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Influence of hole geometry on coating quality

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Abstract

This diploma work is a result of a cooperation between the Faculty of Engineering, Lund University (LTH) and the department of Material Treatment, Tetra Pak Packaging Solutions AB in Lund, Sweden. The production and tests were done at Tetra Pak Limburg respectively Lund, Autumn 2007.

Coating of large holes in a paperboard with few tenth of μm thickness layer of low density polyethylene (denoted LDPE) is challenging. The conditions during coating can lead to the appearance of small holes in the LDPE membrane, called holes in plastics (denoted HiP). The goal of this diploma work is to identify and test new top view hole geometries and evaluate the appearance of HiP located next to the edge of the hole.

The hole in the paperboard could be divided into two sections, inlet and outlet position, where inlet position is the edge of the hole that meets the LDPE layer first. HiP in inlet position could be related to the stretched LDPE layer, while HiP in outlet position could be caused by the LDPE build-up that is a consequence of lift in the paperboard during coating.

Six new test geometries were produced with conventional production machines. These, together with circular reference holes were divided into three theoretical groups and evaluated separately and compared within each group.

Test results showed that the top view geometry has an influence on HiP. It can also be proved that the lift in the paperboard is directly proportional to the amount of HiP in outlet position. Surprisingly, the amount of HiP in inlet position is reversely proportional to the lift in the paperboard, thus a small lift corresponds to a large amount of HiP.

Acknowledgements

First of all I want to thank my supervisors Gabor Benkö at Tetra Pak and Annika Olsson at LTH. Thank you both for your opinions, support and also for guiding me during these months.

Vladimir, my mentor at Tetra Pak, without your encouragement this project had not been the same. Thank you also for given me motivation and the solution when the result seemed far away.

I would like to thank all those who have contributed to the accomplishment of this diploma work:

So many people were involved to make the production of my test roll possible. Pelle (Per-Göran Heide) is the know-all at the department in Lund. Without you there are times I would have been completely lost – and I am sure I am not the only one who is happy to have you here! Lars Månsson is the man to trust when it comes to Pilot Plant and everything around it. Mats Brunnström was an outstanding coordinator and as fast in the turns as the decisions at Tetra Pak – and sometimes that means unbelievably fast!

Stefan at Briggen and the other guys at Pilot Plant for excellent work.

The whole production in Limburg; especially the guys at Laminator 21, and Florence, that welcomed me from the very first day in Germany.

Others that have contributed with excellent information sources – Linus, Karin, Anna-Karin, Niklas and Andreas – thank you all.

Günther Lanzinger and Kaj Johansson for giving me their time to discuss defects.

Ulf Nyman from the division of solid mechanics at LTH for useful information, and Karl-Axel at LTH for an inspiring discussion.

The employees in Lab1, and a special thanks to Enikö Solyom that let me into her lab.

Ilona was fabulous whenever I needed help. You are the mother of this department and a lifeline for us who are new in the building. (and not only the new, I suppose!)

Thank you to the rest of the department for all your support and help! Therese, Micke, Christer, Gotte, Jonas Gottesson, Olga, Magnus, Jonas Håkansson, Rolf, Mats Trulsson, Seppo, Karl Håkan and all the others at the department of Material Treatment– thank you for your friendliness!

My family has always seemed interesting in my activities, not only educational ones. Thank you for always caring of me.

To Mathieu, my daily support and love; thank you so much for being here. You are constantly in a mood to help me out, and you can always make me smile. Je t’aime mon cœur. ☺

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1. Introduction

1.1 Background

This diploma work is a result of cooperation between the Faculty of Engineering, Lund University (LTH) and the department of Material Treatment, Tetra Pak Packaging Solutions AB in Lund, Sweden.

Tetra Pak is a part of Tetra Laval Group, which is a private Swedish industrial group with headquarter in Switzerland. Together with DeLaval and Sidel they are three independent organisations which all can cooperate if there is an advantage. Together these three companies cover almost the whole area when it comes to processing, packaging and distribution of all variants of food.[1]

Tetra Pak itself works for and with its customers to provide preferred processing and packaging solutions for food. It supplies hundreds of different types of carton packaging formats, most of them made of paperboard and low density polyethylene (LDPE).[2]

1.2 Extrusion coating

Coating is the process in which a substance is applied on another substrate. One of the industrial forms of coating is extrusion coating. In this type of coating, a molten substance is extruded from a die and pressed onto or into the surface of a solid object or material in a nip, adhering to the surface and thus coating the surface (Fig 1.1). The purpose of the coating process is to combine the properties of two or several different materials.[3] Some of the materials most widely used in extrusion coating by packaging industries are paperboard, polymer film, and metal foil.[4] Throughout this work, coating refers to a layer of extrusion coated LDPE on paperboard.

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[1] www.tetrapak.com
[2] Ibid
[3] www.specialchem4adhesives.com
[4] www.wikipedia.org

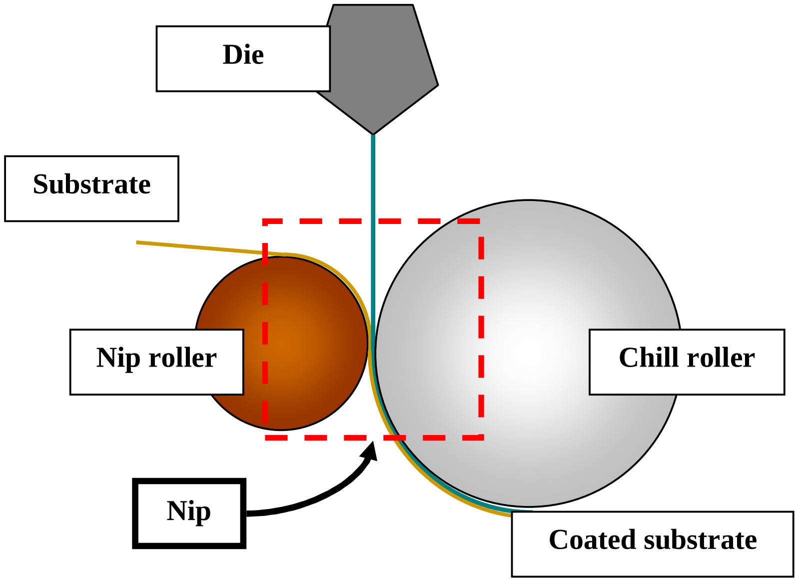

Fig 1.1 Extrusion coating.

1.3 Problem description - Extrusion coating of paperboard with holes

Coating of large holes (dimension >>1mm) with few tenth of μm thickness layer of LDPE is challenging. When applied on a smooth surface paperboard, the molten and tensed LDPE layer hardens uniformly over the surface. When applied over a hole, the LPDE “flows” into the hole. At the edge of the hole on the side that meets the LDPE layer first, (named inlet position, Fig 1.2) the tensed LDPE layer looses contact with the paperboard and becomes stretched. The excess LDPE creates a build-up on the opposite edge of the hole (named outlet position, Fig 1.2).

The conditions described above can lead to the appearance of small holes in the LDPE membrane. The holes are called holes in plastics (denoted HiP). HiP can potentially appear along the entire surface of the LDPE membrane. In case a multi-layer material is produced, i.e. the paperboard is coated with several layers of plastics, HiP in the middle of one membrane is covered by another layer. The probability of having two/several HiPs in two respectively several layers over each other in the multi-layer structure is very low. As a consequence, the multi-layer material can be made leakage proof, even if there are HiPs in the middle of the membrane.

The circumstances are opposite to the above for HiP located next to edge of the hole. In a multi-layer material the layers do not attach well to each other next to the edge of the hole, because it is difficult to assure good adhesion between the layers there. As a result, a multi-layer material with large number of HiP in different layers next to the hole edge is not leakage proof, since HiP are interconnected by tunnels in the low adhesion zone. The focus of this study is therefore on HiP next to the edge of the hole only (Fig 1.2).

