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EXPLORING THE TENSILE STRENGTH OF PERFORATED PAPER FOR PACKAGING

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Abstract: *Contemporary packaging is more than just packaging and has other various roles that raise the product value. Technology development enabled packaging design to become more complex and improve quality and performance. Cutting different and complex shapes and forms has become a standard requirement in the packaging industry. Perforation has become one of the central elements of the packaging to aid the hole opening and product use, to aid the box forming process, and for design purposes. Packaging material requires sufficient tensile strength to maintain the primary role of packaging. Therefore, it is important to investigate the tensile strength of perforated paper in order to control the strength and durability of the packaging. Our research aims to investigate whether the paper material's tensile strength changes by using different perforation designs. We designed different perforations varying the bridge width. Cutting is done using CO2 laser technology Trotec Speedy 300 machine system. The obtained results show that different perforation designs (variations of bridge and gap width) require a different amount of force applied to break the paper material, regardless of paper grammage. Meaning that the same type of perforation design has the same tensile strength regardless examined grammage. This paper suggests further research and experiments regarding perforation for packaging.*

1. INTRODUCTION

There are various perforation purposes in the packaging and paper industry. One of them is to facilitate the folding and tearing off paper. Others are mainly used to allow a sheet of paper to tear out smoothly at a specific point without damaging the packaging material. For example, ease of tear is important for products such as return envelopes, postcards, stamps, tickets, information sheets, and coupons (Gattuso, 1989). Another use is the press-forming process which typically utilizes pre-cut and -creased paperboard blanks, which are subsequently formed into three-dimensional shapes (Leminen et al., 2013; Tanninen et al., 2014).

With laser technology, contemporary packaging is required to be much higher quality than earlier, and wider design possibilities are enabled. Cutting very small details and complex forms became industry standard. Besides the enhanced possibility compared to mechanical cutting and perforation, laser technology has many advantages over mechanical cutting and perforating. When using mechanical perforation, the perforation pattern can be damaged because of the physical contact between the perforating tool and the paper (Gattuso, 1989). Mechanical perforation can cause that holes to be incompletely perforated or missing and tend to weaken the material due to broken fibers (Piili, 2013). Incomplete or missing perforations increase the perforation pattern's tensile strength (Gattuso, 1989). Furthermore, the holes of the mechanical perforations close back after the perforation pins are removed, therefore preventing the air cannot from passing through (Gattuso, 1989). In contrast, laser holes are clean and remain open, allowing the air to pass through. Microscopic analysis showed that the pressure applied to both sides of a bridge performed in cardboard by the punching pins causes microscopic cracks responsible for weakening the perforation pattern (Gattuso, 1989). Their research also showed that the tensile strength of the laser micro perforation pattern is higher than the tensile strength of the mechanical micro perforation pattern (Gattuso, 1989). The loss of strength caused by the damaged bridges of the mechanical perforation pattern is higher than the additional tensile strength brought by the layer of fibers smashed at the bottom of the hole (Gattuso, 1989).

Mechanical tools such as knives on cutter machines also provide fiber sticking edge of the material, compared with laser (Piili, 2013). On the other hand, by using a laser to make a perforation, the holes that are created are open and of equal size (Mommsen and Stürmer, 1990; Brockmann, 1999). However, according to John Powell (Powell, 1998), there are many advantages of cutting paper using laser technology. Advantages are:

- It is a contact-less process, without bending or distortion of material during a cutting operation, unlike mechanical cutting
- Kerf width is very small (approximately 0.1 to 1 mm); consequently, it is possible to cut very small details without tool radius limitations
- It is a thermal process, and material evaporates during the cutting process
- Very high speeds of cutting
- No need for changing the tool – laser beam is the only tool
- High quality of cutting and engraving without defilement of material
- Easier workflow, design is created on a computer and directly sent to the laser
- No need for creating a die; therefore no need to change knifes

Since laser provides the highest cutting quality, this paper aims to test the laser perforation tensile strength, examine cutting perforation and test different perforation bridge widths. Furthermore, we investigate the tensile strength of different perforation designs and their dependence on paper grammage.

1.1. Tensile strength of the paper

An important requirement for the paper substrate is sufficient tensile strength for smooth and undisrupted processing operations without tearing (Riley, 2012). The tensile strength test is conducted according to ISO standard ISO 2758:2003. Tensile strength is a force required to break the material (Kirwan, 2005). During the influence of force, the material shows elastic properties up to a certain point. This means that tensile strength applied to paper material is proportional to deformation or elongation caused by applied force (Kirwan, 2005).

2. METHODS

2.1 Materials

The selected paperboard (*Zenith*) is commonly used for packaging food and drugs. Typical applications for this paper are (Ningbo Zhonguha Paper, 2022):

- Personal and Health care products
- Pharmaceuticals
- Media packaging
- Electronics and Entertainment products
- Book covers (215 g/m^2)
- Cigarette packaging (Offset printing, 215 g/m^2 for iner box and 235 g/m^2 for outer box)
- Base board for foil lamination
- Base board for vacuum metallization
- Chocolates and Confectionery packaging
- Desktop calendars

Paperboard specifications are shown in table 1.

