QUALITATIVE ASSESSMENT OF STRUCTURAL STRENGTH FOR THERMOFORMED HONEYCOMB SANDWICHED STRUCTURES

ABDUL RASHID BIN MARJUKI

UNIVERSITI MALAYSIA PAHANG

UNIVERSITI MALAYSIA PAHANG

DECLARATION OF THESIS AND COPYRIGHT

Author's Full Name	:	ABDUL RASHID BIN MARJUKI
Identification Card No	:	910824-12-6195
Title	:	QUALITATIVE ASSESSMENT OF STRUCTURAL STRENGTH FOR THERMOFORMED HONEYCOMB SANDWICHED STRUCTURES
Academic Session	:	2014/2015

I declare that this thesis is classified as:

☐	**CONFIDENTIAL**	(Contains confidential information under the Official Secret Act 1972)
☐	**RESTRICTED**	(Contains restricted information as specified by the organization where research was done)*
/	**OPEN ACCESS**	I agree that my thesis to be published as online open access (Full text)

I acknowledge that Universiti Malaysia Pahang reserve the right as follows:

1. The Thesis is the Property of University Malaysia Pahang.
2. The Library of University Malaysia Pahang has the right to make copies for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by:

_______________________________	_______________________________
(Author's Signature)	(Supervisor's Signature)
ABDUL RASHID BIN MARJUKI	ASSOC.PROF.DR. ABDUL AZIZ BIN JAAFAR
	Name of Supervisor
Date: ________________	Date: _________________

QUALITATIVE ASSESSMENT OF STRUCTURAL STRENGTH FOR THERMOFORMED HONEYCOMB SANDWICHED STRUCTURES

ABDUL RASHID BIN MARJUKI

Report submitted in partial fulfilment of the requirements
for the award of the Degree of
B.Eng (Hons.) Manufacturing Engineering

Faculty of Manufacturing Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2015

EXAMINER'S DECLARATION

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MANUFACTURING ENGINEERING

We certify that the project entitled "Qualitative Assessment of Structural Strength for Thermoformed Honeycomb Sandwiched Structures" is written by Abdul Rashid Bin Marjuki. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Manufacturing Engineering.

Signature:
Name of Examiner: NUR NAJMIYAH BINTI JAAFAR
Position: LECTURER
Date:

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Manufacturing Engineering.

Signature:

Name of Supervisor: ASSOC.PROF.DR. ABDUL AZIZ BIN JAAFAR

Position: LECTURER

Date:

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature:

Name: ABDUL RASHID BIN MARJUKI

ID Number: FA11063

Date: 16TH JUNE 2015

Dedication,

To my beloved Mum and supportive Siblings for the ongoing love and support

To my late Dad *Al-Fatihah*;

Before family comes nothing ♥

"amare et sapere vix deo conceditur"

ACKNOWLEDGEMENTS

My thanks and appreciation to Assoc. Prof. Dr Abdul Aziz bin Jaafar for persevering with me as my supervisor throughout the time it took me to complete this research. The idea and knowledge that he shared is countless for doing the research. Working with him was one of the most important and formative experiences in my life. I am grateful as well to Mr Ismail bin Mohd. Khairuddin for the endless supports. To Ms.Farah Amirah Binti Mohd.Ghazali who have generously given her time and expertise to better my work. I thank her for her contribution and her good-natured support.

I am grateful to many persons who shared their knowledge and experiences, especially to Nik Ruqiyah binti Nik Hassan and Nur Fadilah binti Mohd. Puzi for generously shared their meticulous thought and insights that supported and expanded my own work and by sharing their knowledge in machine application.

I must acknowledge as well the many friends, colleagues, lecturers and other librarians who assisted, advised, and supported my research and writing efforts over the year. Especially, I need to express my gratitude and deep appreciation to my teammates whose friendship, hospitality, knowledge, and wisdom have supported, enlightened, and entertained me over the many months we works as a team. They have consistently helped me keep perspective on what is important in life and shown me how to deal with reality. I am grateful too for the support and advise from my faculty Administration Staff; The Faculty of Manufacturing Engineering.

Finally, I would like to leave the remaining space to my parents and my siblings as there is no words can describes how big the contribution that they have make in my life and in this project.

ABSTRACTS

Honeycomb sandwiched structures is one of the most valued structural engineering innovations developed by the composites industry. Used extensively in automotive and aerospace technologies, the advanced material construction provides key benefits over conventional metal and structural designs by offering very low weight to power ratio, enhancing structural stiffness, improving durability and cost-effective alternatives. This project involved designing a Thermoforming prototype mould for thermoplastic based honeycomb cores based on industrial general practices. Design consideration includes the sizing of hexagonal cell and low in situ cutting forces. Proprietary polypropylene sheet was thermoformed on wire-cut EDM machined Aluminium (P20) mould. It was found that the 0.006sq.m sandwiched structured fibreglass with 0.001m thickness honeycomb cores stabilized at 0.2MPa compression surface forces.

ABSTRAK

Struktur Sarang Lebah diapit adalah salah satu struktur yang paling bernilai dan berinovasi dalam kejuruteraan struktur yang dibangunkan oleh industri komposit. Digunakan secara meluas dalam teknologi automotif dan aeroangkasa, pembinaan bahan maju menyediakan manfaat utama lebih dari logam konvensional dan reka bentuk struktur dengan menawarkan berat struktur yang sangat rendah kepada nisbah kuasa , meningkatkan kekukuhan struktur , meningkatkan ketahanan dan merupakan alternatif yang kos efektif. Projek ini melibatkan merekabentuk Termopembentukan prototaip acuan untuk termoplastik berasaskan teras sarang lebah berdasarkan amalan umum yang dipraktikkan oleh industri. Pertimbangan reka bentuk termasuklah saiz sel heksagon dan rendah daya pemotongan “in situ”. Lembaran polypropylene akan menjalani proses termopembentukan mengunakan acuan yang telah dimesin mengunakan “wire-cut EDM machine”. Ia telah mendapati bahawa 0.006sq.m yang diapit gentian kaca berstruktur sarang lebah dengan teras ketebalan 0.001m stabil pada 0.2MPa daya permukaan mampatan.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
CAD	Computer-aided Design
PP	Polypropylene

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

A mould is a block contained a shape cavity that is filled with a liquid or pliable material like polymer, glass, metal, or ceramic raw materials. The liquid hardens or sets inside the mould, copy its shape. Mould is the other option to a cast. The very common dual-valve moulding process utilized two moulds, one for each half of the object. Piece-moulding uses a number of different moulds, each creating a section of a object with complex geometry. This is usually only used for big and more hi-end objects. In all manufacturing process there are limitations or the ability of the process in moulding known as mouldability.

Plastic moulding is a type of manufacturing process which is the process of shaping plastic using a rigid frame or mould. This technique allows for the creation of objects of all shapes and sizes with highly design flexibility for both simple and huge complex designs. A popular manufacturing option, plastic moulding techniques are use for many car parts, containers, signs and other high volume items. Other than that, there are many plastic moulding processes and techniques, this investigation discusses on the techniques of drape forming.

The study shows that the thermoforming process is widely used to fabricate honeycomb base structure which is a highly valued engineering structure developed by the composites industry. It used extensively in automotive, aerospace and many other industries. The honeycomb sandwich provides the following key advantages over others structures such as light weight, massive stiffness, high durability and production cost savings.

1.2 PROBLEM STATEMENT

The application of advanced thermoforming equipments is widely used in today industries to produces high potential product honeycomb based structure which is not cost affective for a small scale manufacturer and will use up a bigger space to place the machine itself.

As to this, this research is conducted to assess the possibility of producing Honeycomb structure using low cost in-house built Thermoforming equipment.

1.3 OBJECTIVE

The objectives of this project are:

- to design positive thermoforming mould for honeycomb cores.
- to design positive drape thermoforming process for honeycomb foil.
- to evaluate compression test on sandwiched structured composites with honeycomb cores.

1.4 SCOPE OF RESEARCH

This project started by reviewing the product shape and relates it to the type of mould that will be use. The crucial thing in this process is the relation of the mouldability, shapes, process and expected product. After the review several decisions will be made to get the best design to fabricate the positive mould. The decision should be fulfil several factors such that effect several process such as application of the mould during the thermoforming process, process removing the product from the mould after the thermoforming process and force apply during cutting process after thermoforming process. The selected design will be used in CAD software(ANSYS) to generate the mould analysis and the shape achievement to investigate the mouldability of the product. Based from the limitation, some feature will be added to the mould for improvement to ease the production of the product.

CHAPTER 2

LITERATURE REVIEWS

2.1 INTRODUCTION

As a rule, the item shapes direct the state of the mould. Mould can be divided into three types, they are male or positive, female or negative and blended where the mould having both positive and negative attributes.

Parts produce by using male mould have a tendency to have more noteworthy draft angles , heavier base and corner and more slender edges, with within the item repeating the mould surface. Parts produce by using female mould have a tendency to have more modest draft edge, more slender base and corners and significant edges with the outer surface of the item recreating the surface of the moulds.

2.2 THERMOFORMING MOULD

Numerous moulds utilized as a part of thermoforming procedure have normal gathering and working parts. The instrument's pit is intended to structure the yearning last item shape and size focused around the plastic's qualities, for example, degree and bearing of shrinkage. The mould performs two similarly critical capacities particularly for thermoforming methodology. It characterizes one surface of the item and it goes about as heat exchanger to cool the item quickly from initiate temperature to launch temperature. The cooling capacity has an immediate connection in methodology connection on procedure matters in profit making.

The idea ceaseless became additional productive done despite the fact that there might be an issue. The fundamental issue is actually that the heat has to be targeted through one surface area on the product. The insulating space created due to imperfectly close contact between mould and the sheet in use. The cooling rate drastically drop due to this matter and lead to cause defects on the product after the process, for example uneven cooling process with uneven stresses attribute along the plastic. Moderating up the cooling pace will solve the problem, but lead to developing the cost use and resulting growing expenditures.The heat exchange function of the mould brought to an attention. Drape forming is carried out at relatively very low pressure, so moulds can be fabricate from light, cheap and can be machine materials as shown in table 2.1:

TABLE 2.1: Thermal conductivity table

Thermal conductivity-k-W/(m.K)			
Material	Temperature ° Celsius		
	25	125	225
Aluminium	205	215	250
Epoxy Resin	0.35	-	-
Wood	0.45	-	-

Source: Donald V.Rosato(2010)

Simultaneously, to enhance the heat transfer ability of the materials it will include expending expansive expense. The basic material utilized for thermoforming methodology is aluminium because of its properties as well as it's availability: alternative materials that can be use are, porous sintered metals, cast or sprayed low-melting-point, copper alloys or other form of alloys.

2.3 DESIGNING FOR MOULDABILITY

In designing mould there are some considerations to be taking into calculation to maximize the uniformity of the product shape produce. Based from Dr.Maple Plain study on Photomold(1999-2002) the design requirement are illustrate as follow:

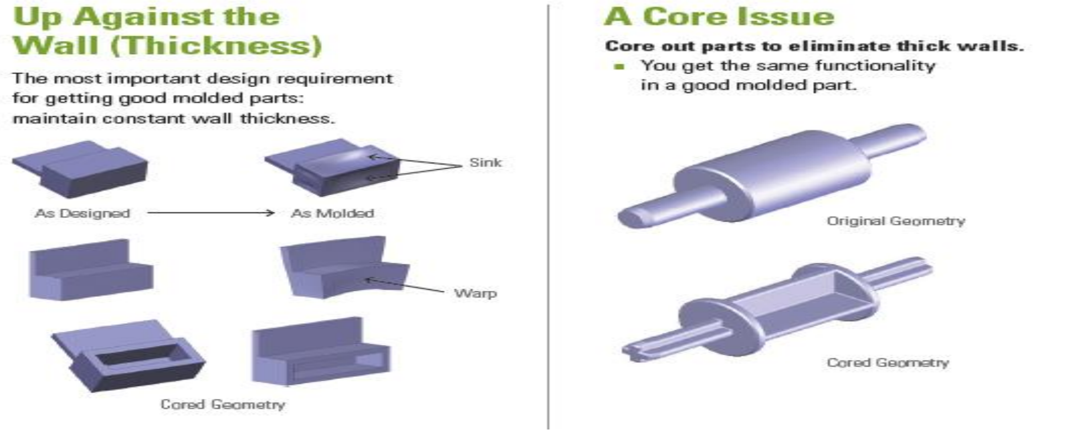
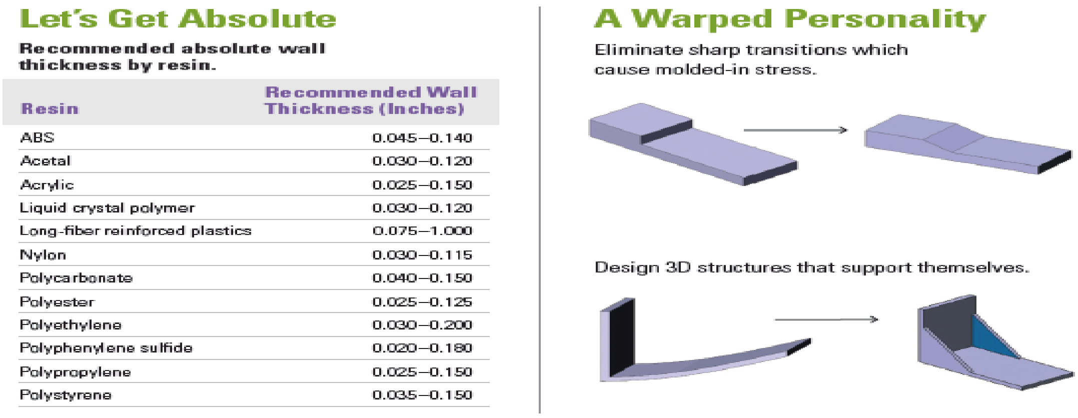