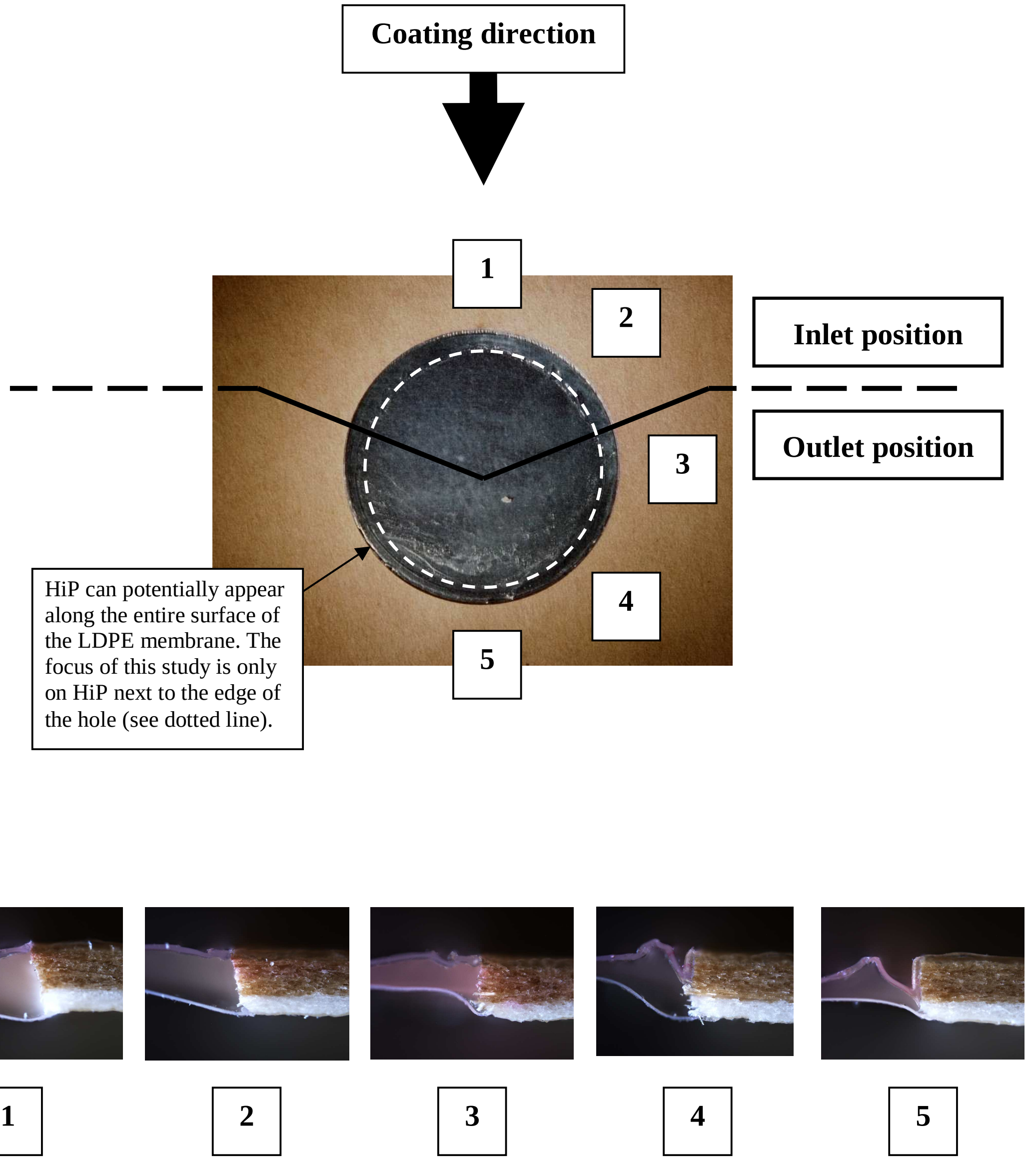

Fig 1.2 Upper image: LDPE coated circular hole.
Lower images: microscopy side view images of the edge of the hole. Pictures 1-5 show the evolution of the LDPE build-up over the hole. The border between inlet and outlet parts of the hole is drawn where the build-up starts.

1.4 Objective

The goal of this diploma work was to identify and test new hole geometries and evaluate the appearance of HiP located next to the edge of the hole, in a single LDPE coating layer. Due to three different hypotheses (Chapter 4.2), three groups of patterns were selected. The geometries within each group were each others opposite, so that a clear outcome of the hypothesis could be seen.

1.5 Focus

1.5.1 Parameters that may affect HiP

Some of the parameters that may affect HiP are presented below. This work focuses on the importance of the top view geometry of the hole only. Other parameters are chosen to be constant (Fig 1.3).

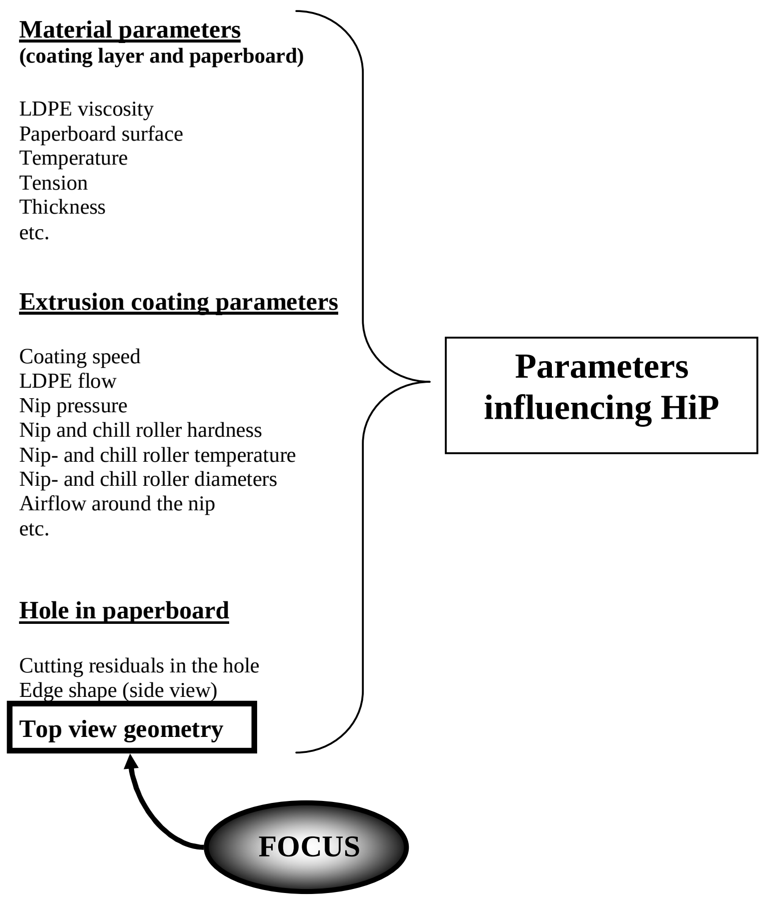

Fig 1.3 Project focus.

1.5.2 Geometrical limitations

A circular hole is chosen as reference in this study. The other geometries, presented later in this work, are derived from the reference with the condition that at least one of their dimensions is equal to the diameter of the reference hole. The study will not consider the affect of nibbled edges, such as “shark teeth”, or other saw teeth shapes.

2. Theoretical consideration

2.1 Extrusion coating at Tetra Pak

Depending on the final package's demand, different layers are added to the packaging material. In order to fulfil the needed properties of the packaging material, all coating machines used by Tetra Pak have between two and four stations of extrusion coating where a similar technique seen in Fig 1.1 is used (Fig 2.1).[5] All through the coating machine a tension is exerted on the paperboard with the purpose to stretch it up. Without this tension the paperboard is impossible to treat and run in the machine and it does not contribute with any problem as long as the paperboard is smooth. However, some of Tetra Pak's packaging solutions demand a hole in the packaging material, which considerably complicates the coating process.

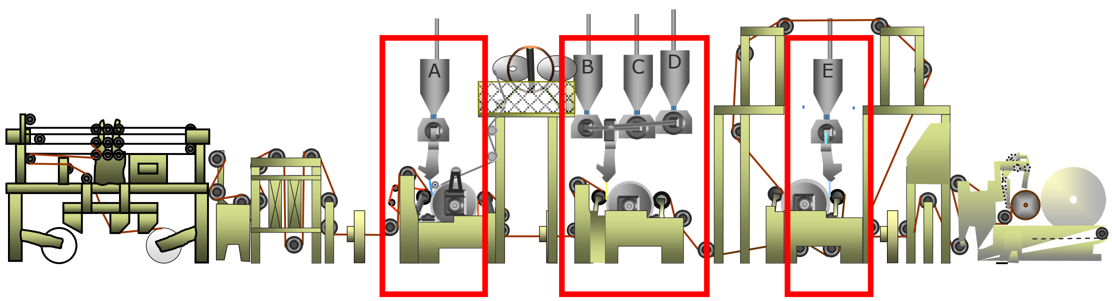

Fig 2.1 Coating machine with three stations of extrusion coating.

[5] Ponjavic Vladimir, Material Treatment, Tetra Pak Packaging Solutions AB, 2008

2.2 The tension theory

All homogeneous materials with holes behave in similar way when a tension is exerted on them. Tension exerted in one direction on materials gives rise to forces around the hole[6] (Fig 2.1). If the material is thin or the forces are large, it makes the material dented around the hole in a direction perpendicular to the direction of tension.

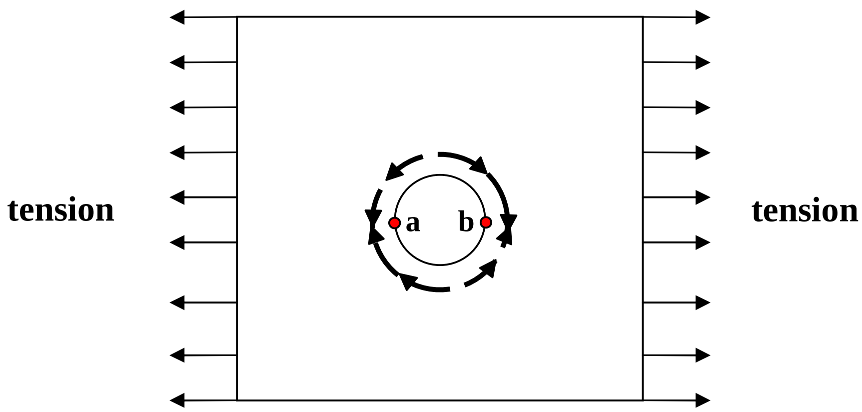

Fig 2.2 Forces arising around the hole when the material is under tension.

