not so even, and this may affect stress concentration during tensile tests.

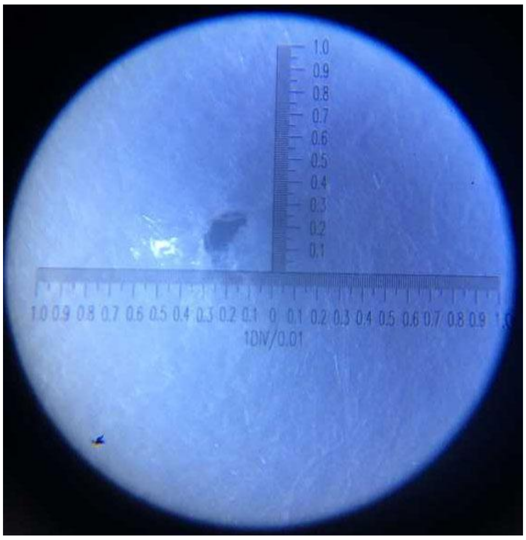


Figure 35. Appearance of a manual perforated hole on PET coated samples under reading microscope (side 1, unit: mm).

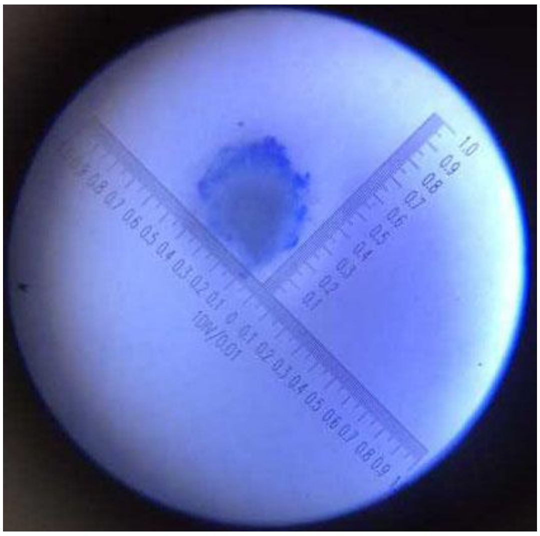


Figure 36. Appearance of a manual perforated hole on PET coated samples under reading microscope (side 2, unit: mm).

Figure 37 shows the breaking surface of sample stripe in MD in tensile tests, while figure 38 shows the breaking surface of CD sample stripe in tensile tests. Both the two breaking area have gone through the position of the hole. White fibers can be seen in the picture along the fracture surface. It can be tell that there are longer fibers in MD section than in CD section, thus can tell the fibers orientation inside the board.

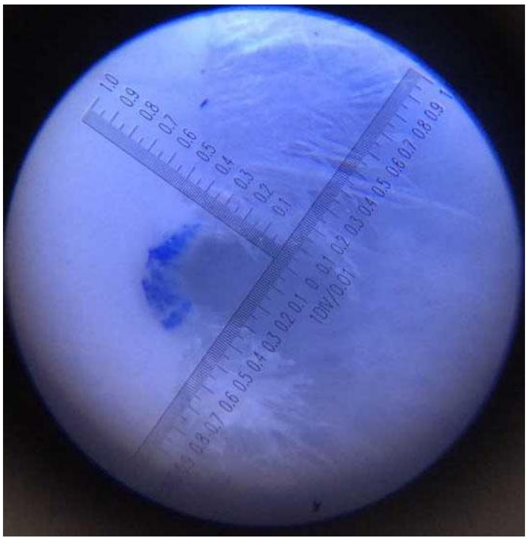


Figure 37. Appearance of the breaking area of manual perforated hole on MD sample stripe (unit: mm).

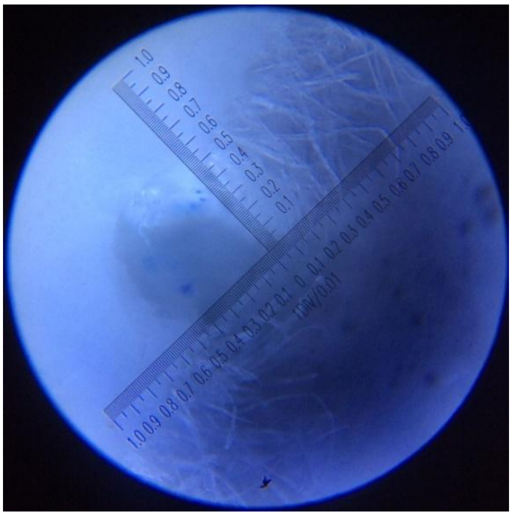


Figure 38. Appearance of the breaking area of manual perforated hole on CD sample stripe (unit: mm).