Figure 2.1: Wall thickness and core issue

Source : Dr.Maple Plain study on Photomold(1999-2002)



Resin	Recommended Wall Thickness (Inches)
ABS	0.045–0.140
Acetal	0.030–0.120
Acrylic	0.025–0.150
Liquid crystal polymer	0.030–0.120
Long-fiber reinforced plastics	0.075–1.000
Nylon	0.030–0.115
Polycarbonate	0.040–0.150
Polyester	0.025–0.125
Polyethylene	0.030–0.200
Polyphenylene sulfide	0.020–0.180
Polypropylene	0.025–0.150
Polystyrene	0.035–0.150

Figure 2.2: Wall thickness and warped personality

Source : Dr.Maple Plain study on Photomold(1999-2002)

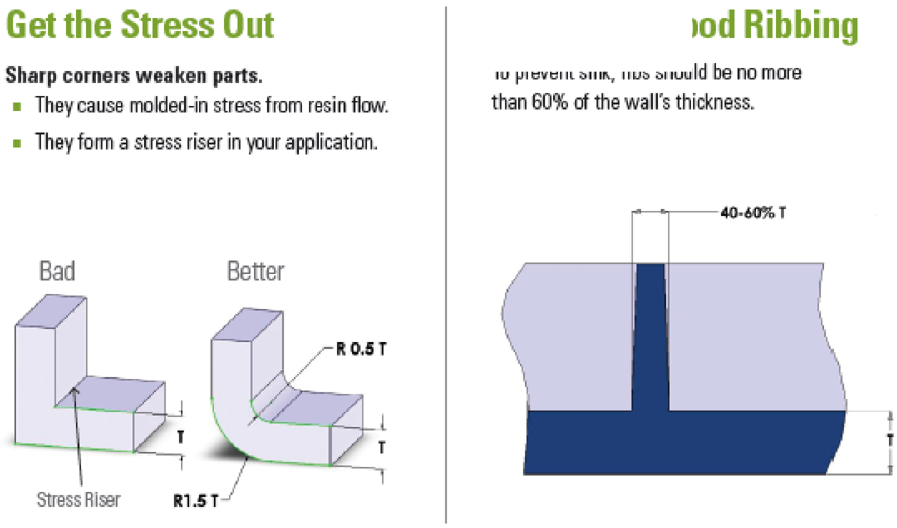


Figure 2.3: Stress and ribbing

Source : Proto Labs (1999-2002)

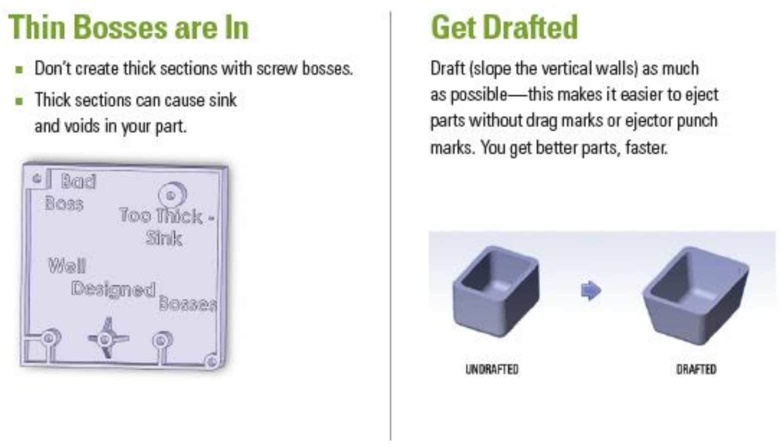


Figure 2.4: Thin bosses and draft angle

Source : Proto Labs (1999-2002)

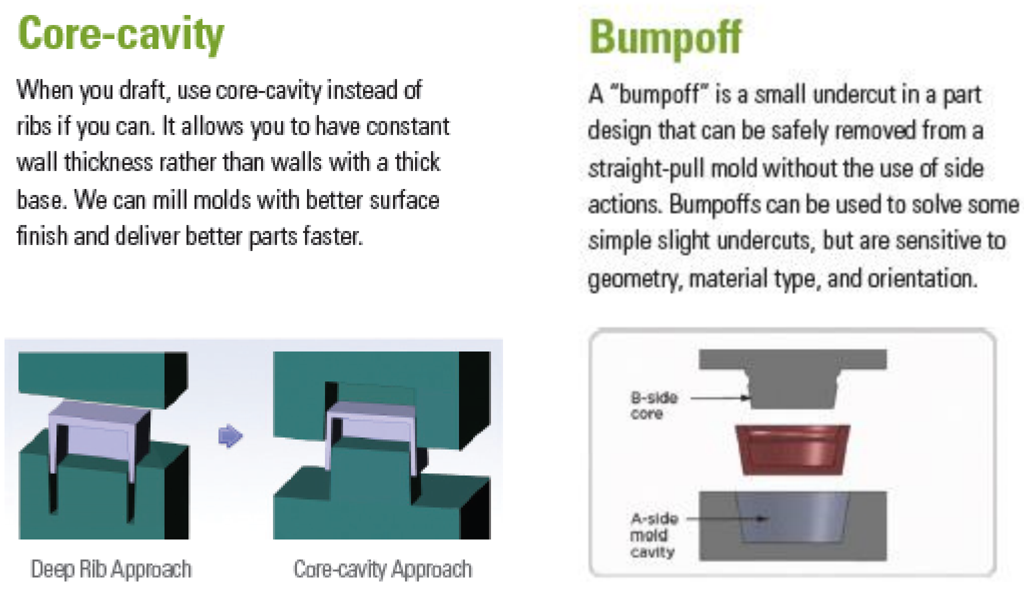


Figure 2.5: Core-cavity and bump off

Source : Proto Labs (1999-2002)

2.4 DESIGN OF MOULD

Based from Materials technology handbook volume 1 by momentum mass media, 2010 there are specific basics facts has to be targeted within the manufacturing regarding moulds. Flat surfaces needs to be avoided if at all, because bit of a domes or maybe dish effect will permit the published to stretch within the entire area. The tendency surface avoided the bit of the bumps that relatively can be found in level section. Maximum permitted vent gap diameters will be different with products and published thickness.

Air evacuation holes ought to be as optimize as possible to reduce restriction of material stream through in-take holes, and the particular opening ought to be back drilled on the surface of the mould. The cavity surfaces ought to be finely sandblasted in order to avoid forming coming from sticking inside the mould and also require several of hover and in-take ports and suppose to be merge along the forming floor and have to be precisely sited throughout ribs, slots, and different features that may very well become isolated since the forming sheet progressively seals over others ports.

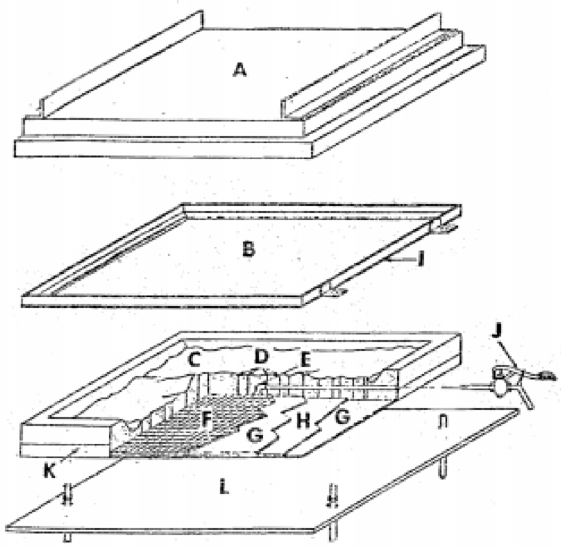
The diameter of the port must be small to make sure that small or no mark of their presence is witness on the produce. One method is to make sure the thickness of the forming at the point is thicker than the vent diameter which subject to a diameter not more than 0.3 mm. The vent is released from the opposite larger bore or a series of diminishing bores drilled to about 2mm at the back of the mould. The number of the holes is depends on the desired rate of drawing. Commonly it is desirable to have as fast as possible rate, so the number of holes should be provided based on previous study or experiment.

In Drape forming, they anticipate descending into regular space at the base of the mould. In parts where fine subtle elements or textured examples must be precisely recreated, vent openings short of what 0.5inch (0.013cm) separated are generally fundamental. The female shaped item has the best divider thickness with the most slender bottoms. The converse happens when utilizing the male mould. Amid the shaping the piece of the hot sheet that touches any piece of the mould will begin to cool, bringing about a thicker divider with conceivable solidified hassles.

Size openings ought to be kept as little as could reasonably be expected so they don't meddle with surface necessities. Diverse sorts of plastics have a tendency to have distinctive prerequisite careful placement of the holes will be helpful in providing fast, efficient airflow during forming. Previous studies basically provide guideline for the placement and size of openings. For impact PS up to 0.030inch (0.08cm), opening may be used for material thickness greater than 0.060inch (0.15cm). For thinner sheet, especially where both sides of the part will be view, it may be necessary to reduce hole diameters to 0.010inch (0.03cm) to avoid hole marks.

2.5 VACUUM/DRAPE FORMING

The oldest method of the thermoforming (figure 2.6), it utilizes the sheet's self-sealing power and evacuation of trapped air through the use of a vacuum. Natural atmospheric force fills the mould cavity, forcing the heated sheet in to the evacuated space. A vacuum pump is necessary in this process. Vacuum forming is the simplest of the thermoforming processes where in my case a positive mould is used in combination with an unencumbered planar upper surface against that's clamped. Detail process is explained in figure 2.7.



This view shows the relationship of the essential components of vacuum-forming equipment as used by the Army Map Service in 1947 to produce three-dimensional maps: (A) superheater; (B) angle-iron frame; (C) mold; (D) vacuum holes; (E) vacuum pipe; (F) wire mesh, 2 layers; (G) aluminum sheet, 0.032"; (H) sponge rubber, ¼" to ⅜"; (I) sponge rubber gasket; (J) poppet valve; (K) heat-resistant tape; (L) aluminum plate, ½". (Courtesy, Relief Map Division, Army Map Service, Corps of Engineers, Washington, D.C.)

ILL. –K Bow Stratton's relief map vacuum former may have been the basis for the first commercial thermoformer.

Figure 2.6 : Components used in thermoforming process

Source : (R.Rosen, 1930-1950)

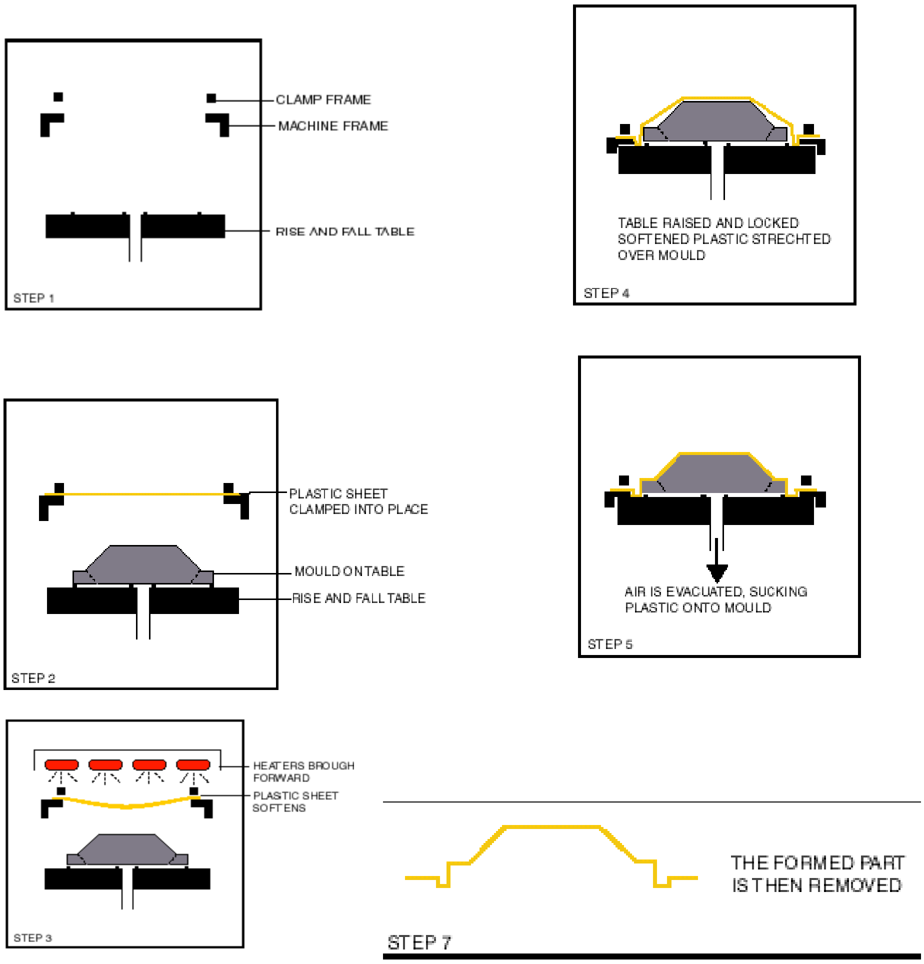


Figure 2.7: Drape forming process

Source : (MULTIFAB INCORPORATED, 2009)

2.6 HONEYCOMB SANDWHICHED STRUCTURES CONSTRUCTION

Honeycomb sandwiched structured is currently leading engineering structures as it offer useful benefits compared to any others structures. It has been commercialize because of its great potential by giving a great structural strength at minimum materials utilization.