In this study the substrate material is paperboard and tension is exerted by the coating machine. Theoretically, the edge of the paper board should rise in positions a and b because of the tension.

[6] Sundström, B. *Handbok och formelsamling i Hållfasthetslära, third edition.* Fingraf, Södertälje. 1999.

3. Methodology

3.1 Qualitative and quantitative method

This diploma work is a scientific project with a need of a scientific valid result. For the methodical approach to receive comprehension of the subject, a qualitative method has been used. Any person that had some kind of relation to the subject and the problem was invited one by one for in-depth interviews and discussions.[7]

As the diploma work progressed, so was also the methodical approach. The second part of the project was distinguished by the quantitative method. Samples from the test roll, further presented in Chapter 3.7, was taken in a large amount and evaluated as a statistic result.[8]

3.2 The inductive and deductive method

Traditionally the scientific approach could be done either by inductive or deductive method.[9] The inductive method represents an open-minded way of thinking, where data is collected without any underlying theories in mind – the theories will be formed soon enough, anyhow.

When deductive method is used, hypotheses are formed more or less in the beginning of the project, and then tested in the following study. Using this single method would result in a very nonflexible study, which make me believe that a mixture of those two methods would be advantageous. This golden middle course is called abduction, and this is also the chosen method used in this diploma work.[10]

3.3 Comparison

Comparison is a very common method within research.[11] This method gives a relative result due to all included variables. The basic required conditions are as follow:

a) The system needs to be comparable. That is to say, all compared variables should only differ to each other in the specific area that is evaluated.

b) Units that are used are possible to compare.

c) A decision about what is worth to compare is made before the comparison.

d) The same measurements are used throughout the whole comparison.

e) Similarity as well as differences shall be described.

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[7] www.wikipedia.org
[8] Ibid
[9] Wallén, G. *Vetenskapsteori och forskningsmetodik, second edition.* Studentlitteratur, Lund. 1996
[10] Alvesson, M. *Tolkning och reflektion*. Studentlitteratur, Lund. 1994
11 Ejvegård, R. *Vetenskaplig metod, third edition.* Studentlitteratur, Lund. 2003

This diploma work is built up by comparison. Of eight different holes hole geometries, two of those are reference holes. I will use the same measurements, and the same techniques for each hole throughout the study.

Due to three different hypotheses, more profoundly presented in Chapter 4.2, three groups of patterns with two new test geometries in each group were selected. The two new test geometries within each group were deliberately one another's opposite, so that a clear outcome of the hypothesis could be seen. An important aspect was to select geometries that easily could be related to the circular reference hole. As a result of this, all test geometries have in common that at least one dimension is equal to the reference hole.

3.4 Reliability and validity

Every technique that is chosen to be used should always contain a good reliability and validity.[12] Since it is often the scientist that designs the measuring instrument, there is a risk that the reliability could be pretty low. A method like this used in this diploma work is the HiP detection method. For that reason a HiP detection test has been done twice, independent of each other. If a large difference between the two results is noticed, there is a risk that the method is non reliability. However, the HiP detection method used in this study proved to be reliable.

3.5 Research tools

3.5.1 Literature studies

This diploma work is a basic study. Therefore, no prior report was available at Tetra Pak or found in general literature.

3.5.2 Oral- and written communication

Where there is a need to understand an opinion or data it is common to use the method of interviewing or questionnaires.[13] Interviewing gives the possibility to get a more detailed answer than a questionnaire could do. Thereby, interviewing qualified employees at Tetra Pak was essential when a detailed input was needed. The basic information required in this diploma work is thus based on their knowledge.

In the very beginning of this diploma work people were invited to an idea generation to bring possible solutions to contribution to this work (Appendix). Individuals with different kind of backgrounds got the same need. The purpose was actually to give as little information as possible so the person could stay open-minded. The idea generation session resulted in many interesting propositions and creative ideas. Some of them were also put into practice in this work.

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[12] Ejvegård, R. *Vetenskaplig metod, third edition.* Studentlitteratur, Lund. 2003
[13] Ibid

3.6 Diploma work plan

The plan of the diploma work (Fig 3.1) and the structure of the written report (Fig 3.2) are presented below. The plan was used as a guideline throughout the project, with certain unexpected changes.

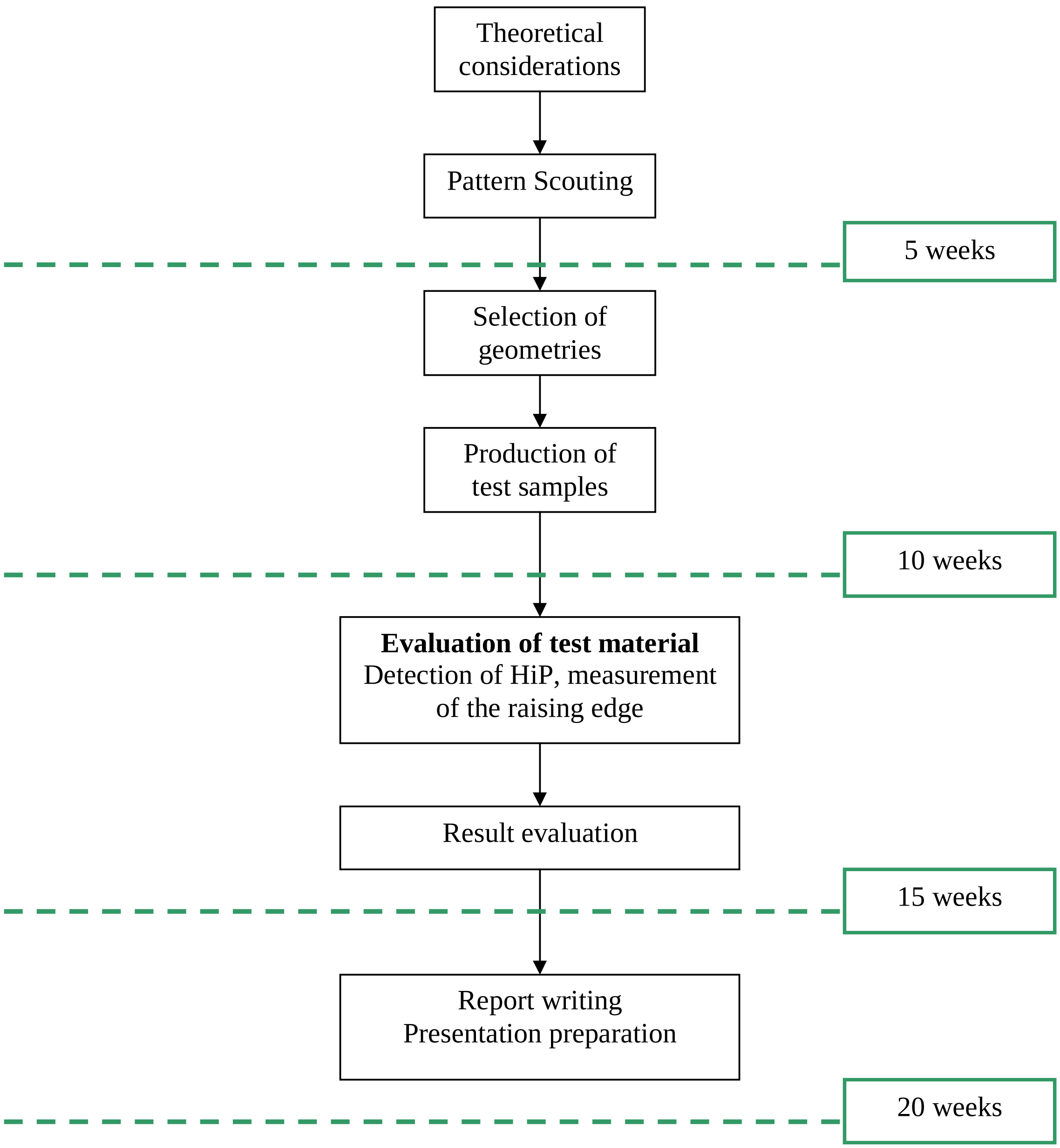


Fig 3.1 Main activities and the timeframe of the diploma work.