Laser perforations

After observation of the micro holes perforated on different kinds of paperboard, appearance was recorded by microscope DPM100, as shown in figure 39, 40 and 41. Side1 is the surface which faces to the laser power while operating. It is obvious that for each kind of paperboard, the area of the side 1 of a micro-hole is larger than the appearance of the same micro-hole in side 2. This might because the surface which faces to the laser gains more power. Besides, the plastic is easier to form after perforation, as plastic was melting and fiber was burning while operation. Moreover, the appearance of the side 1 of three kinds of paperboard is quite different. The surface around the uncoated sample is quite even and flat, an outstanding circle shown up around the PE coated hole, the ring also shown up around the micro hole on the PET coated samples, but the diameter of the ring is smaller than PE coated samples.

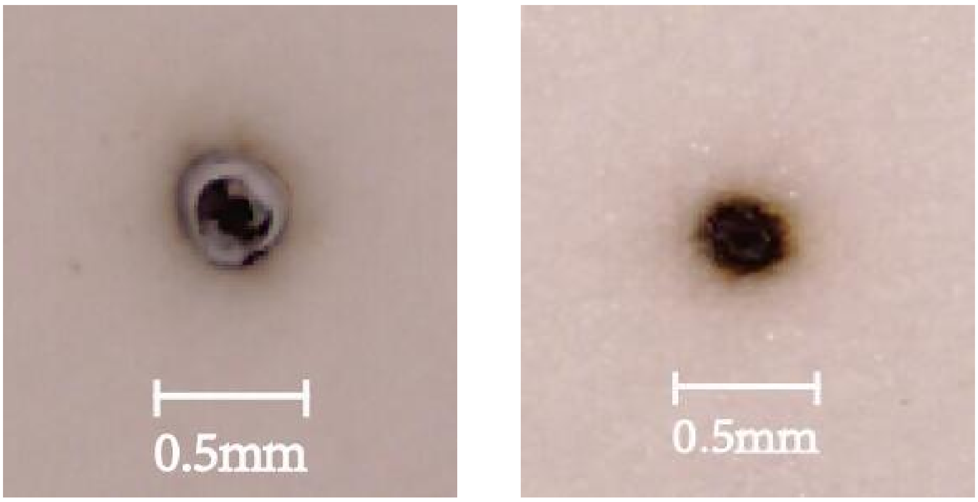


Figure 39. Appearance of a laser perforated micro-hole on uncoated paperboard in 2 sides by DPM100.

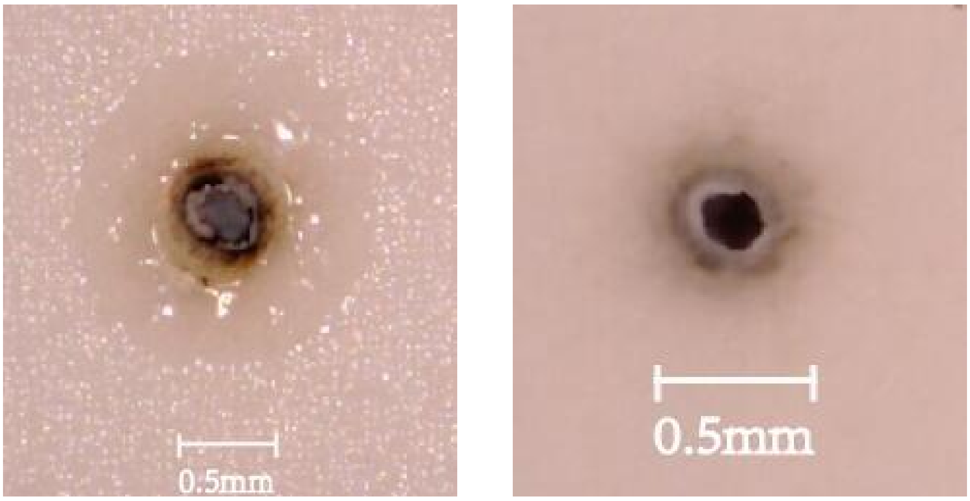


Figure 40. Appearance of a micro-hole on PE coated paperboard in 2 sides by DPM100. Figure on the left has been taken from PE-coated side, whereas the uncoated side is presented on right.