The applications of the sandwiched face of the honeycomb structures can be compared with an I-beam, as bending stress were carried to which the beam is subjected. While one of the facing skin is undergoes compression, the other will undergoes tension. Similarly the honeycomb core corresponds to the web of the I-beam. The core withstand the shear loads, enhanced the stiffness of the structure by holding the facing skins apart, and improving on the I-beam, it gives continuous support to the flanges and facing skins to produce a uniformly stiffened panel. The core-to-skin adhesive rigidly joins the sandwich components and allows them to act as one unit with a high torsional and bending rigidity. The comparison of the panel physique as shown in figure 2.8.

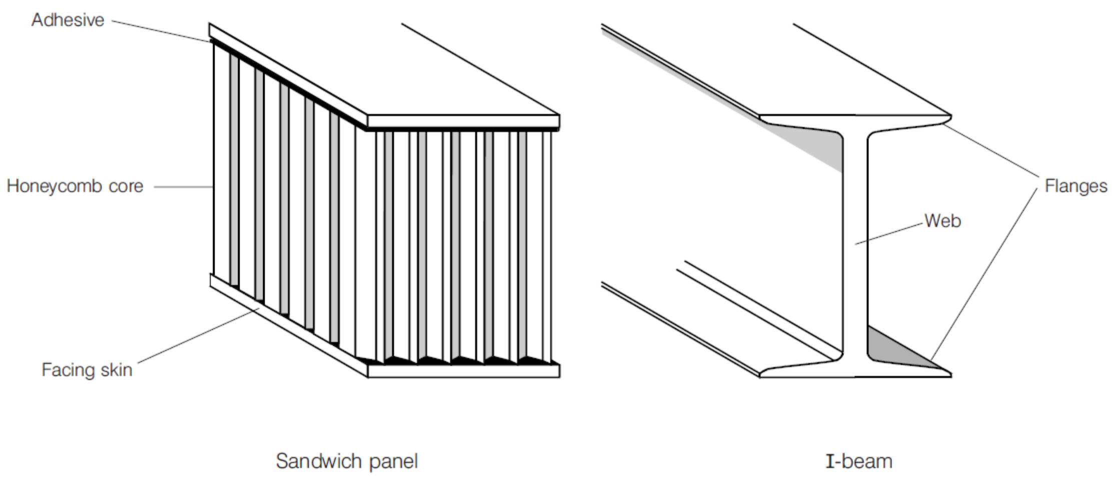
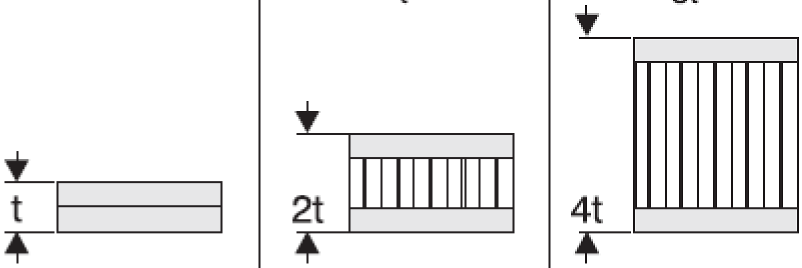


Figure 2.8: Honeycomb panel and I-beam panel

Source : (HEXCELL COMPOSITES, 2000)

Panel with honeycomb cores is said better than solid panel not only because it is cost effective and light in weight but also gives further strength with same weight as the solid panel which can be explained in table 2.2.

Table 2.2: The relative stiffness and weight of sandwich panels compared to solid panels



	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Source : (HEXCELL COMPOSITES, 2000)

2.7 HONEYCOMB CORE MATERIAL SELECTION

There are varies of materials that can be used in honeycomb sandwich construction fabrication. It can comprise an unlimited variety of materials and panel configurations. The composite structure provides great versatility as a wide range of core and facing material combinations can be selected. The following criteria should be considered in the selection process of core, facing, and adhesive.

2.7.1 STRUCTURAL CONSIDERATION

Strength:

Honeycomb cores and many facing materials are directional intended for mechanical attributes and also proper care should be used in order that the particular materials are orientated inside section to take the top selling point of this kind of characteristic.

Stiffness:

Sandwich structures are often accustomed to maximise stiffness with very low weights. Due to the reasonably minimal shear modulus on most centre supplies, on the other hand, the deflection
information need to permit shear deflection on the structure in addition to the rounding about deflections normally regarded as.

Adhesive Performance:

Adhesive should rigidly attach the actual facings on the core material to ensure loads to be fed from one facing to another . Ideal adhesives include things like substantial modulus, substantial strength materials readily available as liquids, pastes as well as dry films. As a general rule, a low remove strength, as well as reasonably brittle adhesive should never be used together with very light sandwich structures which may be subjected to abuse or damage in storage, handling or service.

Economic Considerations:

Honeycomb sandwich structures can offer a cost effective alternative. Price investigation ought to include assessment of generation and assembly fees; and installation fees which includes supporting structure.

2.7.2 HONEYCOMB CORE MATERIALS

Composite industries which manufactured honeycomb sandwiched structures generally offer honeycomb cores that made up from wide range of material depend on customer demands such Aluminium, Nomex (Aramid), Kevlar, Korex, Fibreglass and Carbon. Each material has its own range of strength and were use depending on the honeycomb cores port of application.

Table 2.3: Honeycomb core strength base on material table.

PRODUCT CONSTRUCTION		COMPRESSION		PLATE SHEAR			
Density	Cell Size*	Stabilized		L Direction		W Direction	
kg/m³ (lb/ft³)	mm (in)	Strength MPa	Modulus MPa	Strength MPa	Modulus MPa	Strength MPa	Modulus MPa
3003 Aluminium							
29 (1.8)	19 (3/4)	0.9	165	0.65	110	0.4	55
37 (2.3)	9 (3/8)	1.4	240	0.8	190	0.45	90
42 (2.6)	13 (1/2)	1.5	275	0.9	220	0.5	100
54 (3.4)	6 (1/4)	2.5	540	1.4	260	0.85	130
59 (3.7)	9 (3/8)	2.6	630	1.45	280	0.9	140
83 (5.2)	6 (1/4)	4.6	1000	2.4	440	1.5	220
5052 Aluminium							
37 (2.3)	6 (1/4)	1.35	310	0.96	220	0.58	112
50 (3.1)	5 (3/16)	2.3	517	1.45	310	0.9	152
54 (3.4)	6 (1/4)	2.6	620	1.6	345	1.1	166
72 (4.5)	3 (1/8)	4.2	1034	2.3	483	1.5	214
83 (5.2)	6 (1/4)	5.2	1310	2.8	565	1.8	245
127 (7.9)	6 (1/4)	10.0	2345	4.8	896	2.9	364
130 (8.1)	3 (1/8)	11.0	2414	5.0	930	3.0	372
5056 Aluminium							
37 (2.3)	6 (1/4)	1.8	400	1.2	220	0.7	103
50 (3.1)	3 (1/8)	2.4	669	1.7	310	1.1	138
50 (3.1)	5 (3/16)	2.8	669	1.8	310	1	138
72 (4.5)	3 (1/8)	4.7	1275	3.0	483	1.7	193
HRH10 Nomex (Aramid)							
29 (1.8)	3 (1/8)	0.9	60	0.5	25	0.35	17.0
32 (2.0)	5 (3/16)	1.2	75	0.7	29	0.4	19.0
32 (2.0)	13 (1/2)	1.0	75	0.75	30	0.35	19.0
48 (3.0)	3 (1/8)	2.4	138	1.25	40	0.73	25.0
48 (3.0)	5 (3/16)	2.4	140	1.2	40	0.7	25.0
64 (4.0)	3 (1/8)	3.9	190	2.0	63	1.0	35.0
64 (4.0)	6 (1/4)	5.0	190	1.55	55	0.86	33.0
80 (5.0)	3 (1/8)	5.3	250	2.25	72	1.2	40.0
96 (6.0)	3 (1/8)	7.7	400	2.6	85	1.5	50.0
123 (7.9)	3 (1/8)	11.5	500	3.0	100	1.9	60.0
144 (9.0)	3 (1/8)	15.0	600	3.5	115	1.9	69.0
29 (1.8)	5 OX (3/16)	1.0	50	0.4	14	0.4	21.0
48 (3.0)	5 OX (3/16)	2.9	120	0.8	20	0.85	35.0
HRH78	Typical mechanical properties are similar to HRH10, however, the aramid sheet manufacturing tolerances are wider therefore minimum values may be reduced.						

Source : (HEXCELL COMPOSITES, 2000)

2.7.3 CELL SIZE

Honeycomb core comes from several size of cell size which will determine the products cost, the cell size is measure across a flat. Bigger cell size is the option for lower costs but bigger cell size with combination of thin facing skin will lead to telegraphing. This may cause dimpled happen at the outer space of the sandwiched structure. A good appearance can be obtained by using smaller cell size at the same time will gives a bigger bonding area but at higher cost.

Manufacturer usually supply honeycomb core in hexagonal shape but few other shape also has been use, i.e: circular, rectangular and OX.

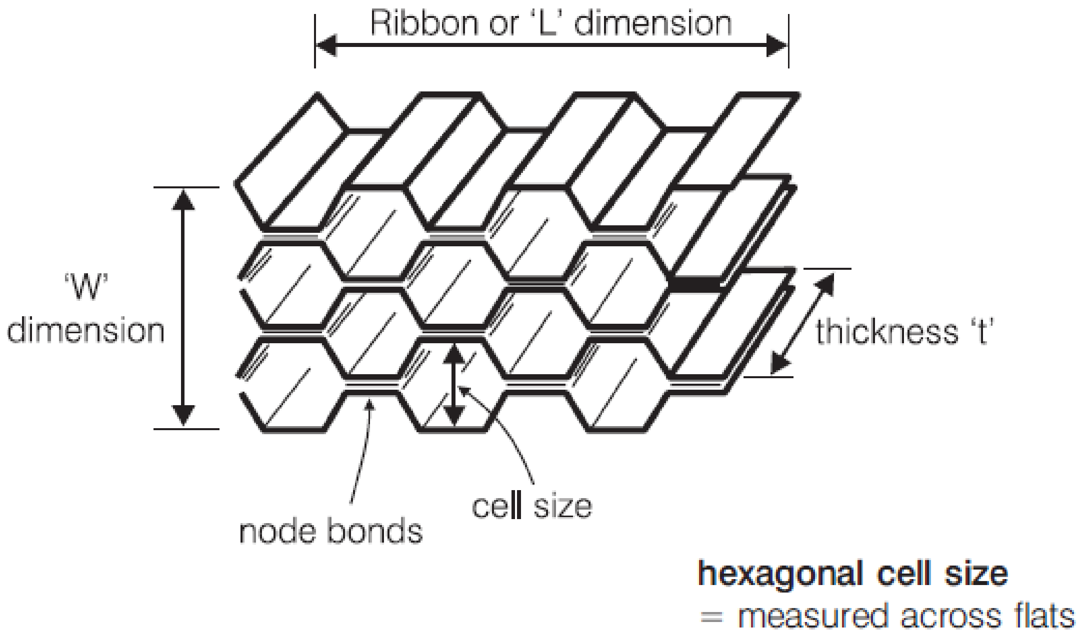


Figure 2.9: Honeycomb core description

Source : (HEXCELL COMPOSITES, 2000)

2.7.4 SKIN MATERIALS

Selection of skin material should be made by considering the weight applied, possible defects and denting loads, corrosion or decorative constraints, and costs. The thickness of the skin will affect the skin stress and panel deflection.