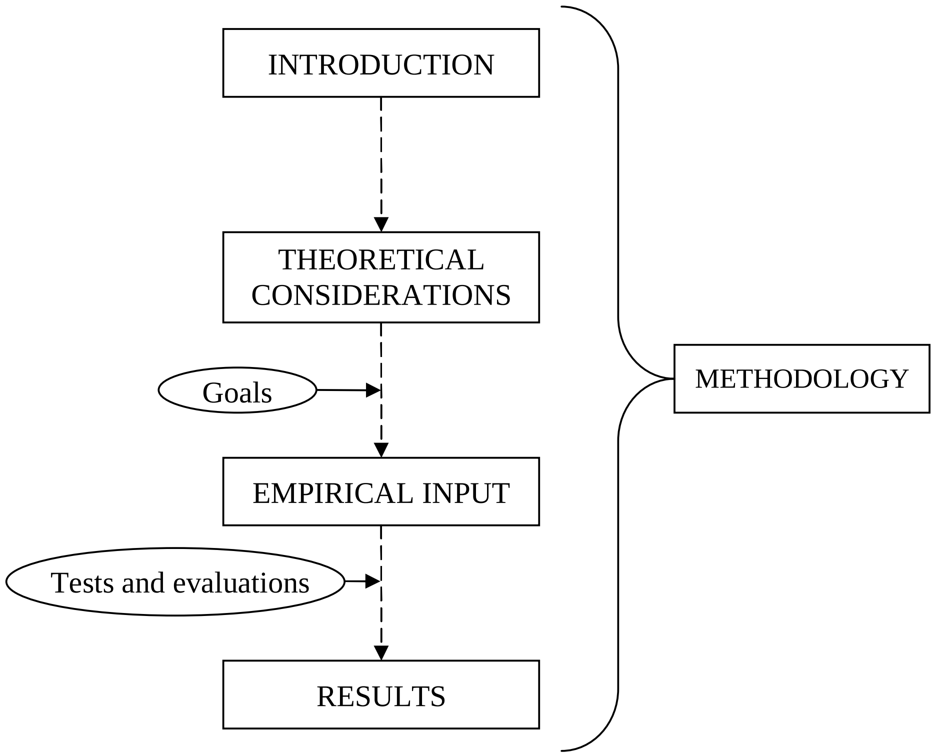


Fig 3.2 Workflow of report writing.

3.7 Production of test samples

The test samples, different hole geometries coated with LDPE, were produced with conventional production machines. In order to achieve good flexibility in hole geometries and good hole edge quality, the holes in the paperboard were produced with laser. As laser was used for practical reasons only, this diploma work will not contain any further information concerning laser techniques.

The thickness of the paperboard was ~0.4 mm and about 4000m long. The paperboard was coated in Limburg with several layers of LDPE in order to simulate production of packaging containers produced by Tetra Pak. The layers were later separated, and only the inner layers at each side of the paperboard were kept intact. The thickness of the studied LDPE layer was ~0,025 mm. The role of the other LDPE layer was to cover HiP in the middle of the hole and by this making the detection of HiP around the edge of the hole easier and reliable. All other parameters, related to the materials and the coating process, were kept constant.

The width of the paperboard roll that was used in this diploma work measured ~1m. To assure that large web width has no influence on the results, two reference holes were placed at both edges of the workspace. The distribution of the holes over the paperboard roll is shown later.

3.8 Evaluation of test material

3.8.1 The raised edge

High speed photography was used to capture the raised edge caused by forces acting around the hole (Fig2.1). With this method it is hard to get an exact measure of the raised edge, since the quality of the photo depends on the angle and distance from the camera to the material. Below, two pictures taken with a high speed camera show the difference between a hole with a large raised edge and a hole with a relatively good contact to the nip roller (Fig3.3).

Fig 3.3 Representative images taken with high speed camera.
Left: large raised edge. Right: Low raised edge.

To obtain a result possible to measure and evaluate, the LDPE build-up in the outlet position of the hole was used as a measure for raised edge. The relation between the LDPE build-up and the raised edge is presented in Chapter 4.1. The exact height of the build-up was measured from side-view microscopy images. The images were taken in the cross sections of the holes where the build-up reached its maximum height. This is usually in the middle of the outlet position, except the hole B1 where the maximum build-up is slightly off (~2 mm) from the middle of the outlet position. See Chapter 4 for more details on the different hole geometries. Five samples per variant were measured and the mean value was used in the evaluation of HiP results.

3.8.2 Detection of HiP

The following test method was used for the detection of HiP:

- Red coloured isopropranol solution was spread over the studied LDPE membrane.
- The solution was kept for about three seconds on the surface. If HiP was present around the hole edge, the solution flew through the HiP and painted the paperboard red (Fig 3.4).
- The red marks were registered and grouped according to their position. Each hole was divided in 8 positions. HiP falling into the 3 upper positions were considered as HiP in inlet position during evaluation. The 5 lower positions were counted as HiP in outlet position. See Chapter 5 for details.

Fifty samples of each variant were tested and evaluated. In order to verify the test method and validate the results, an additional 25 samples of each variant were tested. The results were corresponding, and the method proved to be reliable. The results presented in this work are based on the evaluation of all 75 samples.

Fig 3.4 Positive HiP sample.

4. Empirical input

4.1 The raised edge

Theoretically, the tensions exerted by the coating machine presented in Chapter 2.1 could be seen all over the coating machine. However, it is expected that the tensions which affect the hole increase around the nip, and accordingly raise the edges of the hole, both in inlet and outlet position (Fig 4.1). This is also what high speed photography reveals: the edge of the hole is raised over the nip roller just before the hole enters the nip (Fig 4.2).

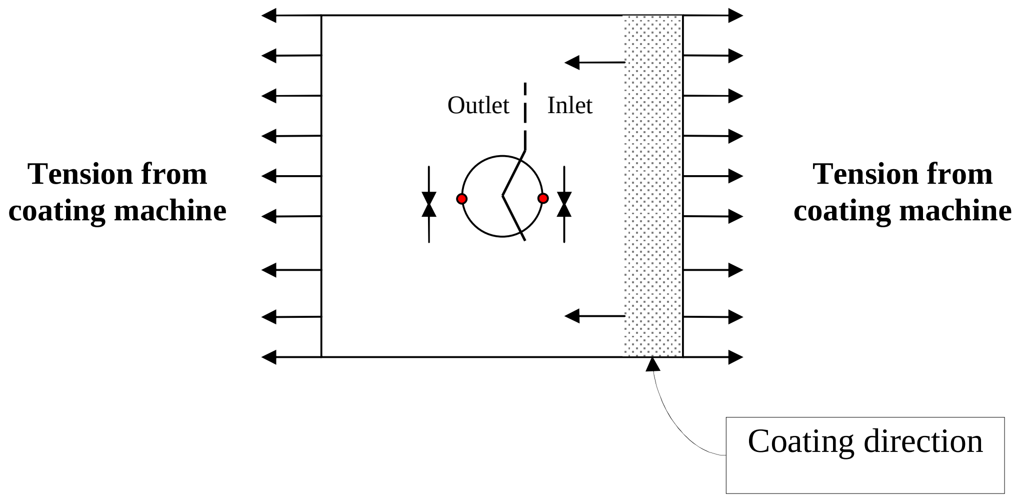


Fig 4.1 Forces caused of the tension from coating machine are acting on the material next to the hole. Forces perpendicular to the tension are formed in areas marked with red colour, and this is the reason to the raised edge in these positions.

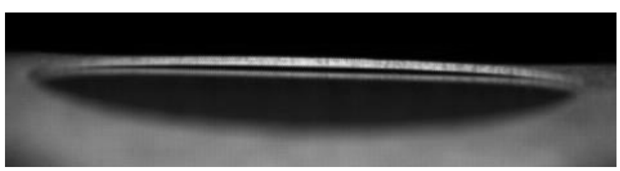


Fig 4.2 The raised hole edge captured by high speed camera.

Below, simplified pictures present what presumable happens during coating in the nip when simulating the raised edge (Fig 4.3). The pictures show that the raised edge is directly related to the build-up presented in Chapter 1.2.