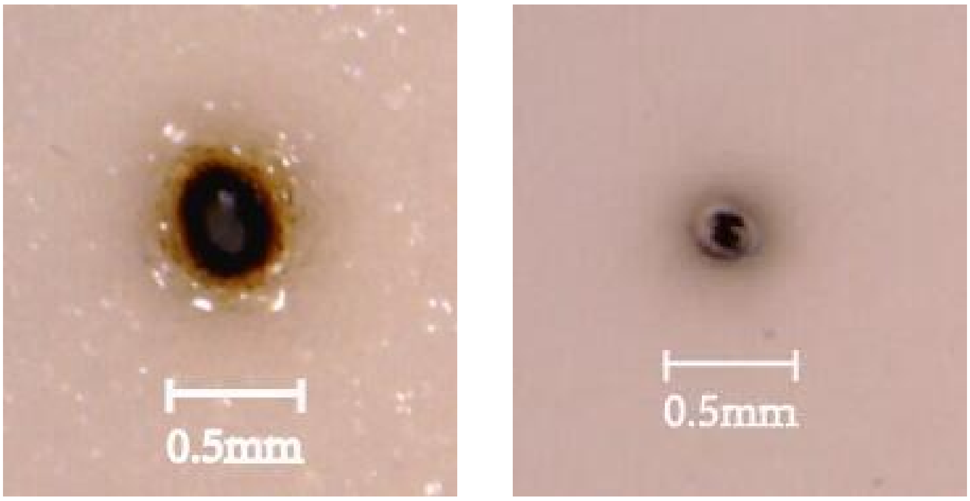


Figure 41. Appearance of a micro-hole on PET coated paperboard in 2 sides by DPM100. Figure on the left has been taken from PET-coated side, whereas the uncoated side is presented on right.

For the micro-hole appearance under ZEISS LSM710, photos with scale are show in Figure 42, 43 and 44. According to the captured pictures by LSM710, the appearance of the side 1 of uncoated paperboard is even and flat. For the side 2 of uncoated samples, it is clear to see the fibers orientation and the situation of fibers interlaced. The appearance of side 1 of PE coated sample micro hole, the circle is quite even, and there are a few bubbles around the hole. On the side 1 of the PET coated micro perforated hole, there are lots of bubbles (diameter approx. 10 µm to 50µm) around the circle. Bubbles can also be seen in the walls of the hole. The circle of micro-hole on PET coated sample is not so round compared to uncoated and PE coated samples. These bubbles should come from the coated polymer melting and evaporation, and some air was stored inside when it cooled down. It is also obvious to see the differences between regular microscope and confocal laser scanning microscope. LSM makes obviously it possible to study the walls of the hole ring. Compared to manual mechanical perforation, the surface of the laser perforation ring is more smooth, which could decrease the stress concentration when enduring shock and impact.