Table 2.4: Facing material table details

FACING MATERIAL	TYPICAL STRENGTH Tension/Compression MPa	MODULUS OF ELASTICITY Tension/Compression GPa	POISSON'S RATIO μ	TYPICAL CURED PLY THICKNESS mm	TYPICAL WEIGHT PER PLY kg/m²
Epoxy UD CARBON tape (0°) 60% volume fraction	2000 / 1300	130 / 115	0.25	0.125	0.19
Epoxy UD GLASS tape (0°) 55% volume fraction	1100 / 900	43 / 42	0.28	0.125	0.25
Epoxy WOVEN CARBON (G793-5HS) 55% volume fraction	800 / 700	70 / 60	0.05	0.30	0.45
Epoxy WOVEN ARAMID (285K-4HS 60% volume fraction	500 / 150	30 / 31	0.20	0.20	0.27
Epoxy WOVEN GLASS (7781-8HS) 50% volume fraction	600 / 550	20 / 17	0.13	0.25	0.47
Phenolic WOVEN GLASS (7781-8HS) 55% volume fraction	400 / 360	20 / 17	0.13	0.25	0.47
ALUMINIUM Alloy 2024 T3 5251 H24 6061 T6	Av. Yield 270 150 240	Av. 70	0.33	0.50	1.35
STEEL carbon 1006 1017	Av. Yield 285 340	Av. 205	0.30	0.5	4.15
Exterior PLYWOOD Fir	30 / 35	Av. 9	0.1	12.7	6.3
Tempered HARDWOOD Teak	110 / 40	Av. 12	0.1	12.7	8.5

Source : (HEXCELL COMPOSITES, 2000)

2.6 SUMMARY

Thermoforming process related to forming products from single-layer plastics, imported multi-layer or coextruded plastics are used to produce many different product such as cups, high barrier container and much more advance product. The terms thermoforming itself is sometimes used to identify any plastic that is processed by any technique. In order to achieve the desired shape, the mouldability of the mould should be investigates to find alternative ways to solve or reduce the limitation. Thermoforming process is able to produce high potential product that in high demand in today industries such as honeycomb cores panel. Research had been made and the finding is use to conduct the research for the qualitative assessment to assess the possibility of producing Honeycomb structure using low cost in-house built Thermoforming equipment.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter will discuss on the methods and parameters used in carrying out this research. Basically, this research was conducted to determine either the honeycomb based structure is able to be fabricate by using low cost in-house thermoforming equipment. This chapter will discuss on the designing of the experiment process, the analysis preparation which include the mould design and fabrication process, the selection of raw material , the process involve as well as the parameter, the machine selection and its parameter , the forming process that will be use in product fabrication and how the experimental process will be done.

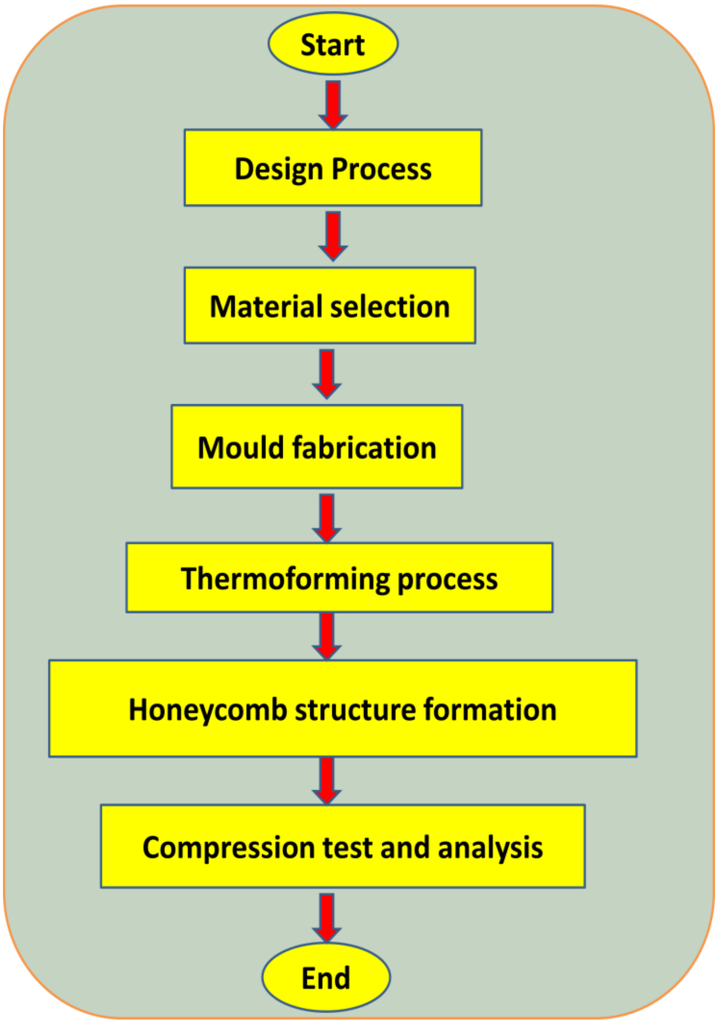


Figure 3.1: Methodology flowchart

Figure 3.1 show the overall process or method to complete this project. The methodology kicks off with design process followed by material selection and mould fabrication. Next, thermoforming process will take place to obtain the honeycomb based structures. The structure then undergoes honeycomb structure formation and compression test is use to check the structural strength of the prototype.

3.2 DESIGN PROCESS

The thermoforming process is a plastic formation process which includes a sheet of plastic and forming it over a male or female mould. The basic thermoforming process involved with clamping, heating, shaping, cooling and trimming. Thermoforming process can be achieved through the pressure forming, vacuum forming or twin sheet processing.

The few stages involved in the vacuum forming process. Firstly, the mould is made from aluminium material with the shape of Honeycomb based structure. Next, the mould shape placed in vacuum former. After that, a sheet of polymer is clamped in the position above the mould. Next, the polymer sheet heated and sealed to the mould and the vacuum is turned on and pumps out all the air. At this stage the shape of mould can be clearly seen through the plastic sheet.

The plastic has cooled and ready to be remove the vacuum pumps switch off. After that, the plastic sheet removed from the vacuum part and the sheet has the shape as mould shape. Lastly, the excess plastic is trimmed so that the plastic container remains.

3.2.1 SELECTION OF MOULD TYPE

Basically mould can be divided into three types which are male mould, female mould and combine mould. The selection of the mould is depends on the process that we are going to choose and the product that we are going to produce. Each mould had its own limitation.

Parts produce by using male mould have a tendency to have more noteworthy draft angles , heavier base and corner with more slender edges, while the material copy the geometry of mould surface. Parts produce by using female mould have a tendency to have more modest draft edge, more slender base and corners and significant edges with the outer surface of the product copied the inner shape of the moulds. Pre-strecthing, especially attachment aiding is simpler to use with female formed items. Blended item has the combination of product feature producing by both type of mould.

Due to cutting process after the thermoforming, the selection also must be made to ease the cutting process as well. During the selection stage of the mould a study had been made. After studied the design, geometry and dimension of the product and all the consideration, male mould or positive mould is chose.

3.2.2 DESIGN CONSIDERATION

Design phase is a critical phase which will affect the end result of the research. Before entering design phase a proper study should be made to ensure that we have enough information to proceed with the design. To designing the part we should know the main function of the product, the limitation of previous design and how to solve the limitation.

For the product size, an optimum size is better as the product will be in motion during application and the sheet size will be in A4 paper size (130mm width and 200mm length). The size of the product should not be larger than that to gives the full view of the mouldability of the product during the forming process.

The design of the honeycomb core mould should be following the industrial practice.

3.2.3 MOULDABILITY

In design the mouldability there are few design parameter that need to be considered throughout the research. For the thickness of the core, a constant thickness will try to achieve by ensure the material flow evenly through the mould during forming process this can be achieve by minimizing the flat surface in product design and control the height of the mould. Other than that get warped personality also aid in material flow, this personality can be made by eliminating sharp edge by replacing it with some radius or chamfer. Furthermore, by eliminating the sharp edge it also can improve the product strength as the sharp corner can be a stress riser which can weaken the part at that specific point.

3.2.4 DESIGN THE MOULD

The product shape was designed by using CATIA V5 software in 3D to get the brief idea on the shape of the mould. Then the design will be redraw in 2D by using AutoCAD software as the drawing will use during machining process as the fabrication of the mould will utilize wire-cut EDM machine. The size of mould is 120mm x 100mm. It can be bigger than that as long as not more than 120mm x 200mm according to the size of the mould box provided. The size of the node bonds is 4.5 mm, for the hexagonal angle 120˚ is applied on the model.

3.2.5 MOULD SIMULATION

The final design will undergoes Mould simulation by using ANSYS software. This simulation is made to monitor the material flow during the thermoforming process. On the simulation stage, several thickness is use to see the effect of mould thickness to the material flow during the process and to see either manual cutting method is applicable after the thermoforming process low in situ forces should be offer. This simulation also will determine the thickness of the mould.

3.3 MATERIAL SELECTION

Material is one of the important factors that should be put under consideration to achieve and improve the mouldability as it will effect during the forming process as well as the product material flow during the process. Different material has different properties which will determine what type of process it can undergoes. Wrong decision in select material will lead any experiment to failure.

3.3.1 MOULD MATERIAL

Based from the previous reading , the most suitable material to be use in fabricating mould for this research is Aluminium, not only because of its property but also because its availability and relatively cheap as shown in figure 3.2.

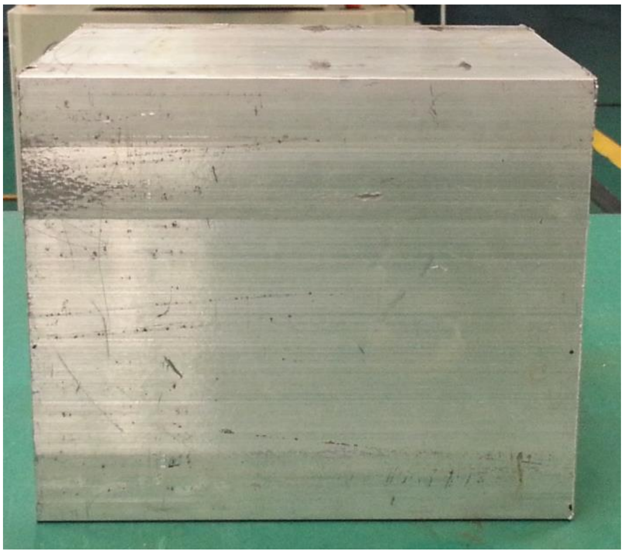


Figure 3.2: Aluminium block

3.3.2 PRODUCT MATERIAL

Polypropylene is an engineering polymers that widely use especially in plastic industries. It commonly use in several processes, i.e: general injection, extrusion blow moulding, sheet extrusion and thermoforming.

Polypropylene is selected as the product material. The selection is due to its ability to be process by using thermoforming process which is the primer process for this research. It has superior clarity so the grid to check on the material flow can be clearly monitored and also has low odour. It also has good rigidity and impact resistance. Other than that, Polypropylene offers cycle time reduction with low processing melt temperature and the most important value is utilities cost saving and process versatility. Due to its properties and its advantage, Polypropylene with thickness of 1mm is chose as the main product material.

Figure 3.3: polypropylene sheet

Table 3.1 : polypropylene Data sheet

TYPICAL RESIN PROPERTIES [a]	UNIT	TITANPRO SM198	ASTM METHOD [b]
Melt Flow Rate, at 230°C	g/10 min	1.6	D1238
Density	g/cm^3	0.9	D1505
Tensile Strength at Yield	kg/cm^2	290	D638
Elongation at Yield	%	14	D638
Flexural Modulus	kg/cm^2	11000	D790B
Notched Izod Impact Strength at 23°C	kg·cm/cm	34	D256A
Heat Deflection Temperature at 4.6 kg/cm^2	°C	78	D648
Rockwell Hardness	R scale	77	D785A
Water absorption after 24 hours	%	0.02	D570

(a) Values shown are average and are not to be considered as specifications.
(b) ASTM test methods are latest under the Society's current procedures.

Shrinkage : 1.3 - 1.4% depending on the product wall thickness and molding parameters.

3.4 MOULD FABRICATION

3.4.1 MOULD MATERIAL PREPARATION

The fabrication of the mould start by cutting the aluminium block into desired dimension as the raw material provide is 100mm x100mm x 500mm. The aluminium should be part off at dimension 100mm x 100mm x 150mm by using horizontal band saw machine. This is to get the nearest dimension of the desired mould based on the provided mould box. This process took a very short time but with less precision result.

The raw material will next to be transfer to milling machine which precision can be control and this stage squaring process will take place to get the exact dimension of the mould that we desired (100mm x 100mm x120mm). During milling process 100MPM of cutting speeds was used and using facing tool with diameter 80mm.