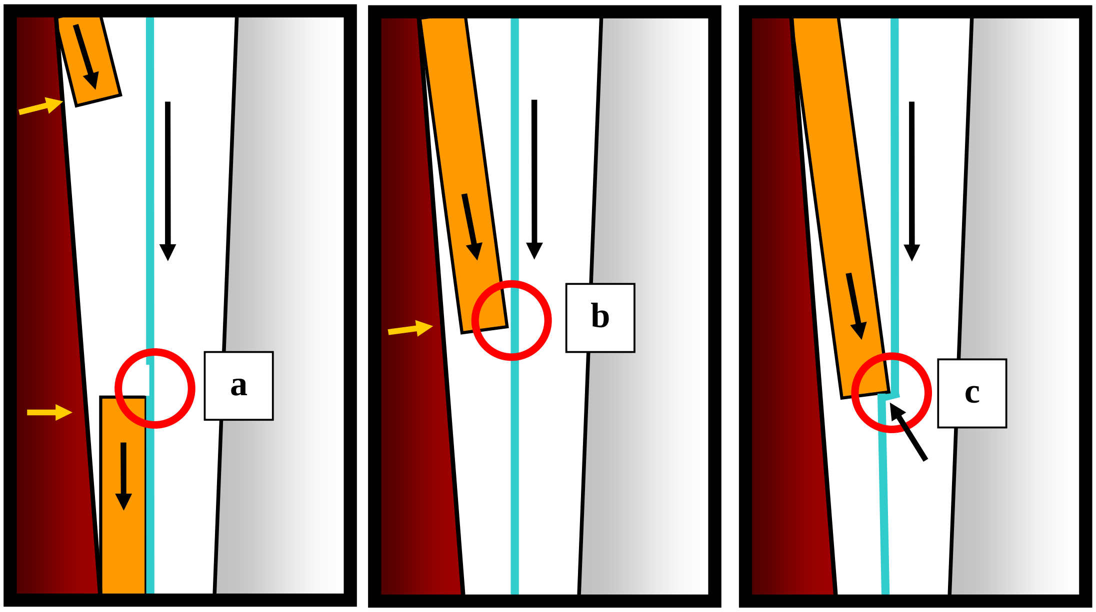


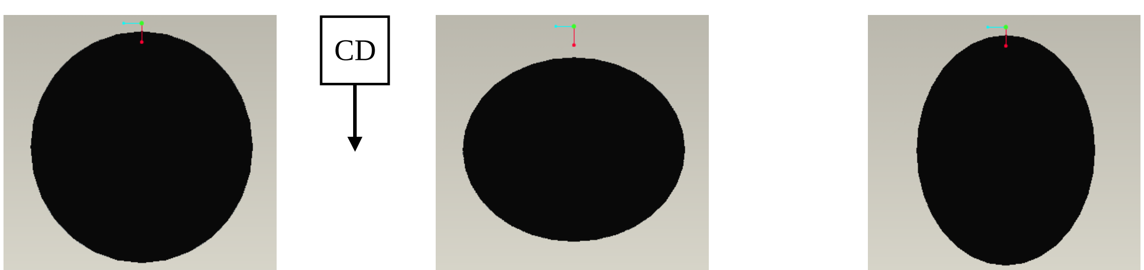
Fig 4.3 The stretched LDPE is pressed to the raised hole edge in the inlet position of the hole (a). Due to the raised edge in the outlet position, the paperboard meets the LDPE layer in an angle (b) and the LDPE build-up is formed (c). Arrows indicate material movement (paperboard respectively coating material LDPE).

4.2 Three groups of patterns

Due to three different hypotheses with the purpose to affect HiP, three groups of patterns were created.

4.2.1 Group A – the hypothesis of tensions

As mentioned in Chapter 2.2, the force acting around the edge of the hole (Fig 2.2) depends on the dimension of the hole perpendicular to the direction of tension. Based on this, it is expected that an elliptic hole with its long axis pointing in the direction of tension will raise less than a circular hole. It is then expected from the theory that the inlet and outlet edges of A2 are going to raise less than those of reference hole and A1.(Fig 4.4)

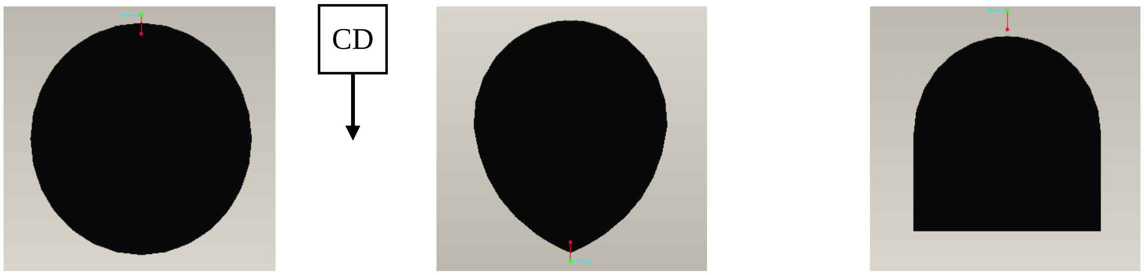


Reference hole *A1* *A2*

Fig 4.4 Group A

4.2.2 Group B – Change of geometry in outlet position

The geometries in this group have a different geometry in the outlet position, where the LDPE build-up is present. It is expected that HiP varies with the LDPE build-up. (Fig 4.5)

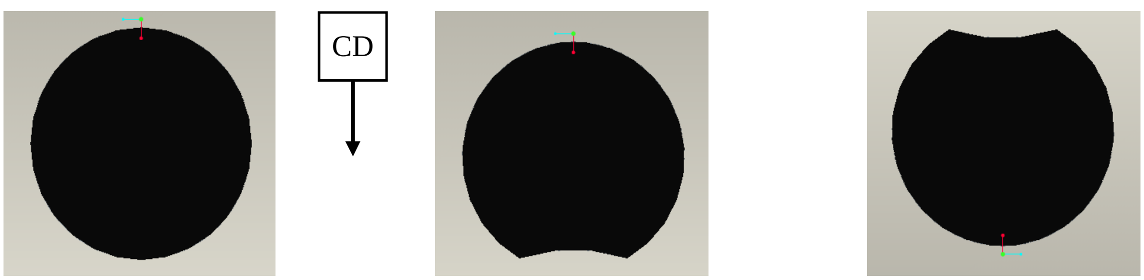


Reference hole *B1* *B2*

Fig 4.5 Group B

4.2.3 Group C – The shovel hypothesis

A common solution from the participants of the idea generation for forcing the hole edge down on the nip roller during coating, was to introduce a concave arc into the hole. This was later called shovel. As an outcome of this shovel hypothesis, two shovel geometries were tested. It is expected that the shovel will force the hole edge down to the nip roller, and as a result the LDPE build-up will be smaller in C1 than in the reference sample. C2 is the mirror image of C1 with the shovel in the inlet position. (Fig 4.6)



Reference hole *C1* *C2*

Fig 4.6 Group C

4.3 Production scheme

The production scheme showing how the geometries were distributed over the paperboard roll during production is presented below. (Fig 4.7) As mentioned in Chapter 3, two circular reference holes were produced.

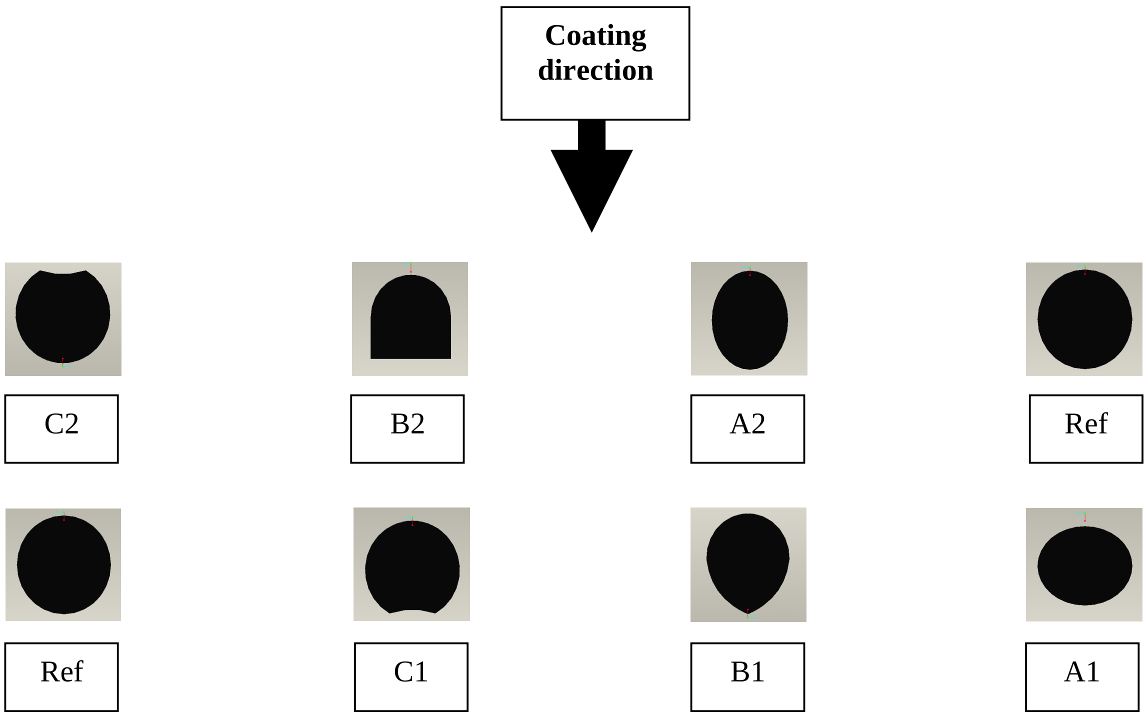


Fig 4.7 Production scheme.

5. Results and discussion

In Chapters 1 and 2 the probable causes for HiP generation in inlet and outlet positions of the hole are introduced. HiP in inlet position could be related to the stretched LDPE layer, while HiP in outlet position could be caused by the LDPE build-up (Fig 4.3). Therefore, it is of great interest to evaluate the results in each position. Unfortunately there are no test methods suitable for measuring the stretched LDPE layer in the inlet position. That is why HiP in the inlet position is not investigated in function of the stretched membrane.

For better understanding, the results are presented separately for the theoretical groups created in Chapter 4. First of all, the total amount of HiP for each geometry is presented; secondly, HiP in inlet position; and finally, HiP in outlet position is discussed.

5.1 Total HiP

Test result show that HiP is a common defect; close to 100% of all coated holes have HiP. The total amount of HiP for each geometry is presented below (Fig 5.1). The color grading shows the probability of finding HiP in each position. The results show a large HiP variation with hole geometry. For white fields, no HiP has been found on 75 samples.