Table 1: Zenith paperboard specifications

BASIS WEIGHT	g/m^2±3%	215	235	250	270	295	325	350	380
SIZE DEVIATION	mm	0 - 2							
MOISTURE CONTENT	%	6.0±1.0							

Testing conditions (ISO) temperature (23±1°C)
Testing conditions (ISO) Relative humidity (50±2%)

2.2 Samples

After laser cutting and perforating, the tensile strength of samples was tested using *Shimadzu Compact Tabletop Testing EZ-LX*. Samples were tested using a measurement cell of 2.5 kN, and the testing speed was 25 mm/min (Shimadzu, 2016). Samples were prepared for testing according to the standard for

tensile strength testing recommended by TAPPI T 494-om-1. Sample dimensions are 25mm in width, and 180 mm in height, with a constant stretching force speed of 25 +- 5 mm/min.
Perforation designs are tested on three different paper grammages: 295 g/m^2, 325 g/m^2 i 380 g/m^2. Several perforation designs were investigated, shown in figure 1. The bridge width and gap width are varied; the variations are:

- 2 mm bridge, 0.5 mm gap
- 2 mm bridge, 1 mm gap
- 2 mm bridge, 2 mm gap
- 2 mm bridge, 3 mm gap
- 3 mm bridge, 0.5 mm gap
- 3 mm bridge, 1 mm gap
- 3 mm bridge, 2 mm gap
- 3 mm bridge, 3 mm gap

Figure 1: Perforation designs

3. RESULTS AND DISCUSSION

One–way ANOVA is used to investigate whether there is a statistically significant difference between the breaking force of different perforation designs, shown in table 2.
Analysis showed that there is statically significant difference between different perforation design, for every paper grammage tested: 295 g/m^2 ($F=50,870$, $p<0,001$), paper 325 g/m^2 ($F=694,450$, $p<0,001$), paper 380 g/m^2($F=734,910$, $p<0,001$). Therefore, another analysis is conducted to find a perforation design requiring the smallest force to break and the highest amount of force. For paper 295 g/m^2 the smallest amount of force is required for perforation with a 2 mm bridge and 3 mm cut (M=5,90), and the highest amount of force is required for perforation of a 2 mm bridge and 0.5 mm cut (M=12,16). For paper 325 g/m^2 the smallest amount of force is required for perforation with a 2 mm bridge and 3 mm cut (M=5,90), and the highest amount of force is required for perforation of a 2 mm bridge and 0.5 mm cut (M=12,51). For paper 325 g/m^2 the smallest amount of force is required for perforation with a 2 mm bridge and 3 mm cut (M=6,80), and the highest amount of force is required for perforation of a 2 mm bridge and 0.5 mm cut (M=14,18). Results show that perforation design was not affected by paper grammage.

Table 2: Differences between perforation design for each grammage

Material	Perforation designs	M	SD	F	p
295 L	2 mm bridge 3 mm gap	5,909	0,299	50.870	0.000
	3 mm bridge 3 mm gap	6,812	0,343		
	2 mm bridge 2 mm gap	7,339	0,365		
	3 mm bridge 2 mm gap	8,855	0,406		
	2 mm bridge 1 mm gap	9,503	0,574		
	3 mm bridge 1 mm gap	10,567	0,505		
	3 mm bridge 0.5 mm gap	12,111	0,639		
	2 mm bridge 0.5 mm gap	12,160	0,523		
	Total	9,157	2,270		
325 L	2 mm bridge 3 mm gap	5,902	0,354	694.450	0.000
	3 mm bridge 3 mm gap	7,029	0,286		
	2 mm bridge 2 mm gap	7,523	0,384		
	3 mm bridge 2 mm gap	9,309	0,401		
	2 mm bridge 1 mm gap	9,705	0,414		
	3 mm bridge 1 mm gap	10,820	0,417		
	3 mm bridge 0.5 mm gap	12,349	0,455		
	2 mm bridge 0.5 mm gap	12,516	0,559		
	Total	9,394	2,331		
380 L	2 mm bridge 3 mm gap	6,804	0,368	734.910	0.000
	3 mm bridge 3 mm gap	8,086	0,315		
	2 mm bridge 2 mm gap	8,593	0,342		
	3 mm bridge 2 mm gap	10,656	0,296		
	2 mm bridge 1 mm gap	10,862	0,549		
	3 mm bridge 1 mm gap	12,020	0,447		
	3 mm bridge 0.5 mm gap	13,773	0,583		
	2 mm bridge 0.5 mm gap	14,185	0,517		
	Total	10,622	2,539		

4. CONCLUSIONS

The research aimed to evaluate and investigate the difference between various perforation designs using CO_2 laser technology. Therefore, different bridge widths and gap width of perforation were tested, and their tensile strength property. The results led to the conclusions:

- Regardless of paper grammage, perforation of a 2 mm bridge with 0.5 gaps required the highest force to break, whereas perforation of a 2 mm bridge with three gap widths required the lowest force to break.
- The highest force is required to tear perforation of 2 mm gap 0.5 bridge width, which is perforation with the smallest amount of cut area, therefore, requires the highest force to break.
- The tensile strength of paper material depends on the cut area size.

Obtained results can guide further investigation about packaging durability when using perforation and how much perforation lowers the tensile strength of the packaging. This research is a preliminary study to investigate the perforation designs further using laser technology. In addition, further research can be based on comparing laser perforation cutting and mechanical perforation regarding the analyzed difference between these two technologies.

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