3.4.2 Mould Fabrication

During mould fabrication stage, wire-cut EDM machine is use. This machine is use because it can achieve complex shape, zero direct contact between tool which can prevent defects, a good surface finish can be achieve and work piece and high precision. During the process took part brass wire with diameter 0.2mm were use as the cutting tool. During the designing part all sharp edge should be removes by applying some radius at each edge that going to be machine to prevent the wire from break during the process. Some important note should be taken before starting the process:

1. The material should be clamp in perfectly angle of 90 degree
2. Work piece must in burr free condotion.
3. Setting the zero for X,Y,X,U,V axis

Throughout the process the machine parameter use as follow:

Table 3.2: Machining parameter.

ON	OFF	IP	HRP	MAO	SV	V	SF	C	EPH
007	013	2215	000	252	+025.0	8.0	0010	0	0
PIK	CTRL	WK	WT	WS	WP			C NO	
000	0000	020	120	110	060			001	

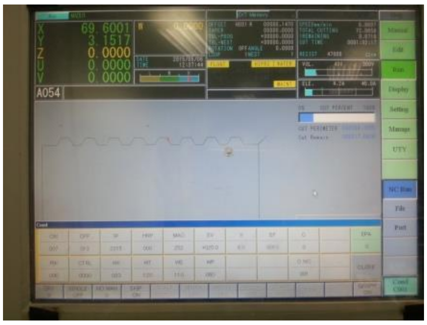


Figure 3.4: Wire-cut EDM parameter

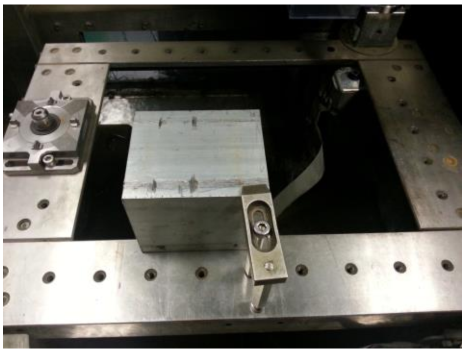


Figure 3.5: The aluminium block is clamp and ready to be machine

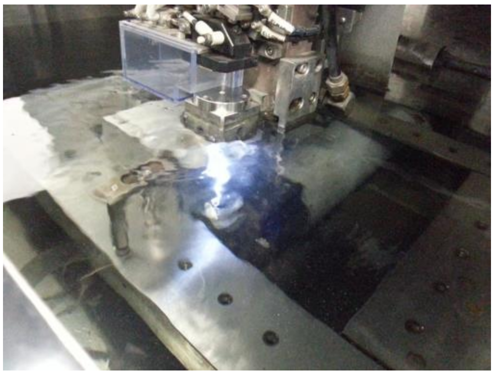


Figure 3.6: Wire-cut EDM process

3.5 THERMOFORMING PROCESS

Thermoforming is the main process for this research. This process will utilize low cost in-house thermoforming machine. Two type of set up were design for the process set up A without platen and set up B with platen. This set up were made to study the effect of vent holes during thermoforming process as what been mention in previous study the vent holes will help in forming process by aiding the material flow by release the air trap which can cause uneven distribution of the material and air bubbles effect on the material surface.

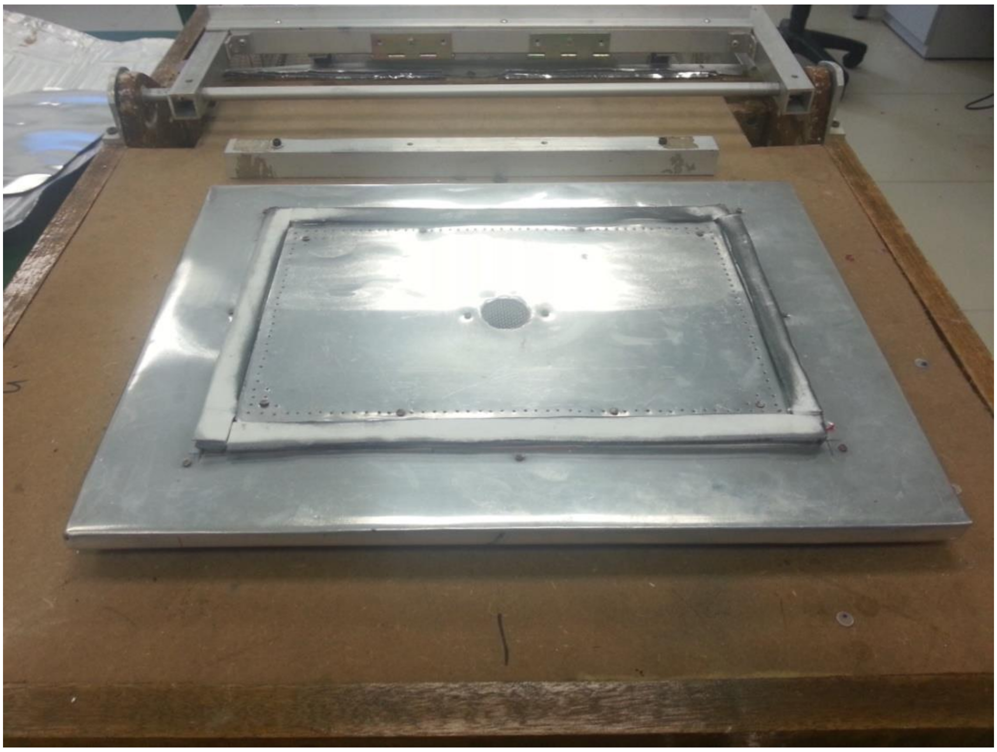


Figure 3.7: Set up A (without platen)

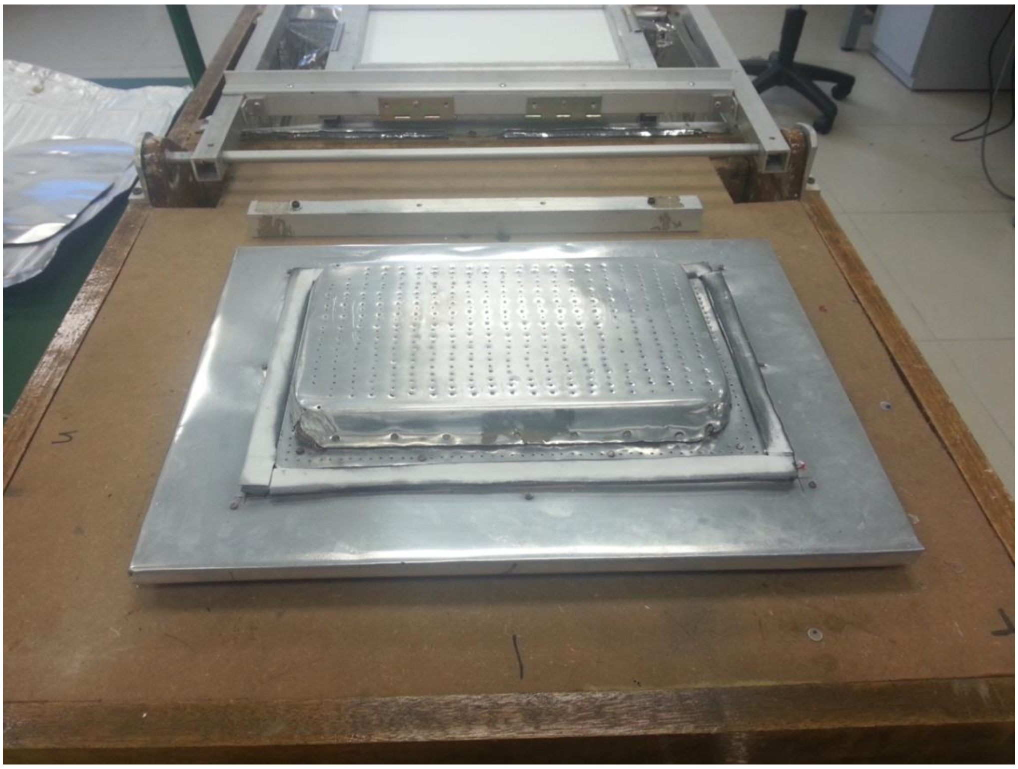
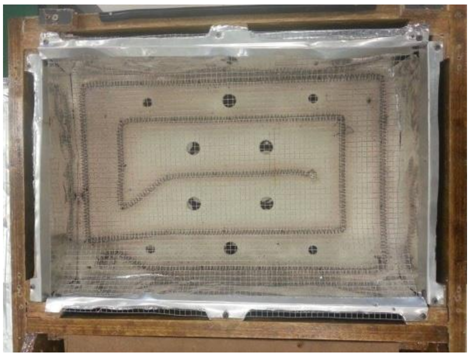


Figure 3.8: Set up B (with platen)

The process started by heating up the heater to at least 100°C. The temperature is observed by using IR temperature gun



.

Figure 3.9: heater

When the heater reach 100°C or more the Polypropylene sheet that already clamped in the clamper then be heated on the heater

.

Figure 3.10: PP sheet is clamped on the clamper

To control the heat in the heater , a pair of aluminium coil is used to minimizing the heater from expose to room temperature to prevent unwanted heat transfer process occur during the heating process.

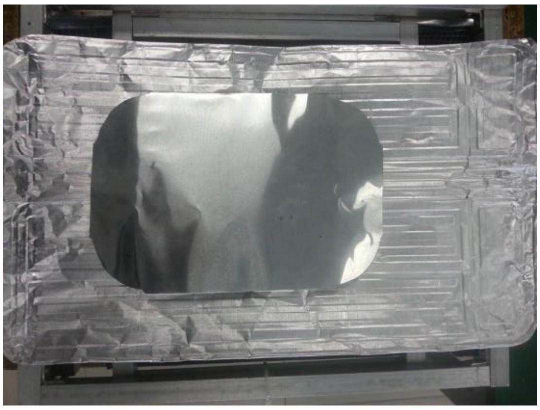


Figure 3.11: Aluminium foil cover

The temperature of the Polypropylene sheet is constantly monitored until it reach ideal temperature for forming that is between range 140°C - 190°C depend on the sheet thickness. When the sheet obtained the ideal temperature and start to saggy the vacuum is turned on before the forming process took place.

Figure 3.12: The PP sheet saggy and ready to forming process

The process should be leave for few second to let the forming process perform completely as the forming process will took pare stage by stage from the most bottom up to the upper part and need a moment to completely form.

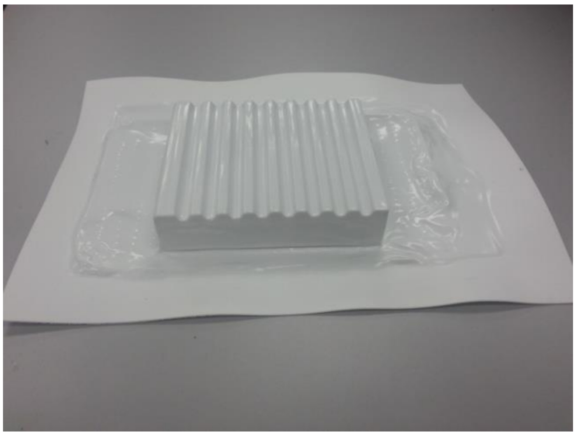


Figure 3.13: Thermoformed product

The complete forming part will be cut manually to get the final product which is the honeycomb base structure. The mould was design in rectangular shape with purpose to ease the cutting process. The mould wall will become the reference for the cutting tools.

3.6 HONEYCOMB SANDWICH STRUCTURE FORMATION

The Thermoforming products is stacks to form the honeycomb structures. During the stacking phase no adhesive were use to fastened 1 part to another. Soldering method is apply by combining melted surface and let it cool and will stick together.

Fibre glass will be use as the skin material. Epoxy and hardener with ratio 1:1 is use to form the sandwich skin. Traditional hand lay-up is applied during this process. The complete skin will be place at upper and lower part of the honeycomb cores. A load is place on the structure during the drying process to gives compress load to the skin and to make sure there is no uneven gap in between the skin and honeycomb core structures.

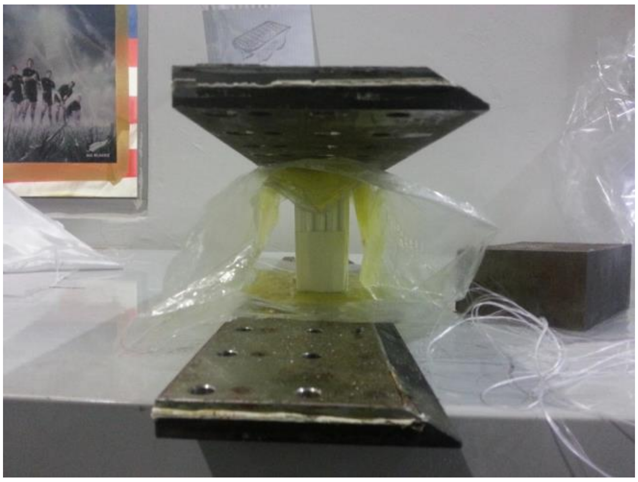


Figure 3.14: Sandwich structure formation

3.7 COMPRESSION TEST

The complete product of sandwich honeycomb core structure will be test by using static compression test to see its strength by applying human weight on it. Load of 50kg and 80kg is applied and observe if the structure can withstand the load without failure.

Chapter 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter will discuss on the results throughout this research. Explain the processes used in more details and results obtained by the processes. The results shall include from the start of the research until the end.

4.2 DESIGN PROCESS

4.2.1 DESIGN OF THE MOULD

Based from the reading, study and the process, a positive mould is selected in this research. The mould was design by using CATIA V5 software. A sample design were designed to get a brief looks of the design before a simulation is made to determine some parameter that will be use in finalize design.

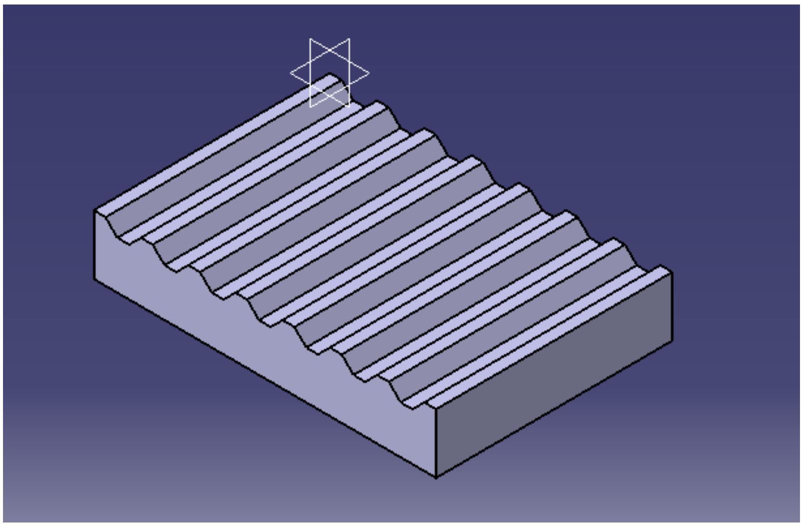


Figure 4.1 : Rough design of the positive mould

The design details as follow:

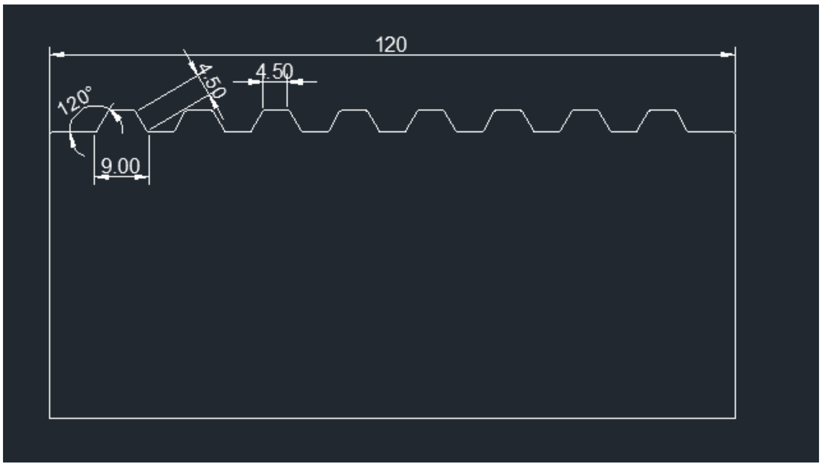


Figure 4.2 : Details dimension of mould features

Table 4.1: The features dimension of the mould

Features	Dimension
Dihedral angle	120°C
Pitch	9mm
Node bonds	4.5mm
Ribbons/ L dimension	120mm
Honeycomb thickness	100mm
Cell size	7mm

The thickness of the mould is yet to be determined after simulation is made. It is important to have a right thickness of the mould because it will determine the side thickness of the thermoform product. The side thickness of the product is significant because it will determine the in situ forces that we are going to apply during the cutting process where it will be done manually.

4.2.2 MOULD SIMULATION

The thickness of the mould was determined by a simulation by using ANSYS (simulation driven product development) software. This simulation is conducted to determine the ideal thickness of the positive mould to ensure a good floor of the materials as well as a good thickness to be achieve.

A variation of thickness is used from 0mm to 40 mm with increment of 10mm from 0mm.

4.2.2.1 SIMULATION 1

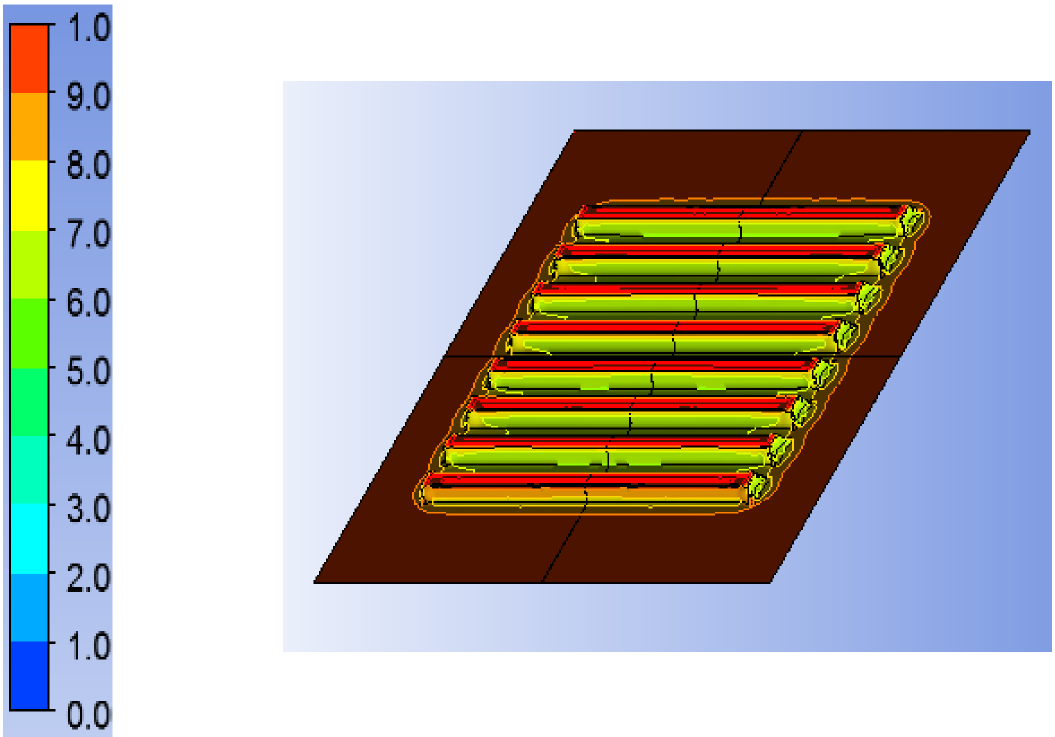


Figure 4.3 : Mould thickness of 0mm and 1mm sheet thickness

Source : Mohd Ghazali,F.A.2015,Private Communication

The results shows in figure 4.3 reveal that the material thickness range by using 0mm of mould is between 0.6mm to 1.0mm which is not so ideal. Other than that, the forming part not copied the mould shape perfectly as less stretcing occur which result in limitation of material flow. The simulation also shows the material flow is not uniform which cause non-uniform thickness on the forming product.

4.2.2.2 SIMULATION 2

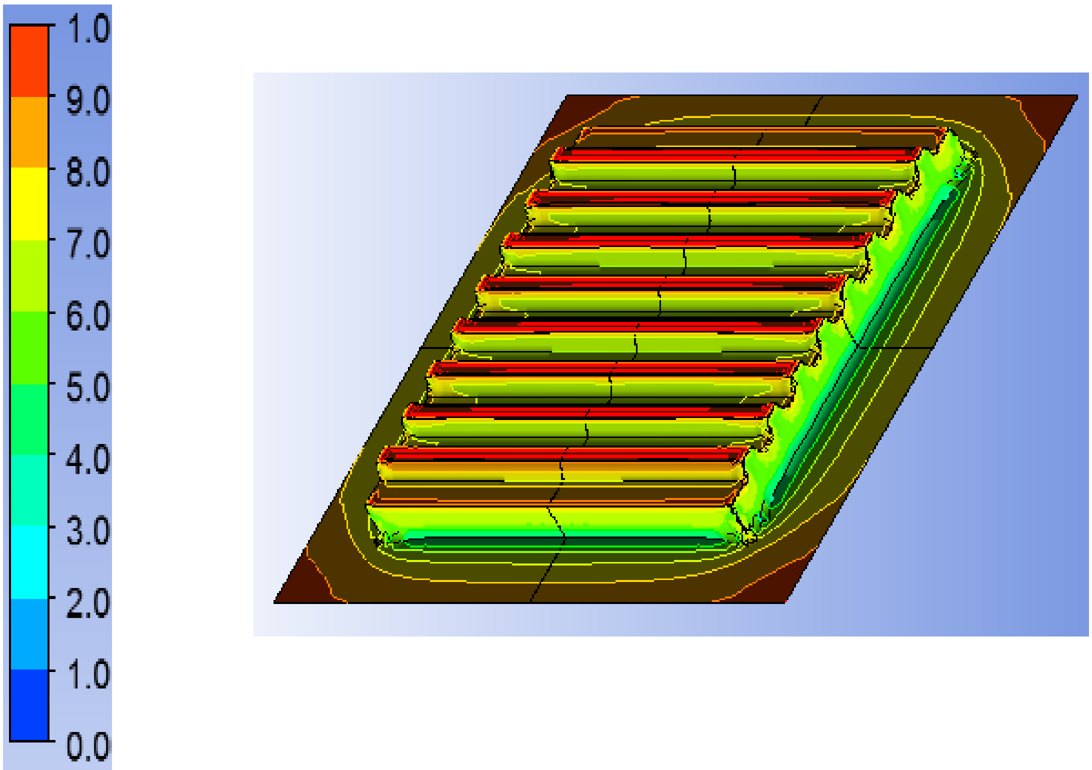


Figure 4.4: Mould thickness of 10mm and 1mm sheet thickness

Source : Mohd Ghazali,F.A.2015,Private Communication

The material thickness range by using 10mm of mould is between 0.5mm to 1.0mm. Based from the result of the simulation as shown in figure 4.4, it shows some improvement in term of the material flow. The side thickness of the product is between 0.5mm to 0.8mm. The shape obtained from the process has improved but still less than expectation result.

4.2.2.3 SIMULATION 3

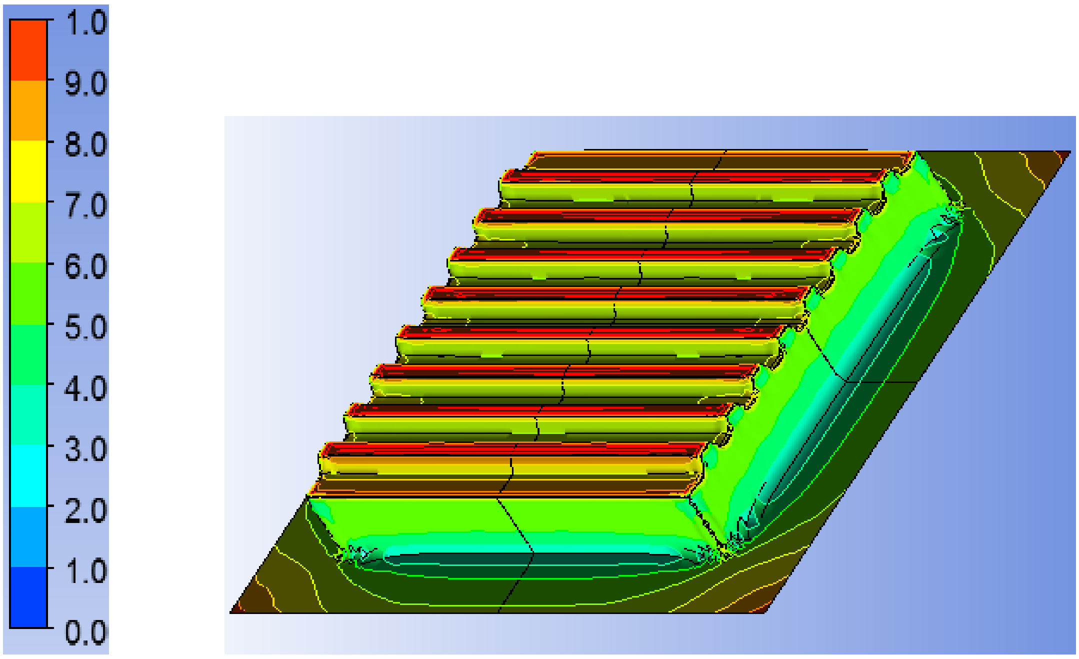


Figure 4.5: Mould thickness of 20mm and 1mm sheet thickness

Source : Mohd Ghazali,F.A.2015,Private Communication

Based on the result from the simulation (figure 4.5), it is shown that the side thickness of the thermoform project is getting thinner as the thickness of the mould is increases. Slightly improvement shows in term of materials flow. The material flow can be monitored by measure the thickness of the thermoform product. The thickness of the thermoform product is in range of 0.3mm to 0.9mm