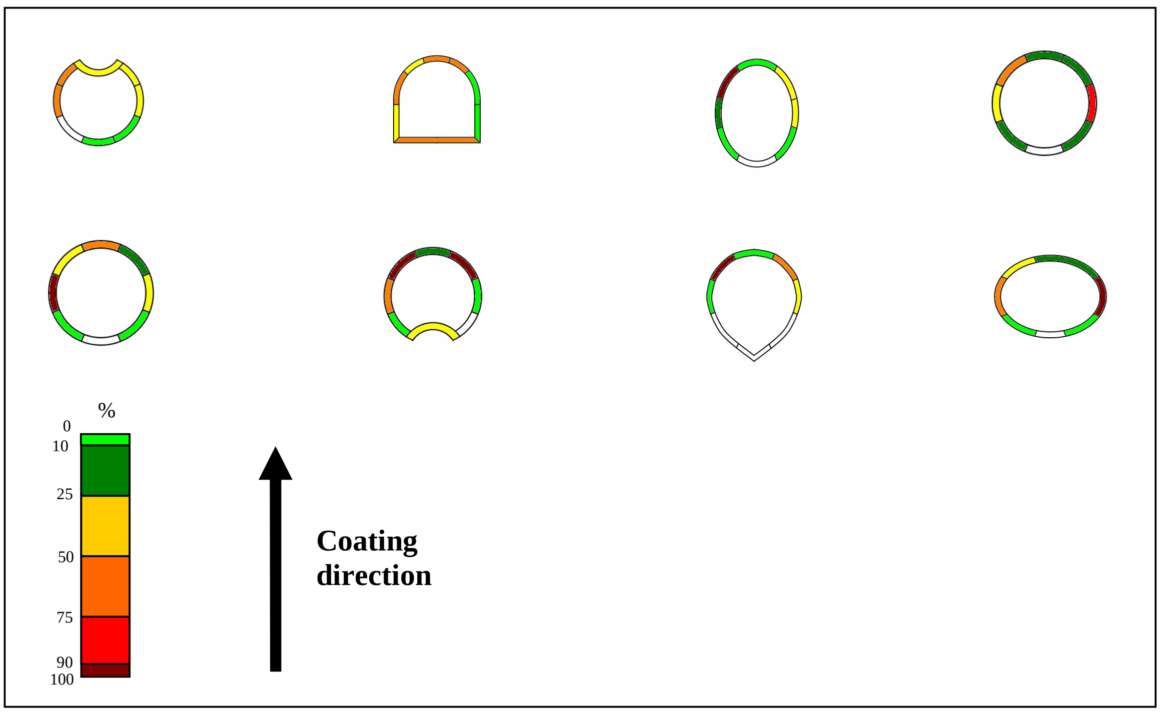
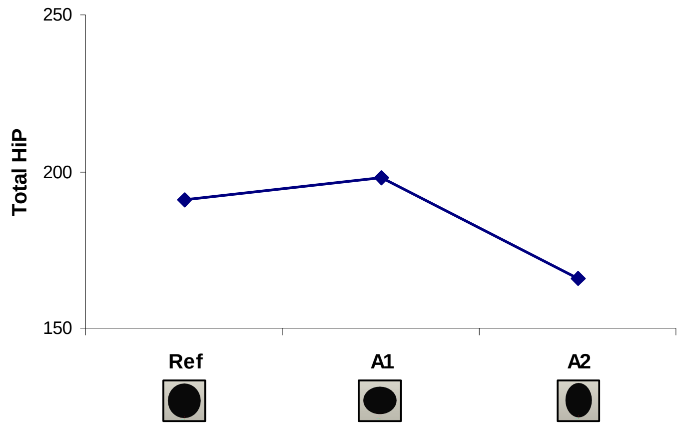
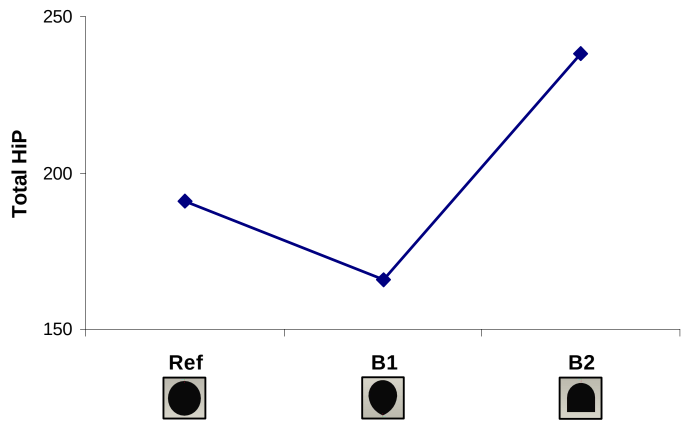


Fig 5.1 Rate of HiP for each geometry.

Group A



Group B



Group C

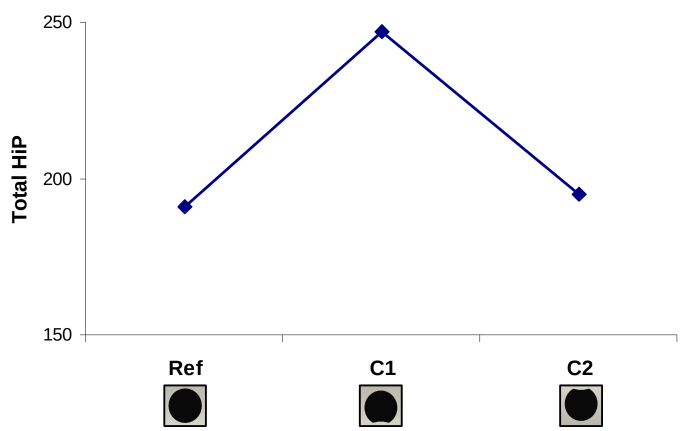


Fig 5.2 Total HiP from 75 samples per geometry.

Generally it is seen that the geometry does affect the total HiP rate. The three geometries with smallest amount of HiP are A2, B1 and the reference hole, where A2 and B1 are prominently better than the reference. These two geometries could also be seen as similar, as these are the only ones with a long and narrow shape in coating direction.

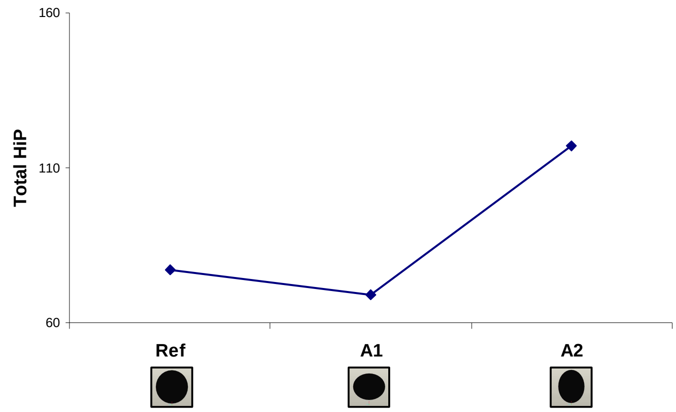
What is more surprisingly, A1 has only a marginally higher rate of HiP than the reference. The difference between A1 and the reference hole was expected to be larger. Here it could be discussed whether the dimension of the reference hole with this particular choice of material composition has reached its upper limit of raised edge.

Changes of geometry in inlet position do not seem to affect the total HiP (Fig 5.2 C2). Contrary, changes in outlet position seem to affect the rate of total HiP remarkable (Fig 5.2 B1;B2;C1)

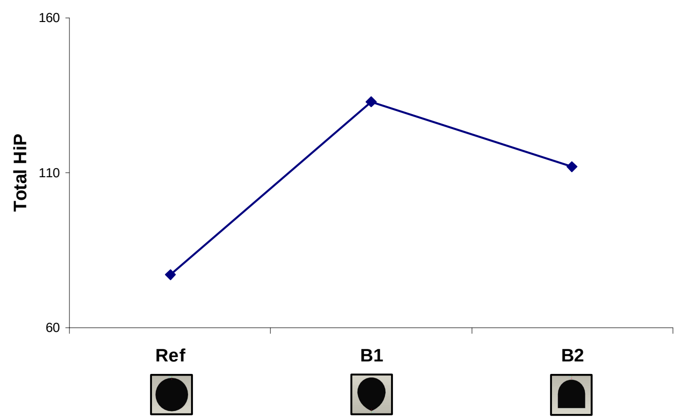
5.2 HiP in inlet position

The total amount of HiP in inlet position for each geometry is presented below.

Group A



Group B



Group C

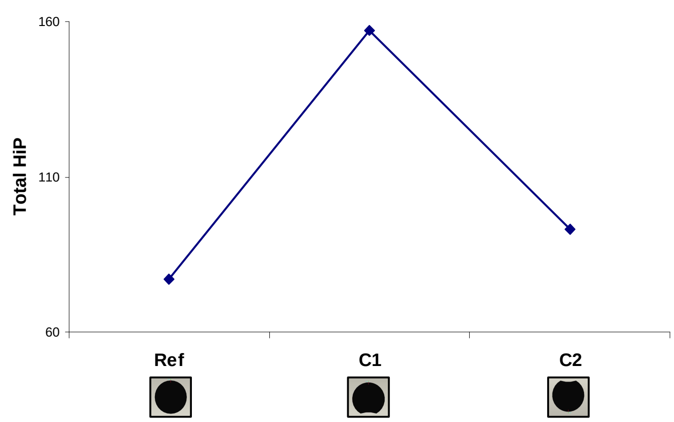


Fig 5.3 HiP in inlet position from 75 samples of each geometry.