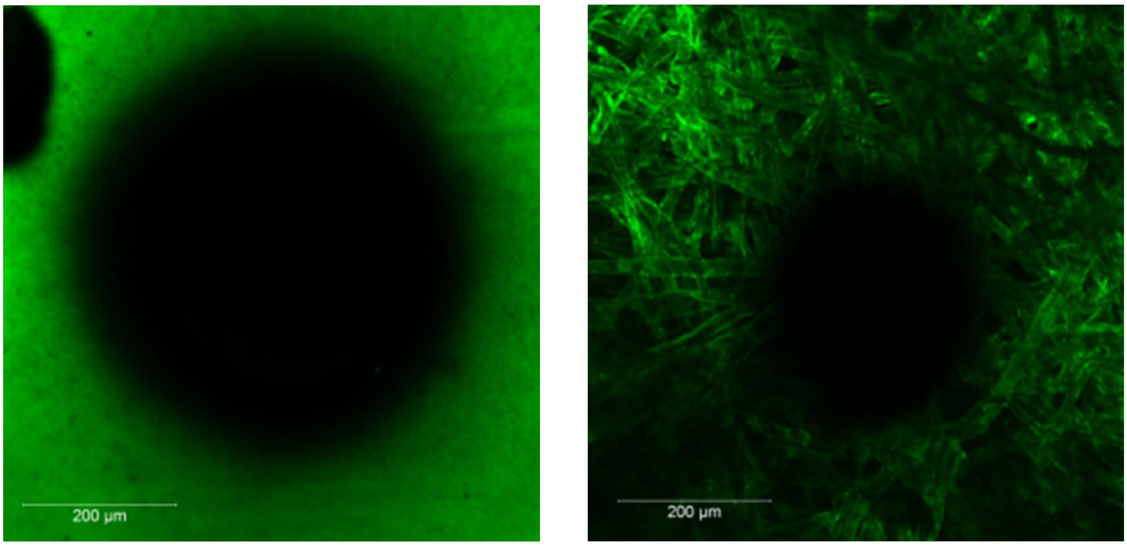


Figure 42. Appearance of the two sides of a micro-hole on uncoated paperboard under ZEISS LSM710. (Side 1 on the left, side 2 on the right.)

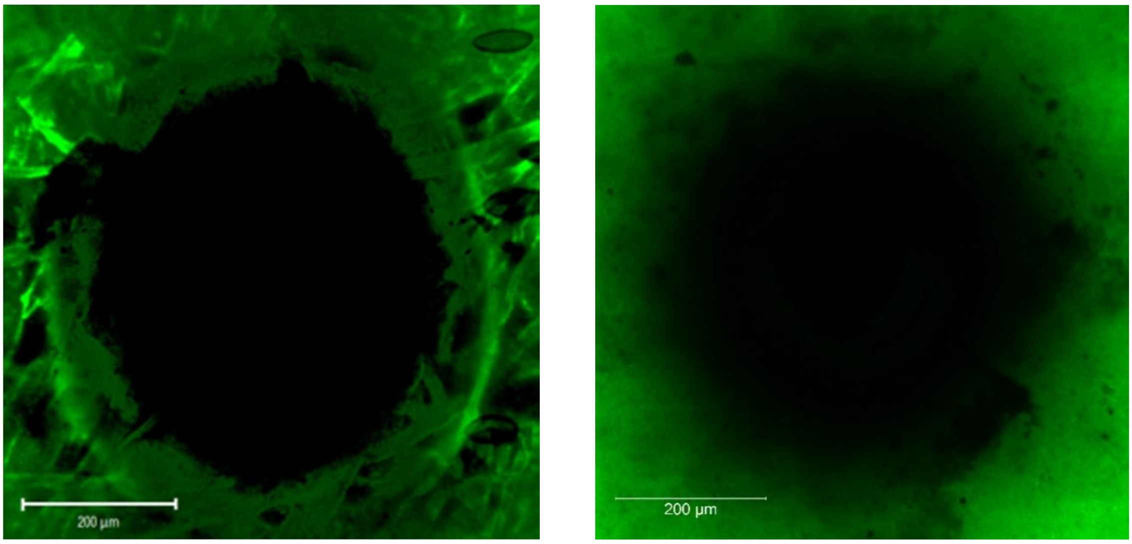


Figure 43. Appearance of a micro-hole on PE coated paperboard in two sides by ZEISS LSM710.(Side 1 on the left, side 2 on the right.)