4.2.2.4 SIMULATION 4

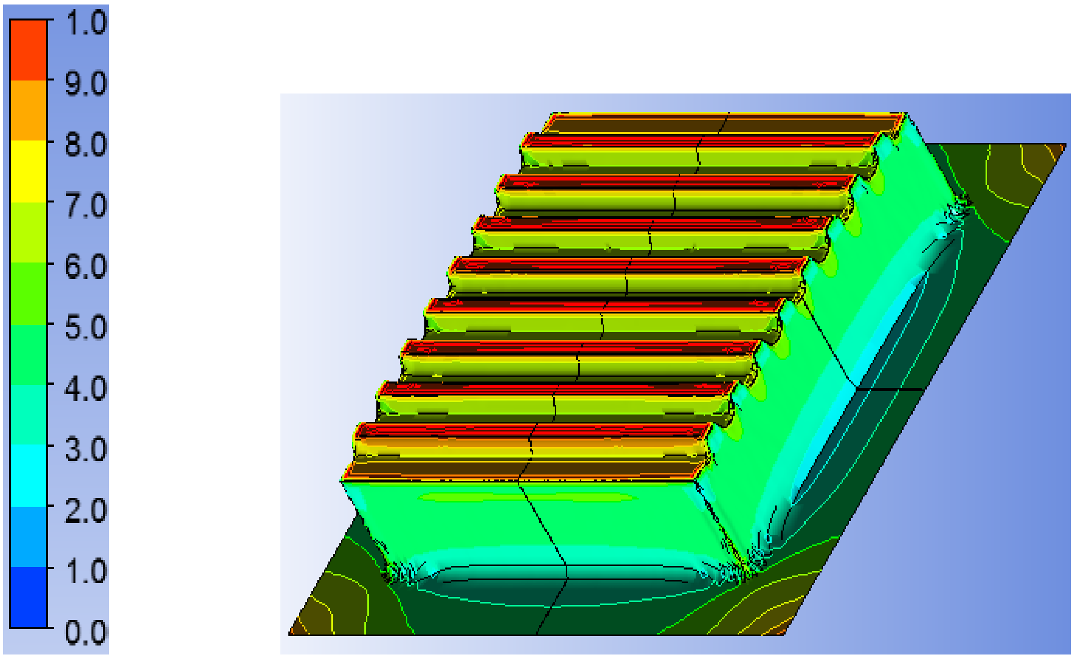


Figure 4.6: Mould thickness of 30mm and 1mm sheet thickness

Source : Mohd Ghazali,F.A.2015,Private Communication

The result obtained from simulation as shown in figure 4.6 by using mould with thickness of 30mm shows the thickness of the cutting area has decrease to a range between 0.3mm to 0.5mm. The material flow is almost uniform through the mould and the thermoform product is almost copy perfectly the mould shape, this can be inspected by observing the colour distribution along the surface.

4.2.5 SIMULATION 5

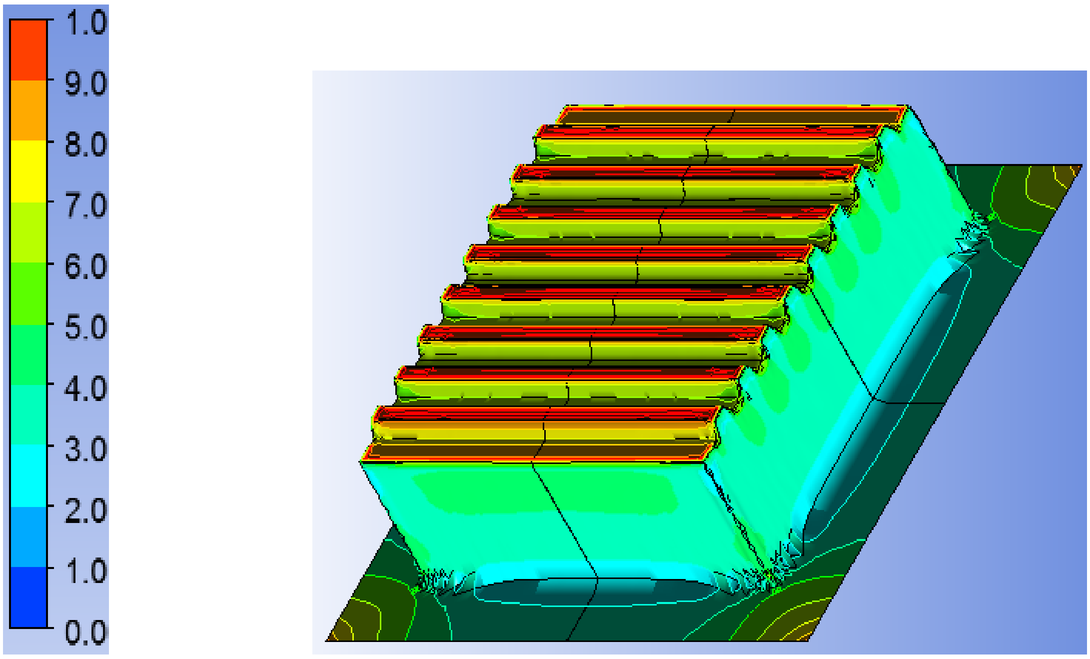


Figure 4.7: Mould thickness of 40mm and 1mm sheet thickness

Source : Mohd Ghazali,F.A.2015,Private Communication

Figure 4.7 shows the simulation results on mould with thickness of 40mm shows a significant change of the side thickness of the product. The thickness almost uniform at 0.2mm and 0.4mm at certain point which can be terminate by increasing the thickness of the mould.

This simulation indicates the thickness of the mould will affect the materials flow during the process as well as the shape of the thermoform product. After conducted the simulation, thickness of 50mm is chose for this research to get maximum material flow and uniform thickness of the product.

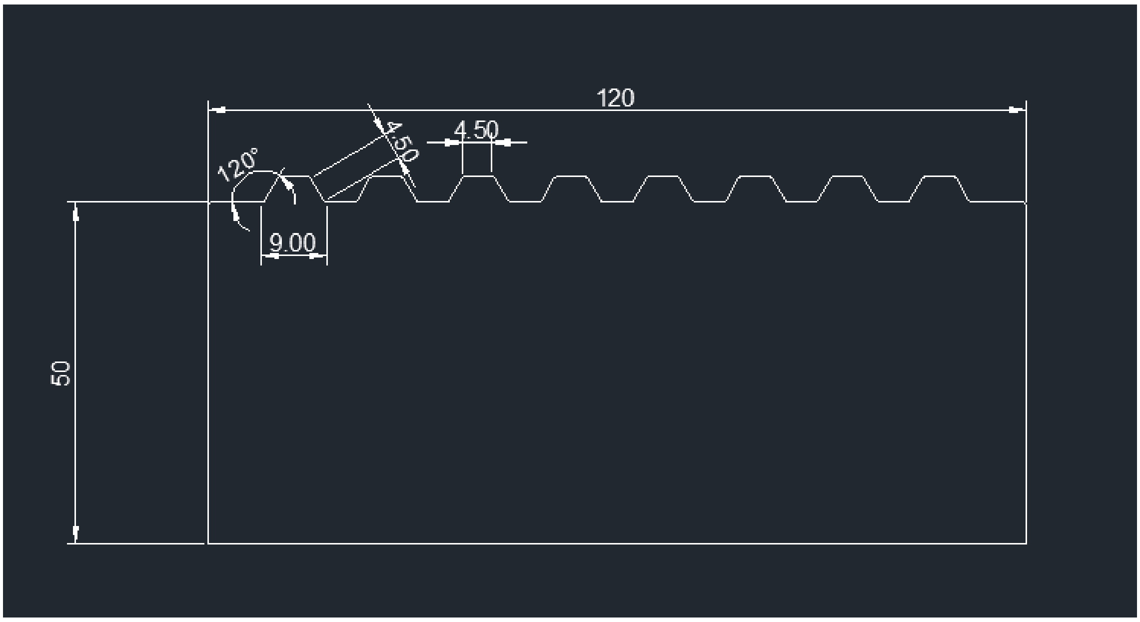


Figure 4.8: Final design of the mould in 2D

4.3 MOULD FABRICATION

Figure 4.9 shows the complete mould of the honeycomb base structure after the thickness was determine by the simulation.

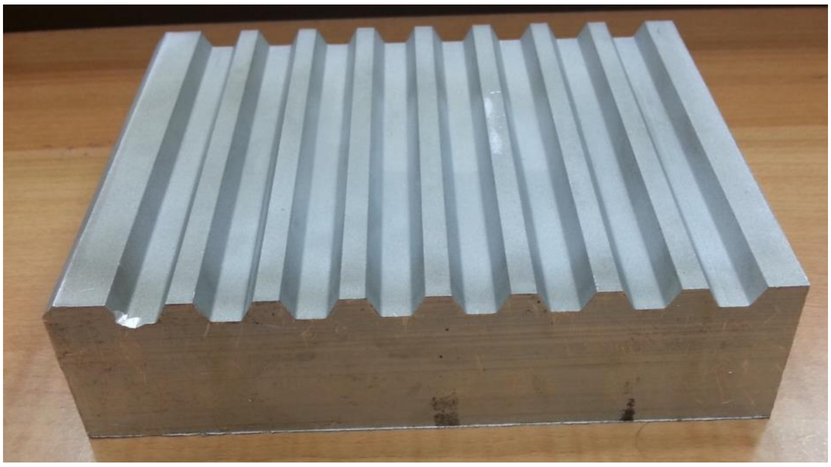


Figure 4.9: Positive honeycomb base structure mould

4.4 THERMOFORMING PROCESS

4.4.1 SET UP A

Result:

Figure 4.10: Thermoform product produced by Set up A

Figure 4.10 shows a thermoform product produced by Set up A where there is no vent holes provided. As what we can observed the product doesn't form perfectly.

4.4.2 SET UP B

Result:

Figure 4.11: Thermoform product produced by Set up B

Figures 4.11 shows products produce by Set up B where a platen was added to provide vent holes mechanism. The product produces by Set up B imitates the mould geometry perfectly and the thickness distribution almost perfectly uniform along the features.

4.5 HONEYCOMB STRUCTURE FORMATION

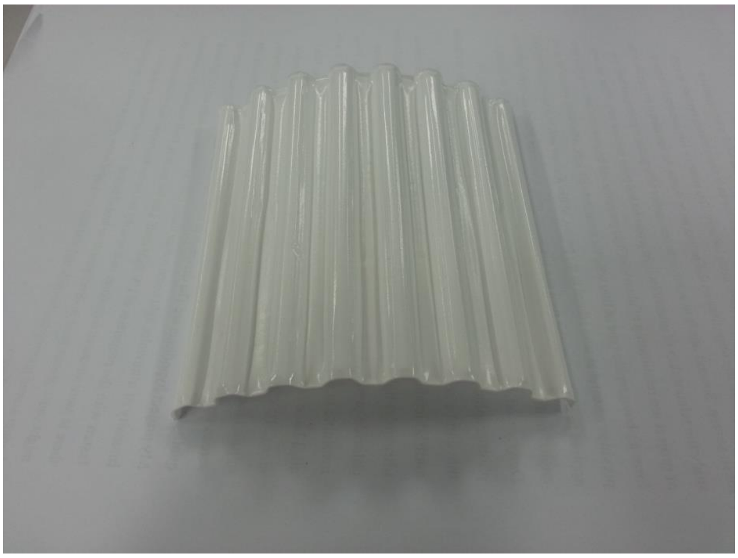


Figure 4.12: A single layer of thermoform honeycomb base structure

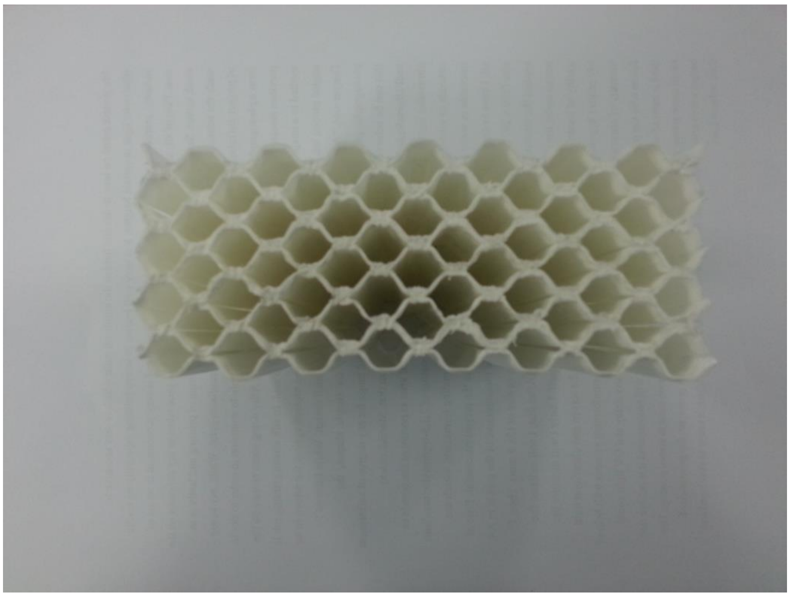


Figure 4.13: A stacks of honeycomb base structures

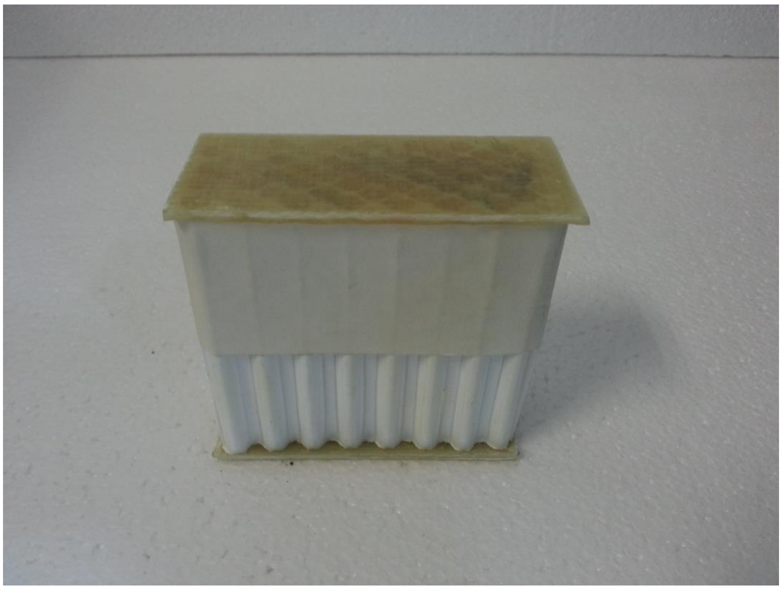


Figure 4.14: Sandwich structure with honeycomb base core

4.6 COMPRESSION TEST AND ANALYSIS

4.6.1 EXPERIMENT 1

Figure 4.15: Static compression test by applying load (50kg)

4.6.2 EXPERIMENT 2

Figure 4.16: Static compression test by applying load (80kg)

The figures 4.15 and 4.16 shows compression test was examine by applying load of 50kg and 80kg on the honeycomb core sandwich structure for several time in range from 1s to 120s. Human weight in standing position is use as the load. It was found that the honeycomb panel can withstand more than 80kg without failure.

TIME(s)	15	30	45	60	75	90	105	120
EXPERIMENT 1	/	/	/	/	/	/	/	/
EXPERIMENT 2	/	/	/	/	/	/	/	/

Note: / indicates no failure occur

4.7 DISCUSSIONS

The positive mould is selected over negative mould because positive mould offered several benefits which cannot be achieve by using negative mould. Other than machine limitation, negative mould require more machining process compared to positive mould which is not ideal in term of time consumption. Furthermore, negative mould also require radius in inner features such as corner to aid on material flow. High draft ratio required if not the thermoform product will be very difficult to pull off and may result defects to the product. The most important reason why positive mould is selected over negative mould is because negative mould may not capture the corrugated shape if thicker sheet is applied. As the sheet thickness of 1mm is used for this research, a positive mould is chose as it offered more benefit compared to negative mould.

The design of the positive mould is trough from one side to another, this is to offer an air path so that the there is no air trap in between mould and the sheet which can cause any defect on the thermoform product surface. The mould also designed with a thick base to ensure a maximum material flow achieve during the thermoforming process. This is because when thermoforming process occur the forming start from the lower part of the mould that is from the base to the body and lastly to the surface of the mould. This can be validate by refer on the simulation also by examine during the real thermoforming process took place.

The compression test can withstand a massive load without failure because the load distribution was even among the honeycomb web which shows that the honeycomb core was cut in really nice manner and evenly in dimension. This can be proved by looking at the product itself. If the cutting line is uneven it will produce one point of interest where all the load will focus at one point cause that point to resist all the load and resulting a failure on the product which doesn't occur during this research. The good trimming line is easily obtained by having a very good mould design. As trimming will be done manually, this consideration had been taking account during designing phase. The rectangular shape was use for the mould shape with a sharp straight edge and flat side. The reason of having this feature is to offer a clear trimming line by having the edge of the mould as cutting reference where the cutter is place with 0mm offset to the mould and the cutting process can be done by following the line provided by the mould. This will gives an even and beautifully cutting line in all thermoform products.

The reason of using mould with mould base of 50mm is to create sufficient material thinning at the mould edges so that small shearing force can be applied for trimming and cutting purposes. The simulation on figures 4.3 to 4.7 shows the thinning of the material at the side of the mould increase as the thickness of the mould increase while the thickness on the surface is maintained. This condition is valid depending on the sheet size and thickness use during the process.

It was found that the optimum sheet temperature for forming for polypropylene is 170°C where in this state the sheet will form perfectly and copy the shape of the mould nicely.

The adhesive will offer a good bonding in between two sheets but also will increase the honeycomb panel weight. On the way to achieve the minimum weight of the honeycomb panel an alternative way is introduced by using heat mechanism to bond one sheet to another. This method was apply in this research and proves that lighter weight can be achieve and yet still offering a good structural strength.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

The purpose of the current study is to assess the possibility of producing honeycomb structure using low cost in-house built thermoforming equipment. This chapter summarizes the whole project and will conclude the finding throughout the project and gives some recommendation that can be implements or practice in future study for improvement.

5.2 CONCLUSION

This project was undertaken to design positive drape thermoforming mould and to assess the possibility of producing honeycomb structures using low cost in-house built thermoforming equipment. This project also was done to evaluate qualitative assessment of structural strength of the thermoform product.

It was found that the designing phase of the mould is the crucial part as it will determine the whole process as well as the finish product quality. The design of the mould must be refer on the suitability of the product as different product has its different requirement. The materials use for both mould and the product also important because wrong selection of material will lead to failure.

The cutting line is important to get even line along the honeycomb core base line because it will affect the load distribution as what we discussed in previous chapter of this project.

The following point emerged the main conclusion from the present assessment:

- A positive thermoforming mould was successfully designed and fabricated to produce honeycomb base structure.
- It is possible to produced honeycomb core based structured using low cost in-house Thermoforming equipment.
- The honeycomb based structure obtained from this project able to withstand a massive load.
- The stiffness enhancement of the product is able to avoid warping defect.
- The significant of the draft angle during drape forming is to ease the thermoforming process and the draft angle used is compatible with thin sheet material.

5.3 RECOMMENDATIONS

5.3.1 PRODUCT MATERIAL

This project is conducted to produce a prototype or a sample of the honeycomb panel. It was recommended to use recycle product materials due to high cost of the Polypropylene sheet. The Polypropylene leftover from the thermoforming process can be crushed and re-process to form another sheet which can help in cost saving.

5.3.2 CUTTING MECHANISMS

This project used manual cutting method where use some time and will have no variation of core thickness produce. By introducing a cutting dies the cutting process can be done much faster and variation of core thickness can be obtained by setting the dimension that we desired. Cut and carry dies also can be introduces for future study where cut and folding process can be done in one process where time consumption can be reduced. This also can control the precision of the cutting line

5.3.3 FASTENED METHOD

Adhesive is not being applied in sticking one honeycomb core to another in this project. Soldering method is introduced but the problem occurs is, it is difficult to control the pitch of the soldering point. It is important to have a constant pitch of soldering point as it will determine the structure stability.

5.3.4 CELL SIZE

The different cell size will affect the structural strength of the honeycomb. If a variation of the cell size can be introduces in one process it will gives more results in term of structural strength.

5.3.5 STRUCTURAL TEST

In this project due to equipment limitation, a simple compression test was done to observe the structural strength which is not follow the proper compression test , for future study a proper structural test(ASTM D7336/D7336M) can be introduce.

REFERENCES

1. BITZER, T. - Honeycomb Technology Chapman & Hall, London (1997)

2. Donald V.Rosato, Marlene G.Rosato, Nick R.Schoot. (2010) Plastic Technology Hanbook(volume 1); Momentum Press

3. MULTIFAB INCORPORATED. (2009). *thermoforming design guidelines.* washington: multifab,inc.

4. Proto Labs,Inc., 5540 Pioneer Creek Dr.,Maple Plain, MN55359, MN 55359 USA |877.479.3680|

5. P Shyam Kumar, G. K. (2014). The effect of material. *Journal of Plastic Film & Sheeting*, 162-180.

6. R.Rosen, S. (1930-1950). thermoforming pioneers. In *A history of the growth of the thermoforming industry* (pp. 2-19). PLASTIMACH CORP.

7. Proto Labs,Inc., 5540 Pioneer Creek Dr.,Maple Plain, MN55359, MN 55359 USA |877.479.3680|

8. ZENKERT, D. - An Introduction to Sandwich Construction Emas Publishing, London (1997)

APPENDIX A

HORIZONTAL BAND SAW MACHINE

APPENDIX B

MILLING MACHINE

APPENDIX C

WIRECUT EDM MACHINE

APPENDIX D1

THEMOFORMING MACHINE

APPENDIX D2

APPENDIX E1

SPECIMEN

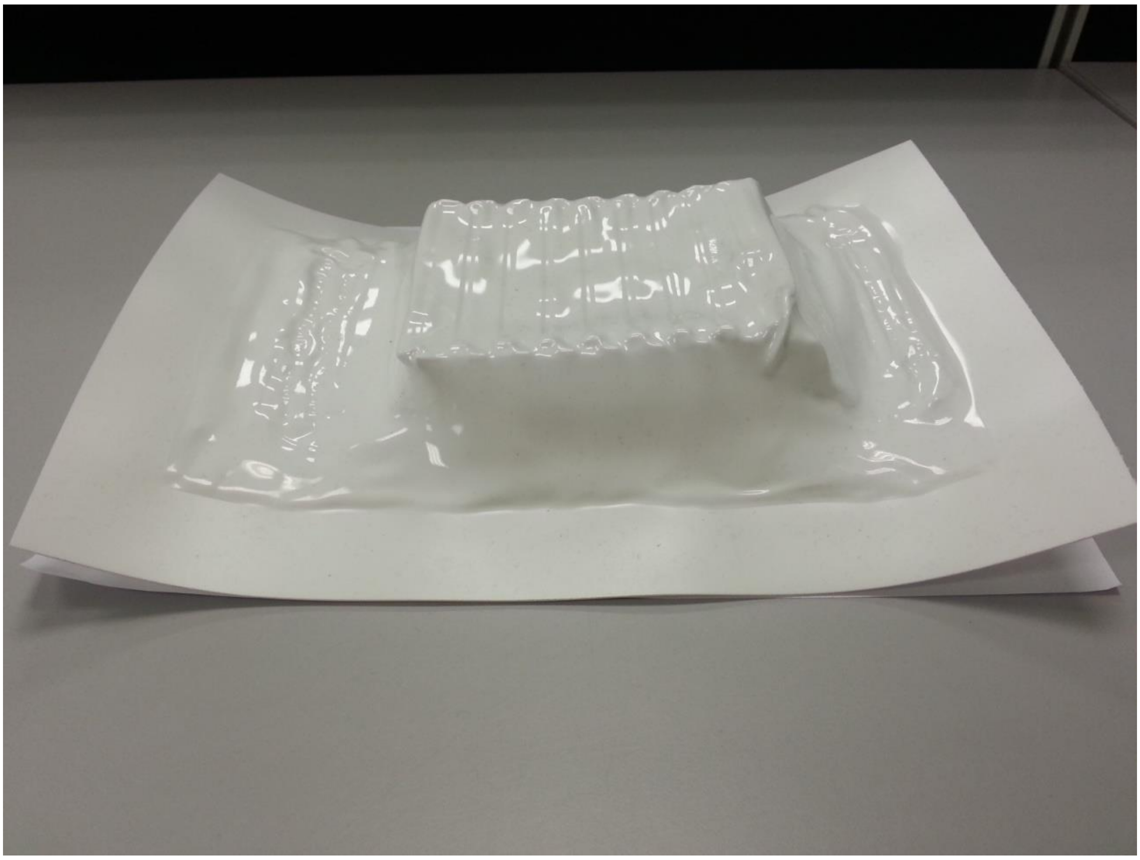
OVERLY HEATED PP SHEET

APPENDIX E2

PP SHEET FORMED UNDER FORMING IDEAL FORMING TEMPERATURE

APPENDIX E3

PP SHEET FORMED WITH NO MOULD PLATEN



APPENDIX E4
MOULD