It is clear that the geometry of the hole does affect HiP in inlet position. Variations of geometry in outlet position seem to affect the amount of HiP in inlet position
(Fig 5.3 Group B).

As C2 has similar rate of HiP compared to the reference hole. Contrary, shovel in outlet position in C1 increases HiP in the inlet position. The conclusion can be taken that the shovel in inlet position does not affect HiP in the very same position. However, the geometry in outlet position appears to have an importance to HiP in inlet position.

5.3 HiP in outlet position

The total amount of HiP in outlet position for each geometry is presented below.

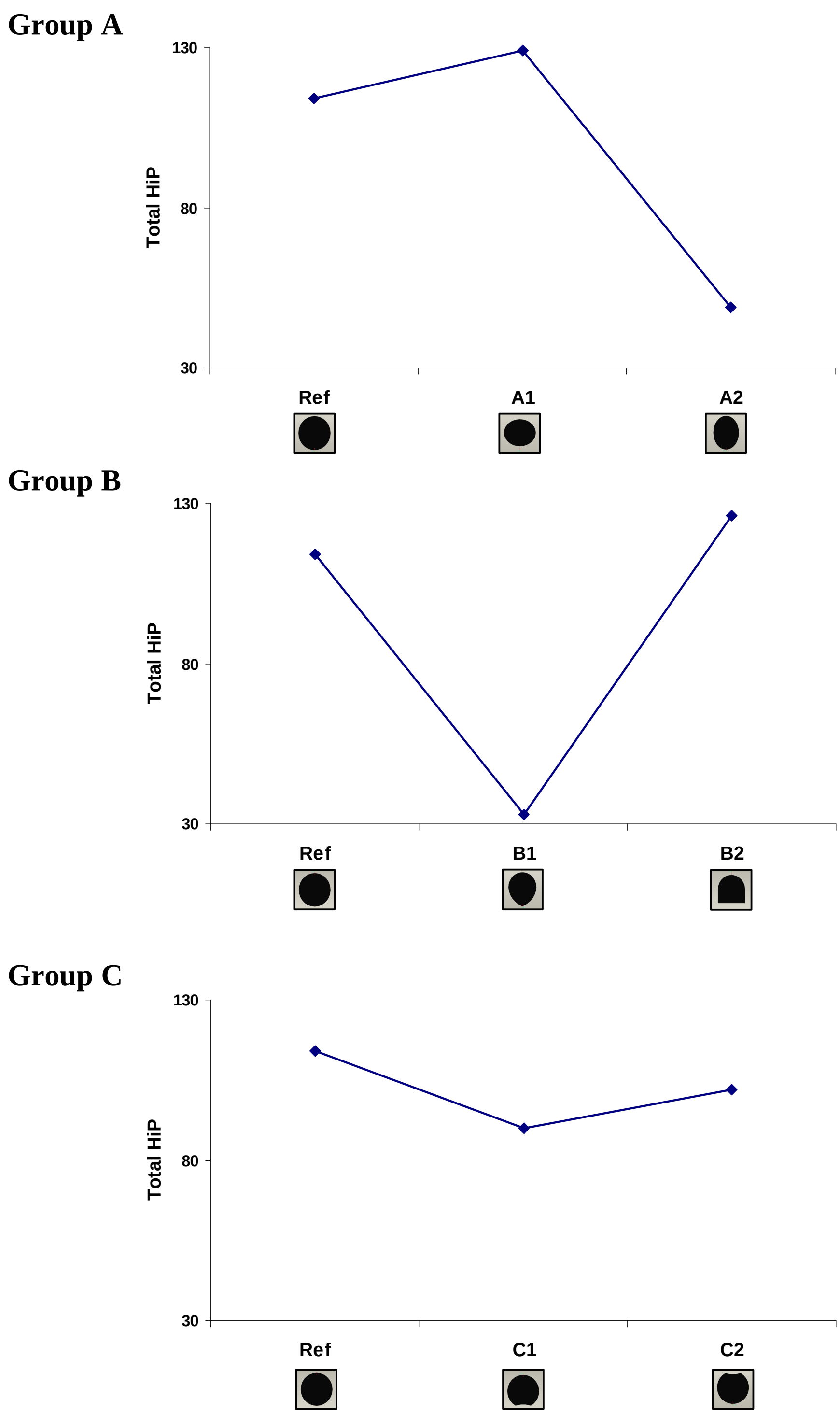


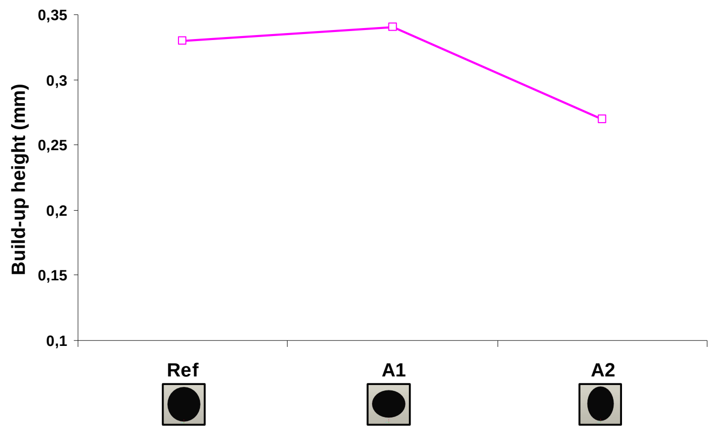
Fig 5.4 HiP in outlet position from 75 samples of each geometry.

It is an obvious fact that the geometry of the hole does affect HiP in outlet position. A2 and B1 have geometries that lead to a remarkable reduction of HiP in outlet position compared to the rest of the geometries. It also seems like a change of the hole geometry in inlet position does not affect the rate of HiP in outlet position (Fig 5.4 C2).

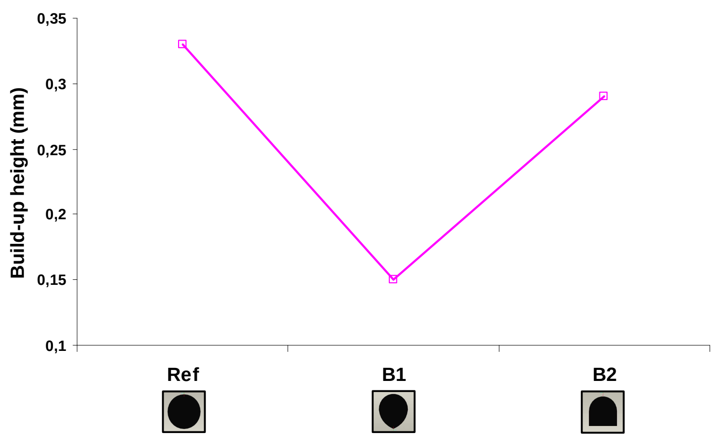
5.4 Raised edge

The largest build-ups in outlet positions are presented below.

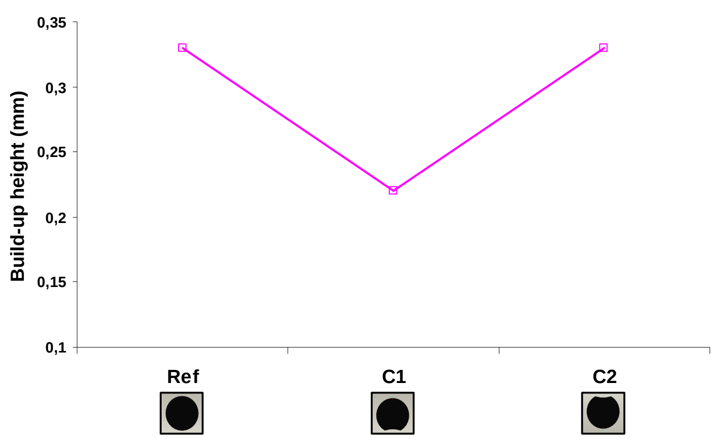
Group A



Group B



Group C



The *Fig 5.5 Mean value of LDPE build-up in outlet position.*

LDPE build-up is the smallest for C1, B1, and A2. Among these could the decrease of build-up in geometry A2 easily be explained referred to the tension theory presented in Chapter 2.1. From the result with the decrease of build-up for geometries B1 and C1, the conclusion is that the special hole geometry in outlet position in those geometries leads to a smaller build-up.

The difference between the reference hole and the laying ellipse, A1, is not as remarkable as foreseen. This could be a design fault made because of the limitations of the dimensions, mentioned in Chapter 4.2. This contributes to a smaller geometric difference between the laying ellipse A1 and the reference hole, than the difference between A2 and the reference hole in the critical area marked in Fig 5.6.