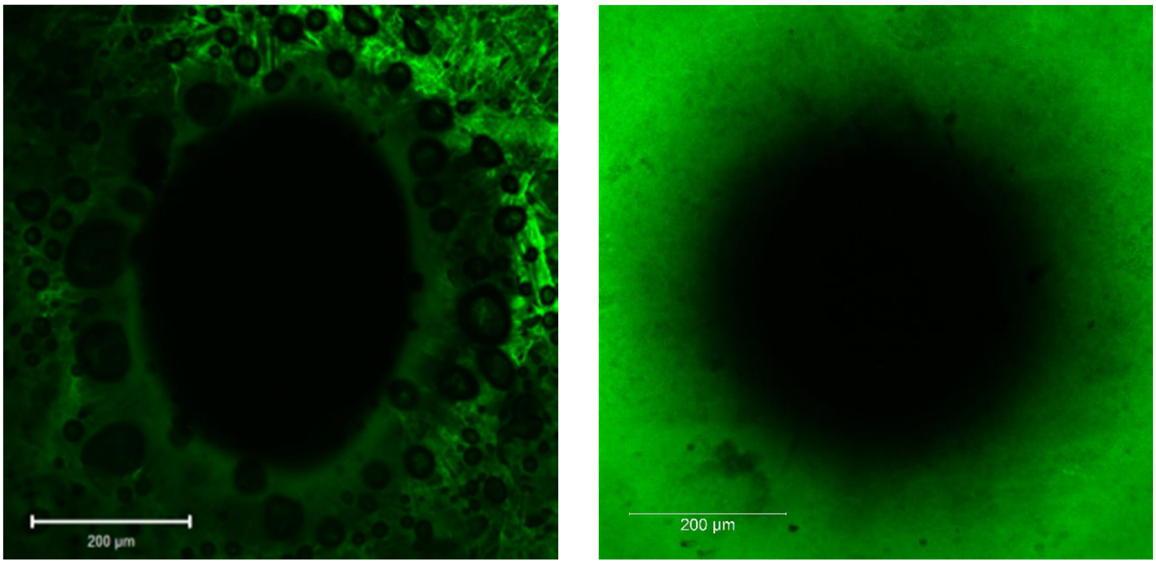


Figure 44. Appearance of a micro-hole on PET coated paperboard in two sides by ZEISS LSM710. (Side 1 on the left, side 2 on the right.)

3.2.2 Diameter and area of the micro-holes

For tensile tests on laser perforated samples, laser power of 11.16W was used for operating. The diameter of the hole was affected by the type of paperboard. On average, it is around 200 to 500 micrometer. Figure 45 and figure 46 shows the area of the micro-holes under laser power, it is obvious that for the same kind of sample, the micro-hole's area in side 2 is much smaller than the area in side1. This is because of the plastic get largely damaged by the laser power. The PET coated samples gained the largest area in side 2, then came the uncoated substrate, and PE coated showed the smallest size. At the same time, it can be said that as the laser power increased from 10.80 W to 18.00 W, the area of the micro-hole increased obviously. The more laser power was used, the more heavily the film melted and the fibers were also burned.

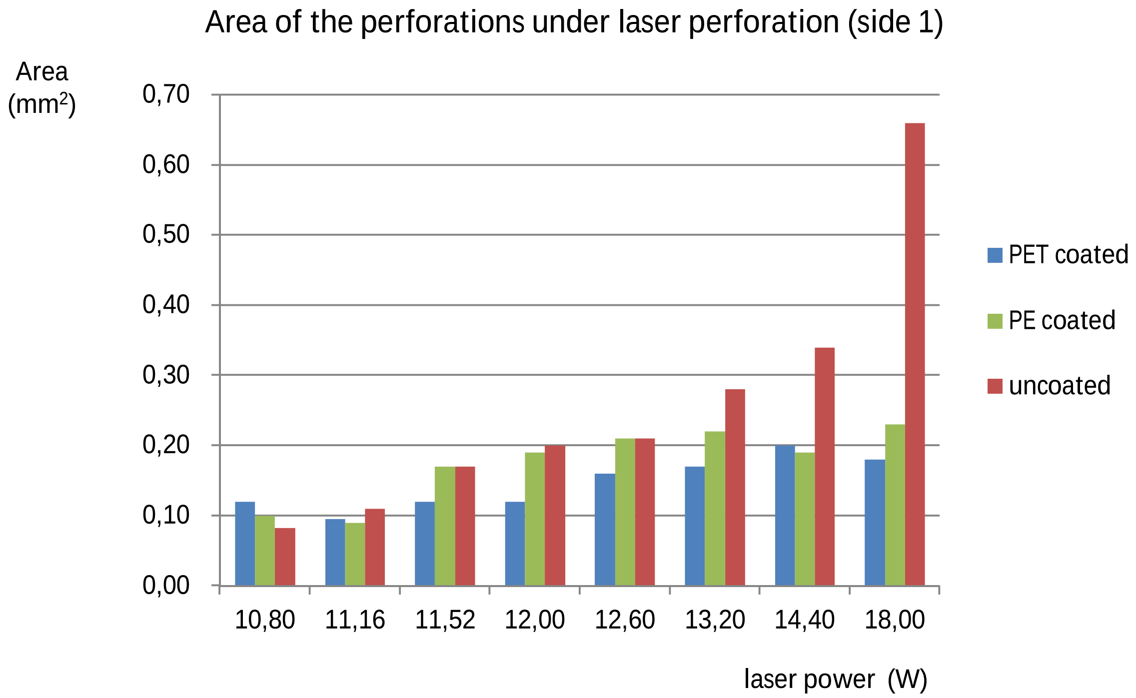


Figure 45. Area of the micro-holes under different laser operating power (side 1).

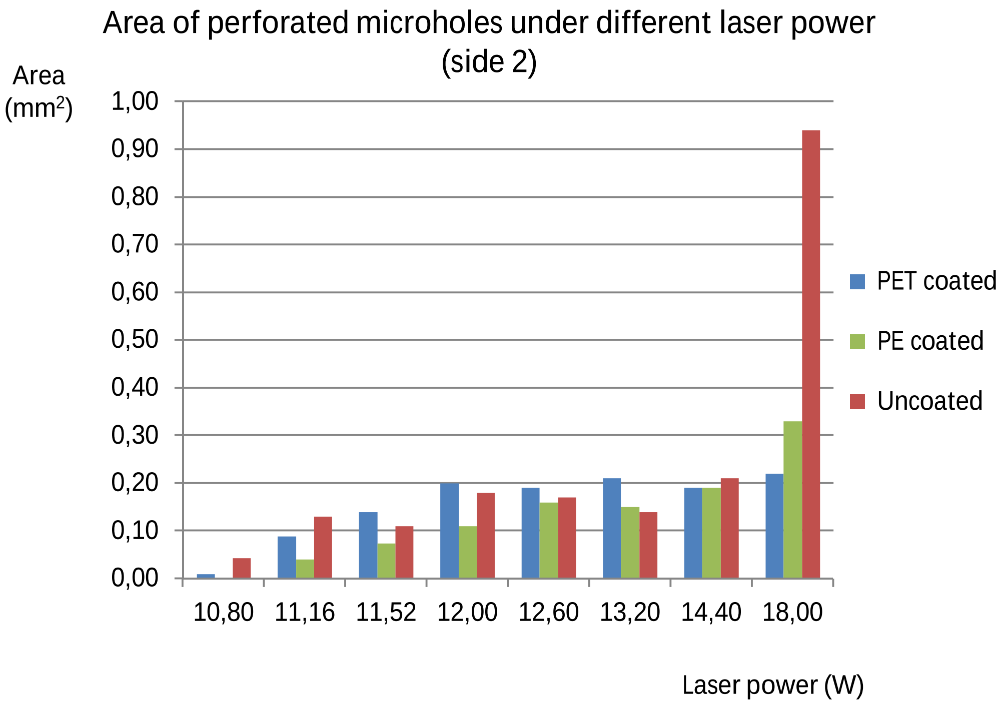


Figure 46. Area of the micro-holes under different laser operating power (side 2).

3.3 Results of GTR and WVTR tests

The non-perforated PET coated paperboard was tested by VAC-VBS GTR tester by Labthink company. The results showed that under the testing condition of 23°C and 0% relative humidity, the GTR of the sample was 17.377cm^3/cm^2·24h·0.1MPa, and the OTR of the material was 73.685 cm^3/cm^2·24h·0.1MPa. This value proved that this kind of PET coated paperboard material is suitable to be packaging material for food. And also, it proved that the consideration of doing perforation mediated packaging on this material is reasonable.

After the WVTR testing, the water transfer condition was recorded as the table 11 and table 12 below. The WVTR of uncoated paperboard is around163.7397 g / (m^2·d), while the PET coated board is 35.4333 g / (m^2·d), and PE coated board is 28.6872 g / (m^2·d). Thus the PET and PE coating made dramatic effect on the material to gain a much better water vapor barrier. The Perforated PET board gain a WVTR of 50.2681 g / (m^2·d), thus perforation density of 3930 micro-holes per square meter improved the WVTR of PET board by 75 % than the non-perforated one.

Table 11. The water absorption (non-perforated)

Coating	Non			PET			PE		
Sample ID	WN1	WN2	WN 3	W1	W2	W3	W1'	W2'	W3'
M_0 (g) Empty bottle	46.5048	46.0900	46.8812	52.0331	51.7279	48.0378	50.8865	47.0203	47.3517
M_t (g) Salt	30.0754	29.9978	30.0329	29.9918	30.0043	29.9928	30.0441	29.9935	29.9998
$M_0 + M_t$ (g)	76.5802	76.0878	76.9141	82.0249	81.7322	78.0306	80.9306	77.0138	77.3515
M_1(g) Bottle+ Salt+Glue ,0h	79.6238	78.7191	79.7572	84.3654	84.9508	80.9588	84.1774	80.2210	81.1885
M_2(g) Bottle+ Salt+Glue,24h	79.8064	78.8727	79.9210	84.4104	84.9874	80.9854	84.2085	80.2502	81.2158
M_2-M_1 (24h Gained Weight)	0.1826	0.1536	0.1638	0.0450	0.0366	0.0266	0.0311	0.0292	0.0273
Average gained weight 24h(g)	0.1667			0.0361			0.0292		
WVTR (g/ (m^2·d))	163.7397			35.4333			28.6872		

Table 12. The water absorption (perforated)

Coating	Non			PET			PE		
Sample ID	WN4	WN5	WN6	W4	W5	W6	W4'	W5'	W6'
M_0 (g) Empty bottle	46.3906	46.5134	45.7568	50.7529	46.9036	47.2368	51.9063	51.6039	47.9083
M_t (g) Salt	30.0306	30.1290	30.0305	29.9550	29.9764	29.9901	29.9578	30.0533	29.9996
$M_0 + M_t$ (g)	76.4212	76.6424	75.7873	80.7079	76.8800	77.2269	81.8641	81.6572	77.9079
M_1(g) Bottle+ Salt+Glue,0h	79.1775	79.2445	78.4064	83.3652	79.1689	79.3828	83.8427	84.3995	79.9427
M_2(g) Bottle+ Salt+Glue,24h	79.3724	79.4543	78.6068	83.4236	79.2009	79.4459	83.8781	84.4259	80.0134
M_2-M_1 (g) (24hGain Weight)	0.1949	0.2098	0.2004	0.0584	0.0320	0.0631	0.0354	0.0264	0.0707
Average weight gained 24h(g)	0.2017			0.0512			0.0442		
WVTR (g/(m^2·d))	198.1577			50.2681			43.3910		

4 CONCLUSION

The tray package which contains a tray container part and a lidding film layer is widely used in fresh fruit and meat packaging industry along with Perforation mediated MAP technology. Previous researchers did much research on perforation on the lidding film to gain modified atmospheres. In this study, perforation was located on the body of the tray.

4.1 Research questions

This study was an approach to the perforation on paperboard materials and how to design its patterns and distributions. The study focused on to which degree does the perforation influences the strength of the paperboard materials with pigment coating, PE coating and PET coating. The third research question was related to the reliability of perforation techniques, i.e. whether the diameter and the shape of perforations is uniform.

4.2 Main Findings

Among the testing of 25 patterns, the largest decrease range in tensile strength was 22%. It is inferred that the better tensile strength could be achieved when perforations placed with more distance. The results show that when distance between the perforation holes is less than 2.1 mm, the affects to the mechanical strength is dramatic. Therefore the tray body should have enough area for perforations to modify the air and vapor transmission.

The less perforation made along horizontal direction of the sample, which is the direction vertical to the stretching direction, the better tensile properties the sample gains. The less destructing rows made on the samples, the better tensile strength the sample gets. The variation trend of the tensile strength and strain at break of the samples does not have obvious consistency.

More even and straight fraction surfaces appeared in MD samples, while CD samples also have slant and more layered fraction surfaces. Tensile strength in MD is close to two times higher than CD samples. The strain at break of one CD samples is about triple of the MD samples. The operation time to strain one CD sample to break is about two times of one MD sample. The changes of tensile strength in MD are clearer than in CD. These results are caused by the fibers orientation.

For manual made perforated hole, the surface is not smooth enough, and the diameter in side1 is bigger than in side 2. For laser made perforation, the paperboard got discoloration due to laser, perforation on uncoated board is more flat, outstanding ring circles appeared on PET and PE boards, and a few bubbles could be seen around the ring circle of PET coated board. Even for each micro-hole, its appearance differs from two sides. Compared to manual perforations, laser perforations are smaller and more even, thus destroyed less in the effective width of the sample stripes, and have less conditions of stress concentration.

Uncoated samples absorbed the largest amount of water than PET coated samples, and PE coated samples absorbed the least. The perforation could increase the WVTR of boards effectively. Perforation density of 3930 micro-holes per square meter on PET paperboard increased its WVTR in a range of 42%. In engineering application, manufactures could modify the amount of WVTR by modifying the size and density of the micro-holes. The design of patterns and the micro-hole observation could give the theoretical reference for manufactures or engineers who wants to apply the laser perforation on composite paperboard.

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