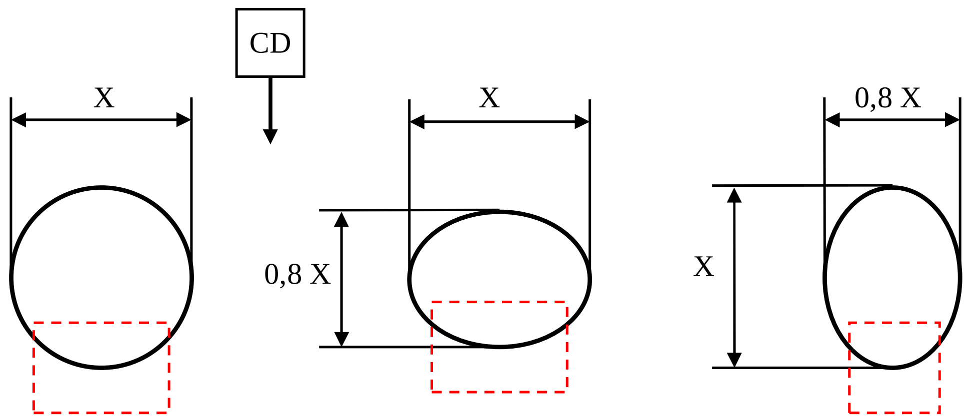


Fig 5.6. Geometric differences in critical area.

5.5 HiP vs. LDPE Build-up

The comparison between HiP and the build-up is presented below.

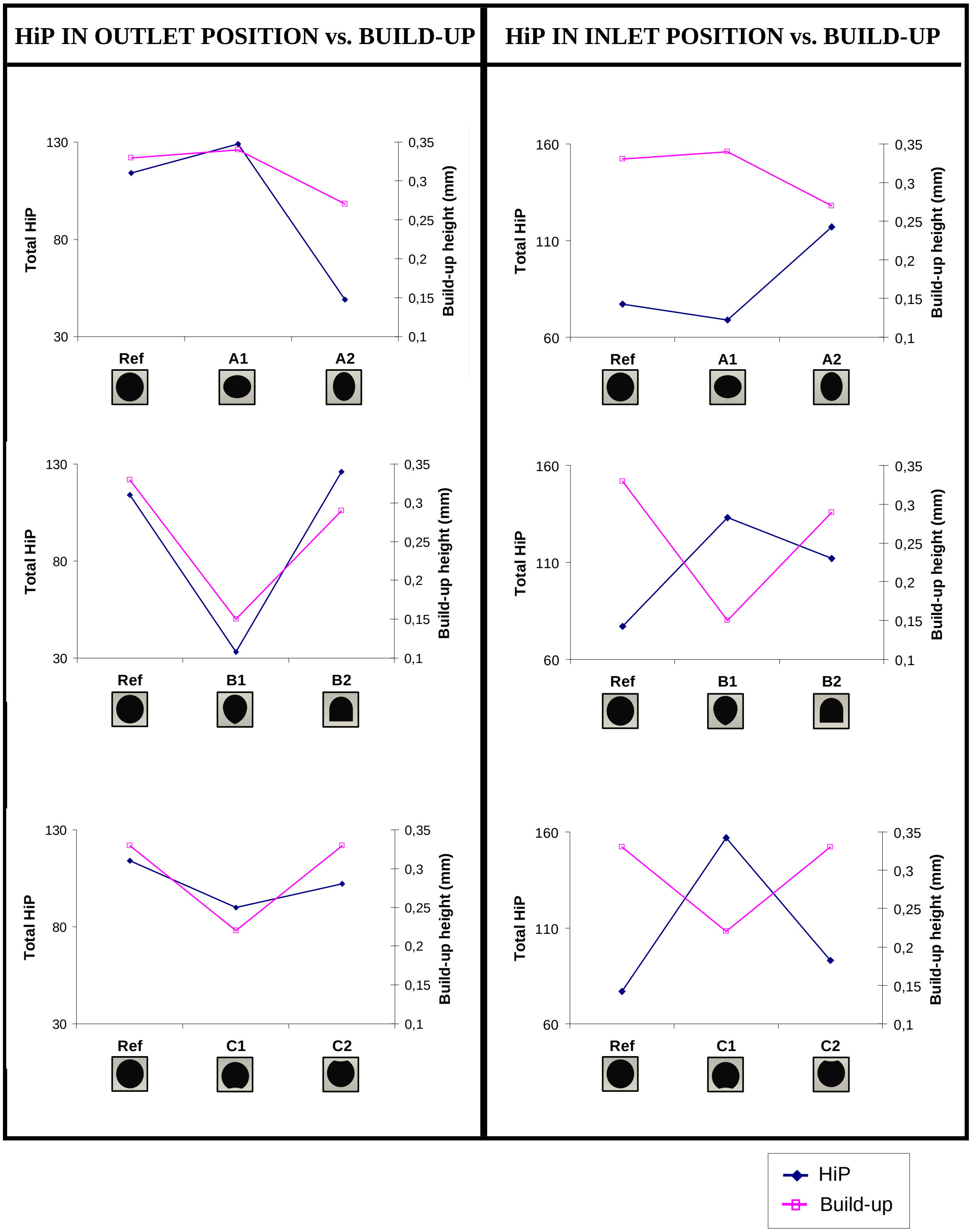


Fig 5.7 Comparison between HiP and LDPE build-up.

The build-up height does have an influence on the amount of HiP in outlet position. A small build-up leads to a low rate of HiL in outlet position. Opposite, a large build-up leads to a high rate of HiL in outlet position.

Surprisingly, the build-up height also has an influence on the amount of HiP in inlet position, thus a small build-up leads to a high rate of HiL in inlet position. Opposite, a large build-up leads to a low rate of HiL in inlet position.

6. Conclusions

6.1 Findings

The results show that the geometry of the hole in the paperboard does influence the appearance of HiP in the following ways:

- Hole geometry influences HiP.

- The geometries that give a small LDPE build-up in outlet position, i.e. relatively low lift of the paperboard edge, gives a high rate of HiP in inlet position and a low rate of HiP in outlet position.

- Opposite to the above, a large LDPE build-up in outlet position, i.e. relatively high lift of the paperboard edge, gives a low rate of HiP in inlet - position and a high rate of HiP in outlet position.

TOTAL RATE OF HiP	
Geometry	**Rate of HiP**
A2	87%
B1	87%
Ref	100%

RATE OF HiP IN INLET POSITION	
Geometry	**Rate of HiP**
A1	90%
Ref	100%
C2	121%

RATE OF HiP IN OUTLET POSITION	
Geometry	**Rate of HiP**
B1	29%
A2	43%
C1	79%

Fig 6.1 Top three of geometries in each test group. The percentages show the rates of HiP in each geometry relatively the reference sample.

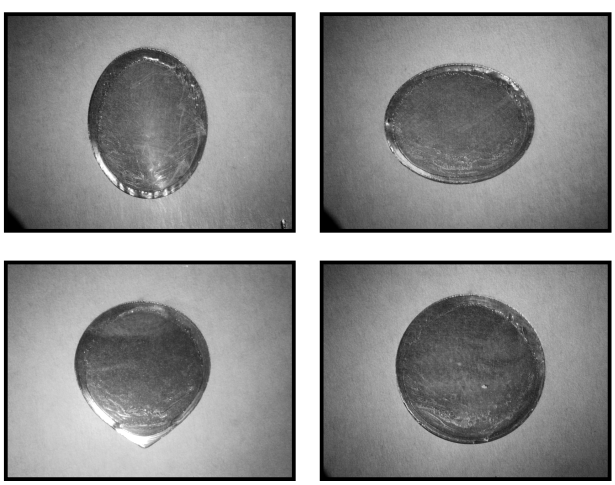


Fig 6.2 Images of A1, A2, B1 and reference.

6.2 Future study

Depending on Tetra Pak's interest for the result, this diploma work can be seen as a platform to further investigations. There are plenty of different ways to evaluate the geometries before they are totally confirmed as packaging solution. Whether Tetra Pak wish to continue the evaluation of the total rate of HiP, or if they prefer to concentrate their research on inlet or outlet position, the top three geometries could be the tested to see which one is the most suited for the purpose.

The world of HiP is far from fully discovered. In Chapter one, a list is showed where some of the parameters that may affect HiP is presented (Fig 1.3). Another not-yet-discovered parameter with changes on the product itself is for example to modify the side view edge shape of the hole.

References

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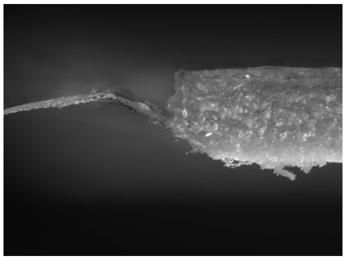
Appendix

IDEA GENERATION

You are invited to this idea generation where the goal is to come up with completely unprejudiced, new, fresh and creative ideas. The information you will be given is deliberate concisely, as an attempt to not make you locked up in the same old standard of thoughts.

The need

The need is to find new hole geometries (top view only) that reduce the LDPE build-up in the outlet edge of the hole after coating, and thereby reduce the number of HiPs around the edge.



Example of the LDPE build-up in the outlet position

Task

Your task of today is to generate at least three suggestions of hole geometries in 15 minutes, geometries that facilitate the coating process in outlet position.

Instructions

1. Please draw each new geometry on a new post-it note.
2. Do not forget to indicate the coating direction.
3. Write additional comments on the particular post-it note.
4. Please do not draw geometries with nibbled contours, such as shark teeth.

Example: