DESIGN OF A THERMOFORMING PROCESS FOR A SEMI-CRYSTALLINE POLYMER

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ABSTRAK

Penggunaan bagi produk plastik yang diperbuat daripada pembentukan termal terus meningkat setiap tahun yang menyebabkan pembuatan barangan ini semakin meluas. Reka bentuk dan peralatan yang berkos rendah berbanding proses pengacuan suntikan dan pengacuan tamparan digunakan dalam prosess pembentukan termal ini menjadi faktor utama proses pembentukan termal lebih dipilih. Lebih-lebih lagi, proses ini juga dapat menghasilkan produk plastic berbentuk mudah dan kompleks. Dengan meluasnya pembuatan produk plastic isu kecacatan pada bahagian-bahagian produk juga semakin menular dimana ia menyebabkan kualiti produk semakin merundum. Isu kecacatan pada produk plastic termasuklah ketidaklengkapan pembentukan termal produk dan ketidakseragaman pada ketebalan dinding bahagian produk plastic tersebut. Isu-isu ini menyebabkan kualiti yang baik produk merundum. Objektif dalam kajian ini adalah untuk mereka bentuk dan membangunkan proses pembentukan termal produk plastik menggunkan acuan positif dimana perlaksanaan teknik "drape forming" dan ciri-ciri pembolongan digunapakai. Satu bahan polimer bersifat semi-kristal, Polypropylene (PP) ditekan ke atas acuan positif dengan bantuan tekanan berjumlah 20 kPa. Beberapa percubaan eksperimen dalam proses pembentukan termal produk plastik yang dijalankan memberi suatu kefahaman mengenai sifat-sifat bahan polimer apabila dipanaskan pada suhu yang tinggi sewaktu proses pemanasan kepingan plastik sebaik sebelum proses pembentukan. Perisian simulasi ANSYS ® Polyflow digunapakai dalam pemodelan simulasi proses pembentukan termal. Tempoh masa yang diambil bagi keseluruhan proses simulasi tersebut adalah 2.6 saat. Selepas proses termopembentukan, ketebalan plastik yang telah dibentuk yang berada di kawasan sistem pembolongan (bahagian AB dan DE) masing-masing hanya berkurang sebanyak 22.5% dan 37.5% . Di bahagian ini, udara yang terperangkap dialirkan oleh sistem pembolongan supaya plastic termo mengikut bentuk acuan. Ketika proses pembentukkan termal, plastik mengedar lebih baik tanpa kedutan pada bahagian sistem pembolongan.

ABSTRACT

The use of thermoformed plastic products continues to escalate each year causing vast productions of these plastic manufactured merchandises. A low-cost in design and tooling for the production of thermoformed products compared to injection and blow moulded products has become a major factor in which the former is preferred over the latter; in cases of manufacturing simple to complex shapes of plastic products. As plastic productions continue to grow, issues in defects of these parts begin to spread whereby causing low quality thermoformed plastic products to be manufactured. The issues of the defects include incomplete forming and non-uniform wall-thickness distribution of the thermoplastic product which leads to the decreasing the high quality of the thermoformed plastic product. The objective of this research is to design and develop a thermoforming process for the production of a thermoformed plastic part using a positive mould whereby implementing drape forming technique and venting features. A semi-crystalline polymer material, Polypropylene (PP) is heat-softened and drawn onto a positive mould with the assistance of a constant pressure of 20 kPa. Experimental investigations and visualisation observations were carried out in the understanding material behaviour of the polymer material when treated to elevated temperature during the heating of the plastic sheet prior to forming. ANSYS ® Polyflow simulation software was used to compute the modelling of the thermoforming process simulation. The total amount of time of the simulation is 2.6 seconds. Post-thermoforming, the thickness of the thermoforming plastic sheet in the regions in which the venting systems are allocated (region AB and DE) only decreased 22.5% and 37.5% respectively. In regions AB and DE, air is removed through the venting system allowing the plastic sheet to conform onto the mould. The material distribution on these regions are better distributed compared to without using venting system.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Plastic industries are known as one of the fastest growing industries in the United States, with an economic impact exceeding $100 billion annually and providing approximately 1.5 million job opportunities. As both sales and consumptions continues its rapid growth, the plastics industry will continue to lead other industries in both stability and expansion ("Associate of Applied Science in Plastics Engineering Technology", 2017).

Figure 1.1. shows a recent study done by Plastics Europe (PEMRG) in 2013, whereby the ranking of plastic productions throughout the globe was highest in China with 24.8% while Europe ranking the second highest with 20% and the rest of Asia with 16.4 % of plastic productions. This shows that the plastic industry has crucial significance in economic and developmental impact to other industries ("An Analysis of European plastics production, demand and waste", 2015).

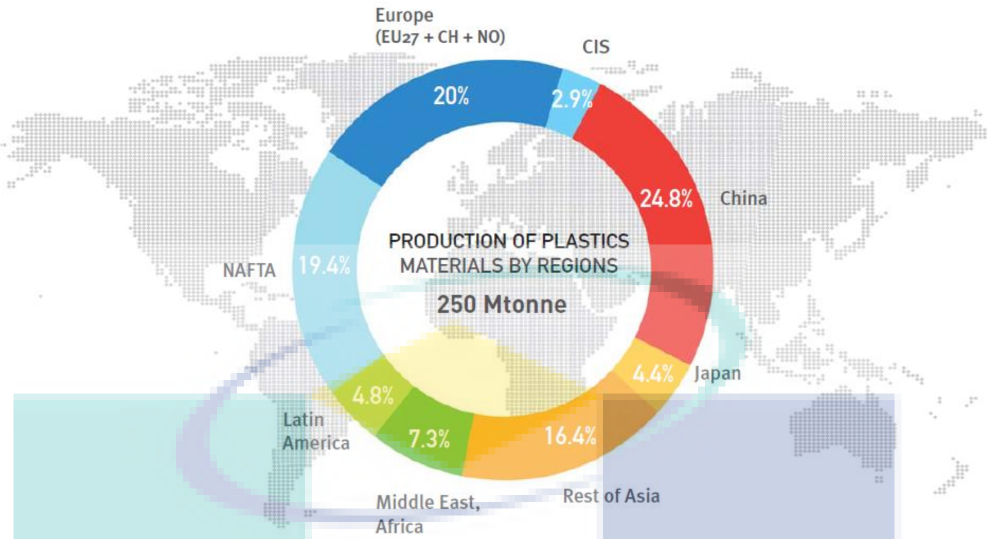


Figure 1.1 Word production of plastic materials

Source: An Analysis of European plastics production, demand and waste, (2015).

Plastics provide a wide variety of markets causing the rise in plastic manufacturing to continuing to develop throughout the globe. The bar chart in Figure 1.2 shows the sections of plastic manufacturing demands in Europe in the year 2014. The largest application sector was the packaging applications which represent 39.5% of the total plastics demand. Other sectors with consecutively decreasing demands include building and construction, automotive, electrical and electronics, agriculture and other appliances such as household, consumer products, furniture and medical products (Plastic Europe). This is due to the increase in demands of plastic packaging that are essential in major industries such as food, toys, stationary, electric and electronic industries. As the productions of these sales market continue to rise, so does the plastic packaging industry leading to rapid growth of the sector.

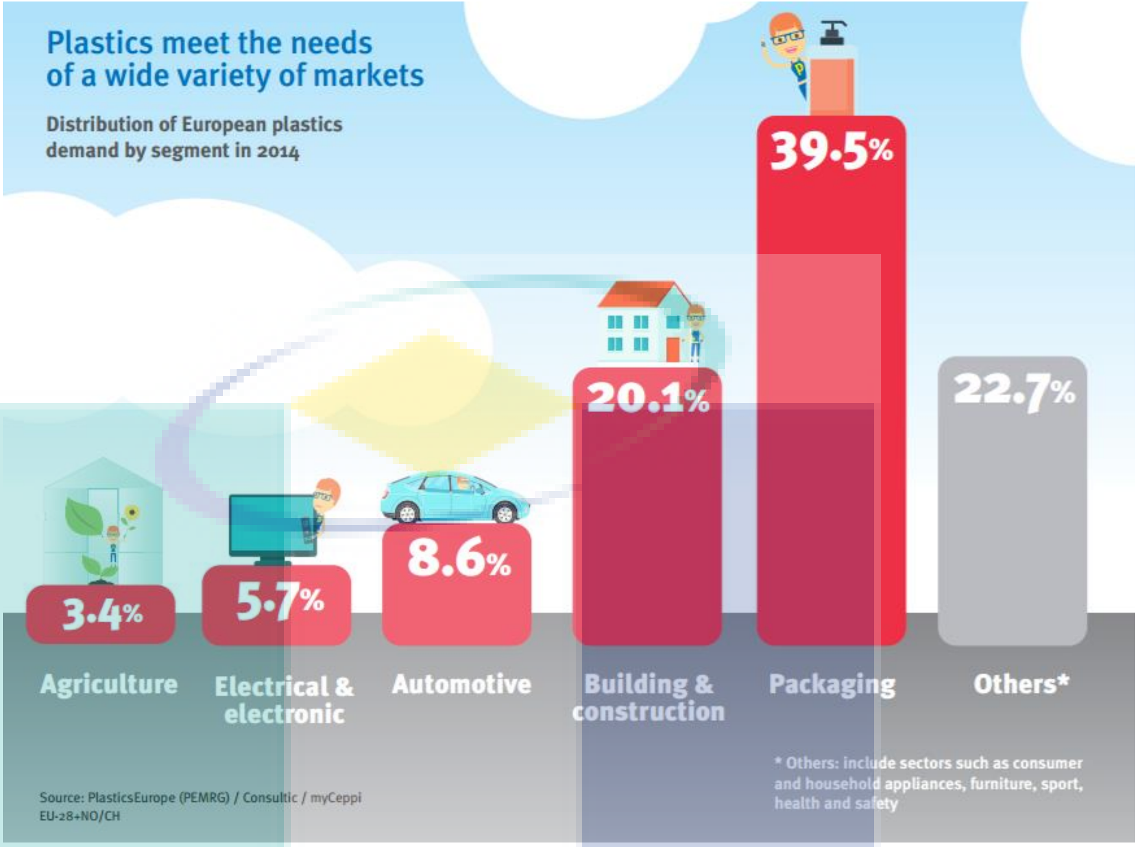


Figure 1.2 Bar chart of varieties of uses of plastics in 2014
Source: An Analysis of European plastics production, demand and waste,(2015).

One of the plastic manufacturing process increasing in packaging industries today is the thermoforming process (O'Connor et al., 2013). Similarly relying on the features of the mould as in injection and blow moulding manufacturing process, thermoforming proposes a low cost in tooling design and process ("Fundamental Manufacturing Processes Series Study Guide",n.d.). Basically, this thermoforming process begins by heating a thermoplastic sheet and subjecting it onto a mould for shaping. This thesis contains sections that describe an investigation carried out to test the validity of the problem statement of the study.

Although thermoforming process has widely been developed in many countries for plastic mass productions of various products, however, researchers struggle to achieve low-cost in manufacturing and high-quality products. Issues in these findings are studied to understand the problem in a wider angle hence to provide a solution.

1.2 Problem Statement

Achieving a good quality thermoformed part requires deep understanding in thermoforming process, the behaviour of the thermoplastic material used, and the tooling design and mould fabrication. This study intends to understand the thermoforming equipment used in relation to using a semi-crystalline polymer material. The components used are revised and developed to be compatible with the mould structure. An understanding of the behavioural of the semi-crystalline thermoplastic material is recorded whereby it is visually investigated under elevated temperature. A typical positive mould is used to understand the material distribution of the semi-crystalline polymer material under positive mould conditions.

From previous studies, a poorly conformed thermoformed part is produced when using a positive mould with no venting system (Throne, 2008; Kumar et al. 2013; Kommoji et al., 2014; Thermoforming Guide for Stat-Right, n.d.). A thermoforming positive mould is designed to counter this problem by developing a modular approach of mould design. Simulations of this method using vented positive mould are also conducted to understand the material distribution of the polymer flow using an idealised pure polymeric material.

1.3 Objectives of Research

In relation to this research, the objectives of this study are as follows:

a) To design a thermoforming process of thermoformed semi-crystalline parts using positive moulds.

b) To implement drape forming technique on the thermoforming process of thermoformed plastic parts.

c) To design a venting system feature for the thermoforming mould in assisting in thermoforming process.

d) To compute a simulation of the thermoforming process using ANSYS® Polyflow.

1.4 Scope of Study

This study intends to focus on the understanding of a thermoforming process for a semi-crystalline polymer material using positive moulds. Drape forming technique is applied whereby a positive mould is used as the primary tool. A semi-crystalline polymer material is chosen as the thermoplastic material. The material behaviour of this polymer is studied under high temperature. A simple simulation for the thermoforming process is conducted to understand the material behaviour during forming process.

1.5 Overview of Thesis

Chapter 1 introduces the topic of this thesis. A general background of the thermoforming process is briefly explained in relation to the objective of the research. A statement of the problem in the field is presented with references to previous studies. The objectives of this thesis are presented in order to provide a clear view on the purposes of the study.

Chapter 2 introduces the research literature relevant to the topic. Critical studies from previous research are intensively informed in an organized sequence. The reviews provide the background information that is significant in the understanding of the purpose of the study.

Chapter 3 describes the approach in constructing the thermoforming process of the thermoplastic sheet. A flow chart is presented to provide a systematic view of the progress that has been carried out throughout the study.

Chapter 4 represents the data from the results collected from the experiment and discusses the analysis made from the results.

Chapter 5 explains the results in chapter four and interprets the conclusion from the finding of the study. Here, the problem statement of the study is discussed in relation to the findings. The significant findings of the study are interpreted and discussed in relation to previous studies. The limitations of the study's design and recommendations issued with the conducted study for future research are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of literature related to thermoforming process whereby it is chronologically organised to give an insight of the past and present studies. It comprises the issues related to thermoforming process; fundamental components, basic process and problems faced.

2.2 Thermoforming Process

Thermoforming is a plastic manufacturing process of shaping softened plastic sheets into three-dimensional geometrical parts (Throne, 2008). In this process, thermoplastic sheets are initially heated to a temperature range where it softens and is then stretched against a mould surface to imitate the shape of the mould. Thermoformed parts are produced in the production of automotive, medical appliance, aerospace and also in food packaging industries.

The thermoforming process has been introduced as a plastic forming process since early in the year 1870. Back then, thin sheets of cellulose nitrate were fitted into metal moulds and heated with steam to produce three-dimensional parts (DuBois, 1972). During the 1870s, moulds were initially quenched in water and the formed shapes were removed and trimmed to shape. Products made by this method included baby rattles, mirror cases, and sharp piano keys.

Today, thermoforming has expanded its feasibility in a wide range of sectors. This is due to the ability of the mould to be fabricated in a variety of shapes and sizes with less consideration on the high cost of mould fabrication and process. Transportation, recreation, electrical and electronics, medical and disposable food packages make the highest ranking in industrial thermoformed products (Productive Plastics, Inc.). As to this, a variation of moulds is produced according to economic demands in productions.

In general, thermoforming is divided into two main techniques; heavy-gauge and thin-gauge thermoforming. Heavy-gauge thermoforming utilises a plastic sheet with a thickness greater than 3 mm while thin-gauge thermoforming utilises a plastic sheet with a thickness of ranging from less than 1.5 mm (Throne, 2008). Heavy-gauge thermoforming involves manufacturing of housings in aircraft and automotive and enclosures and large windscreens while thin-gauge thermoforming mainly are the manufacturing of packaging and “disposable” containers. Differences in plastic thickness require different methods of thermoforming to be applied.

Thermoforming is currently being employed in plastic industries today for the manufacture of lightweight, thin-walled products for packaging applications (O’Connor et al., 2013). With the increase in the manufacturing of these products, numerous research has been conducted for the design and development of this specific process.

Figure 2.1 shows an example of several food packaging thermoplastic products manufactured by thermoforming process that is widely available in convenient stores worldwide. The thermoforming process for these food packaging products is determined by the thickness of the initial and final wall thickness distribution. To obtain a specific thickness of a food package container, the initial thickness of the plastic material needs to be taken into account to avoid undesirable final thickness of the product. In this study, a thermoformed food packaging container shaped of a truncated cone will be studied to match the type of thermoforming process conditions suitable.

Figure 2.1 Thermoplastic products manufactured by thermoforming process.
Source: Alfa, (2014).

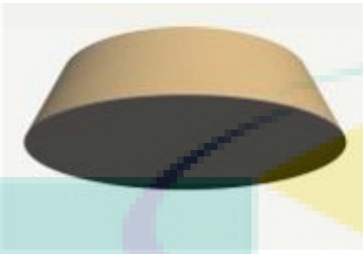
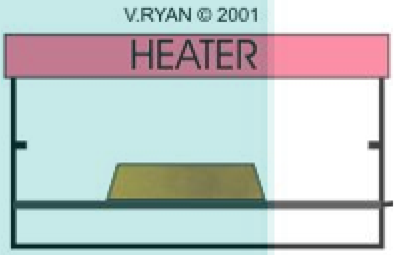
2.2.1 Vacuum Forming

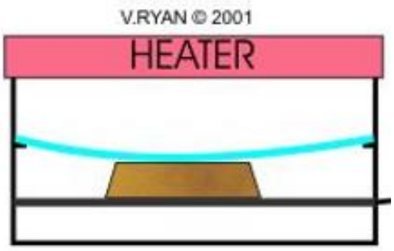
The most extensively used method of thermoforming is by vacuum. A heated polymer sheet is subjected onto a negative or positive mould, and vacuum is then used to remove the trapped air between the sheet and the mould (Multifab, Inc., 2009). Although, to Throne (2008), Understanding Thermoforming Second Edition, he explains that vacuum forming process is much used with negative moulds as it concentrates in the detailing of the outer surface of the mould. Other than suitably used for the productions of heavy-gauge thermoforming products, it is also implemented in the productions of thin-gauge products such as containers, picnic plates and cups and pharmaceutical containers. This forming process however, yields parts with uneven wall thickness and are suitable for shallow-draw parts or where wall thickness variation is not a crucial function of the product. The conditions of the part used for this specific process should therefore consider the depth of draw of the product to allow even wall thickness distribution. Although vacuum forming is primarily used for the productions of negative mould products, this study attempts to implement the method in the use for producing thermoformed plastic parts using positive moulds by incorporating shallow depth of draw and acceptable design of mould features.

In plastic production firms, vacuum forming manufactures mass productions of plastic products within minutes to achieve their target productions every day. Moulds with internal cooling channels are employed to control the temperature of the mould for consistent mould temperature (Multifab, Inc., 2009). Although materials such as wood, epoxy and plaster are the least expensive for a mould fabrication product, aluminium is the material of choice because of its exceedingly high coefficient of thermal conductivity that enables it to heat and cool at a faster rate throughout the process.

Table 2.1 shows the illustration process of vacuum forming technique of a bowl shape product. The mould is initially fabricated according to the allowable guidelines in shape, draft angles and draw ratios. It is then placed inside the forming machine in which the heater is installed above the mould. The plastic sheet is clamped between the mould and the heater and the heater is switched on to heat the plastic sheet until it becomes pliable to be shaped. The temperature of the plastic sheet prior to forming varies according to different types of plastic materials used. After the plastic sheet is in a pliable condition, it is then pressed onto the mould and the vacuum is switched on to allow air removal from between the plastic sheet and the mould. Air is evacuated until the plastic sheet replicates the mould completely and left to cool for several minutes. The thermoformed part is then removed after it is cooled and the excess plastic is trimmed to allow only the bowl shape product to be remained (Ryan, 2001). In this study, a similar approach is implemented to produce the thermoformed plastic part as vacuum system is used.

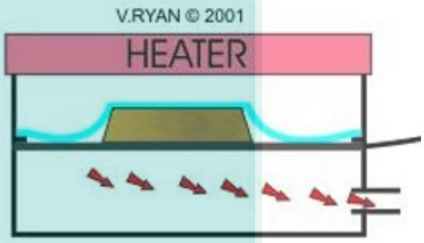
Table 2.1 The Process Flow of Vacuum Forming

Process Flow Illustration	Description
	1. The mould is fabricated. The sides and edges are designed according to the guidelines in draft angles to allow easy removal of thermoformed part.
	2. The mould is placed in the vacuum former.
	3. A thermoplastic sheet is clamped above the mould.
	4. The thermoplastic sheet is heated by the heating element.

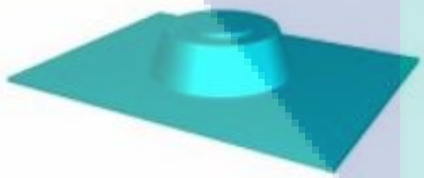


5. The thermoplastic sheet is softened and pliable to formed onto the mould.

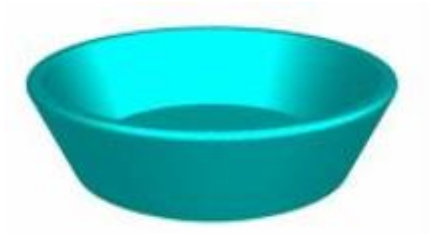
6. The thermoplastic sheet is draped onto the mould.



7. The vacuum system is switched on to allow air between the thermoplastic sheet and the mould to be evacuated. The atmospheric pressure exerts a force onto the thermoplastic sheet assisting forming of the part. The thermoformed part is then cooled after switching off the vacuum system.



8. The thermoformed part is removed from the mould.



9. The excess plastic is then trimmed so that only the bowl shape plastic part remains.

Source: Ryan, (2001).

2.2.2 Drape Forming Technique

Similarly to vacuum forming, the process of which a heated plastic sheet is pressed onto a positive mould is termed as drape forming (Sala et al., 2002; Klein & Ph, 2006; Rezazadeh-bahadoran, 2005; Simon et al., 2014). It demonstrates the basic concept of forming a plastic product by employing a positive mould. Positive moulds, used in drape forming, compared to negative moulds are generally less expensive (Universal Plastics, 2014). A thermoforming process for producing a part by positive mould using a drape forming technique is conducted in this study.

Figure 2.2 shows a schematic process of thermoforming process using a simple designed positive mould adapted from Design Guidelines for Product Engineers on the Thermoforming Process by T-ForM, 2008. The basic three stages of thermoforming on a positive mould is initially heating the thermoplastic sheet, subjecting the soften thermoplastic sheet onto the positive mould in which it will form the shape of the mould by vacuum and cooling stage and the thermoformed part is left to cool for a period of time before removing the thermoformed part from the mould. These three basic stages are similar to that implemented in this research in which a positive mould is employed with the technique of drape forming.

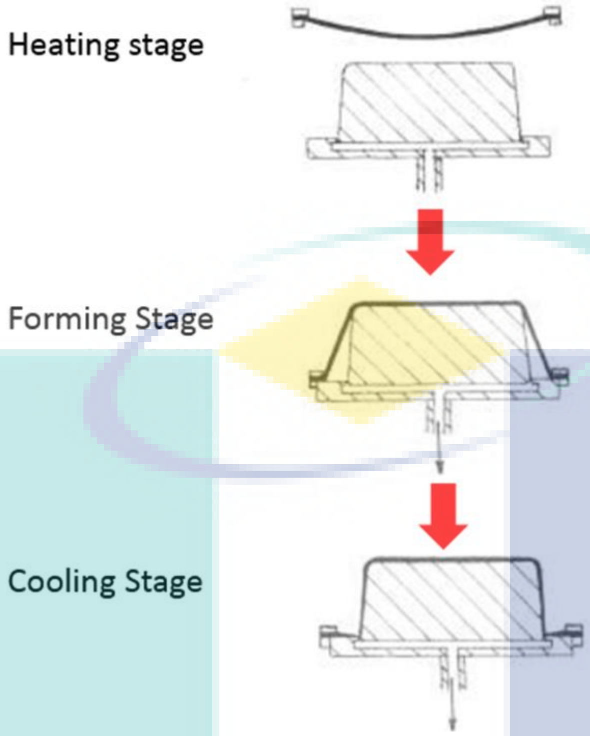


Figure 2.2 A schematic process diagram of Drape Forming Technique

Source: Design guidelines for the thermoforming process (T-ForM)

2.3 Thermoforming Equipment

Thermoforming equipment is used associated with the tooling features and type of process applied. Most thermoforming equipment consists of three basic principles which are the heating element, mould platform and air evacuation system. Figure 2.3 shows a schematic structure of one of the earliest thermoforming equipment in which includes of top and bottom heaters, a platen, plug assistance and stacking device.

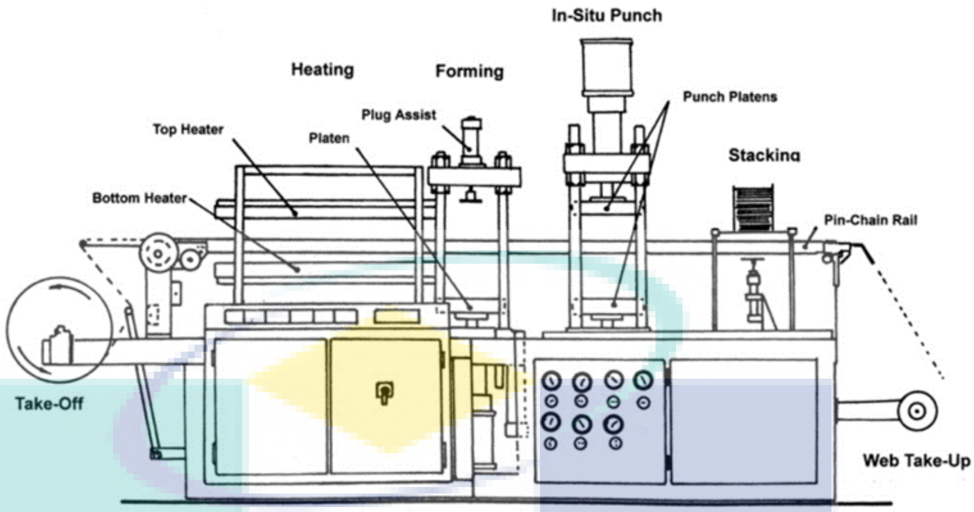


Figure 2.3 Thin-gauge roll-fed thermoforming equipment.
Source: Throne, (2008).

Kumar et al. (2013) utilized a two-sided heating element to their thermoforming equipment to heat a thick Polypropylene (PP) sheet for their studies. The thickness of the PP sheet that they used was a thickness of 5mm thick of two grades, one having linear polymer chains (PP-TF-1) and the other having long-chain branches (PP-TF-2). In another study, which was carried out by Walczyk and Yoo (2009) developed a rapid tooling method, Profiled Edged Laminas (PEL), based on profiling, assembling, and clamping an array of thick layers which is suited for the use of thermoforming large and heavy-gauge parts. While in a study conducted by Kommoji et al. (2014) high impact polystyrene sheets (HIPS) of 1.5 mm and 2.5 mm thicknesses was used in a medium-gauge thermoforming process in which only one-sided heating element was employed. This shows that the type of thermoforming equipment required depends on the thickness of the plastic sheet employed. Thus, for a thin-gauge thermoforming process, a one-sided heating element is sufficient to heat the plastic sheet to a soften state.

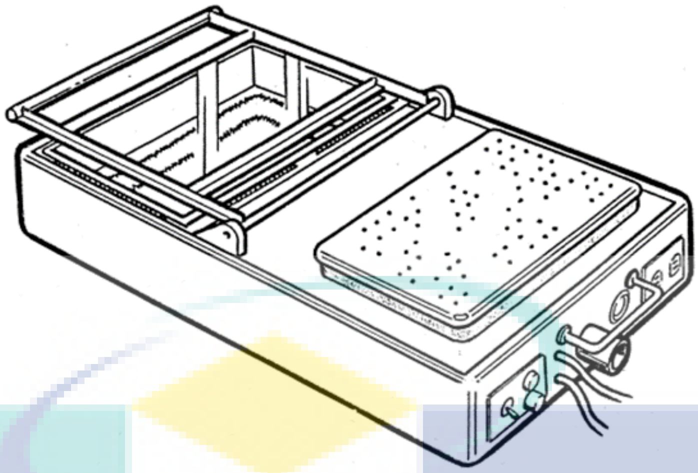


Figure 2.3 A schematic diagram of the thermoforming equipment

2.3.1 Oven

The oven of a thermoforming equipment significantly represents the method of the heating of the thermoplastic sheet. Some thermoforming equipment comprises of an oven that will heat the thermoplastic sheet from below the heating element while others above the heating element. This all depends on the designated thermoforming equipment and the method of forming the thermoformed part.

Another significant component in the oven is the heating element. Earlier studies showed that infrared heaters were employed in the ovens for heating stage in thermoforming process (Brogan & Monahagan, 1995). Infrared heaters were applied to decrease the temperature difference between the surface and the centre of the plastic sheet. Schmidt et al. (2003) conducted a study on the modelling of infrared heating of polystyrene (PS) sheet in thermoforming process. They conducted an experimental and numerical study to determine the efficiency of shortwaves infrared emitters (halogen lamps) for the heating stage. However, regarding on the size of the thermoforming equipment and the thermoplastic sheet employed, halogen lamps would demonstrate less suitability for its purpose. In this research, infrared heaters similar to the previous studies are implemented as to reduce cost.

2.3.2 Platen

Platens in thermoforming assists in many ways. Basically it is used as a platform to place the mould (Outline, 2014). Aluminium platens were used by Marjuki et al.(2015) in their study to place a honeycomb-shaped positive mould. From other resources, it is used as a technique to counter improper sheet sag by mounting the mould onto the platen (Thermoforming Trouble Shooting Guide by Marplex Australia, n.d). An aluminium covered platen will be used as a mounting base for the mould and assist in removal of trapped air between the thermoplastic sheet and mould.

2.3.3 Clamping Frame

Clamping frames are a fundamental component in the process of thermoforming. It functions to hold the thermoplastic sheet during the heating stage, shifts the sheet to the forming area and securely holds the sheet during forming and cooling (Moore, 2002). However, it is only capable to handle one single sheet per operation. Common clamp frames are constructed from conductive materials such as aluminium rather than steel, as it assists the system to absorb and dissipate heat better and faster (MAAC Machinery Corporation, 2016). In addition, it enables the clamp frame to sustain its solid form during intense heat.

Erdogan and Eksi (2014), claims that the geometry of a clamp frame extensively affects the wall-thickness distribution of the plastic material during forming process. They found that in order to produce uniform thickness distribution of thermoformed products, the selection of the clamp frame geometry is essential according to the geometry of the thermoformed product. Meanwhile, Gilormini et al.(2012) stated that the clamping of a sheet in thermoforming process induces a rotation of sheet element near the edges which leads to decreasing thickness of the sheet. As to this, it is essential to design the clamp frames according to the required condition. However, the clamping frame produced in this study is shaped as a rectangular shape with a size that fits the mould when it is operated.

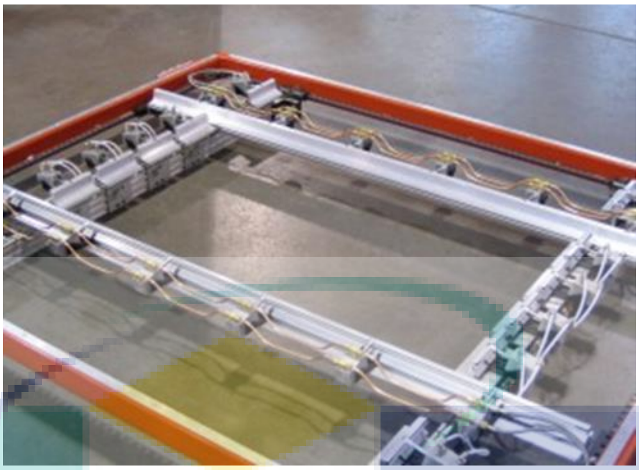


Figure 2.4 Pictorial of an adjustable clamping frame used in high end thermoforming equipment

Source: MAAC, 2017.

2.3.4 Vacuum Systems

Vacuum in thermoforming assists in the replication of the thermoformed part during forming stage. A simple electrically driven vacuum system is designed to allow air between the sheet and the mould to be evacuated and conduct proper formation of the part. Normally employed in the thermoforming of female or negative moulds, vacuum systems has numerously been used by researchers in their studies on this area (Aroujalian et al., 1997; Dong et al.,2006;Chang & Cheng, 2013; Erdogan & Eksi, 2014; Marjuki et al., 2015). The vacuum system in this study uses a conventional vacuum system with a pressure of 20 kPa.

2.4 Thermoforming Moulds

Thermoforming moulds are used to accurately shape and hold a part that meets the desired dimension specifications. When a plastic sheet is pressed onto it, it provides a dimensionally stable surface to allow efficient flow and conformation of the plastic sheet. In addition to that, it also functions as a heat exchanger whereby the heat from the sheet is removed repeatedly and efficiently (Throne, 2008).

A mould must also allow air to vent through the openings in a manageable way. It must be robust enough to withstand repeated forming at elevated pressures and polymer sheet temperatures, withstand possibly corrosive gases from the plastic, and erosion and wear from filled or reinforced plastic. Besides the fact that it should also survive various environmental conditions during long-term storage, it must also survive being moved repeated from storage to machine and back, and in the event of misuse and abuse, it must be more than just cosmetically repairable (Throne, 2008).

The type of thermoforming technique also contributes to an aspect in the thermoforming mould used in the process (“A Vacuum Forming Guide,” n.d.). It avoids any defects of the end product by using the correct method of designing a mould. For any type of thermoforming technique, the aspects that should be considered include the type of shape and dimensions of the end product and thermoforming technique. In example, a positive thermoforming technique is taken place when a thermoplastic sheet is subjected on top of the mould and shaped according to the shape of the mould in accordance to significant mould features such as draft angle, the aspect of draw ratio and radius. Figure 2.6 shows the basic structural differences between a positive and negative mould. To implement drape forming technique, a positive mould is used.

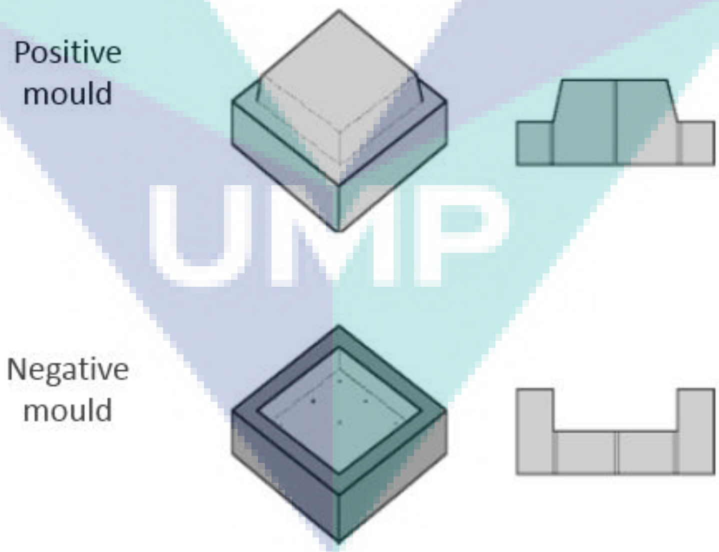


Figure 2.5 Basic structural design of male and female mould

Source : A V acuum Forming Guide,(n.d.)

2.4.1 Mould Materials

There are two general categories of thermoforming moulds namely production moulds and prototype moulds. Production moulds are common of aluminium, with certain types of steel used for high-temperature, high-pressure, or reinforced sheet forming. Prototype moulds may also be made of metal, but are usually fabricated of more easily worked materials such as plaster or wood (Throne, 2008). However, aluminium moulds were preferred tooling materials for thermoforming compared to other materials due to its excellent heat conductivity and ease of machining (Illig, 2001). Apart from that, aluminium is frequently the material used for production tooling due to its good surface hardness, low wear, lightweight and excellent strength to weight ratio.

Most thin-gauge thermoforming moulds are made from machined aluminium. This is to ensure smooth surface of the thermoformed part is obtained during the forming stage. Besides that, thermal conductivity of the mould material is also a factor in which aluminium has higher thermal conductivity compare to other materials whereby when hot thermoplastic is pressed, rapid energy transfer occurs, thus allowing the thermoformed part to cool at a faster rate and machines easier (Leidschendam, 2008) . Table 2.2 shows a list of material conductivity for the tooling material that is relevant in this study.

Several criteria are highlighted in designing the thermoforming mould to comply with dimensional and thermal requirements of the process which are:

a) It should be capable of repeated thermal cycling,

b) It is easily modified,

c) It should be able to transmit vacuum from all areas of its surface,

d) It should be highly robust,

e) It must have an accurate dimension,

f) And it should have a known shrinkage.

Source: T-form, (2008)

Table 2.2 Tooling Conductivity Data

Tooling Material	Thermal Conductivity (10^{-3} kw/m ºC)
Aluminium	124
Resin	1.3
Plaster	0.298
Wood	0.125

Aluminium materials are commonly used as thermoforming moulds in thermoforming processes (Walczyk & Yoo, 2009; Kumar et al., 2014; Kommoji et al., 2015. Marjuki et al., 2015., Nik Hassan et al., 2015). This is due to its highly machinable characteristics with high thermal conductivity. Aluminium moulds can be fabricated by casting or machining process, or a combination of both processes (Leidschendam, 2008). It can either be machined from blocks or cast from specific patterns. Moreover, due to its higher thermal conductivity, heat from the formed thermoplastic sheet able to be dissipated quickly and efficiently ("A Vacuum Forming Guide," n.d.).

2.4.2 Venting Systems in Moulds

Venting holes are used to maintain the mould surface temperature and to obtain actual mould replication. They are required to be located in areas where air can be trapped (Walczyk & Yoo, 2009). They are designed and machined in the thermoforming mould areas that have extreme changes in slope or sharp corners. The surface gradient is considered sharp when its angle increases from zero whereby signifies a flat surface. A clear understanding of venting systems in moulds is essential for the material distribution of thermoformed parts. The positive mould in this study is designed to be incorporated in the areas that have changes in slope or sharp corners. The mould is fabricated into three pieces in which the gap between the pieces becomes the venting system.

2.5 Part Design

The main idea of a thermoforming operation is for it to make it into the market at a certain profit. Commonly, polymers that are produced into sheets can also be thermoformed into a functional part. Various selection of polymers can be formed into sheet by various methods and thus be thermoformed. A specific protocol is established for the selection of the appropriate polymer for each application. As described by Unwin et al. (2005), the two requirements for the data on the polymer materials are, first, it is able to predict the plastic deformation in the polymer that occurs as a result of the of the initial forming operation to shape a container of the defined geometry, and second, it is crucial to define the mechanical properties of each element of the specific container so that its overall response to mechanical loading can be predicted.

In the year 2000, Ayhan and Zhang conducted a study in the thermoforming of food containers using a combination layer of polymers consisting of high impact polystyrene (HIPS) as the outer layer, low density polyethylene (LDPE) as the inner layer and polyvinylidene chloride (FVDC or Dow's Saran) in between as the barrier layer. Although they were successful to produce a single thermoformed part using multi-layered polymer materials, the production of a thermoformed part using three types of polymer materials would eventually disturb the study of the behaviour of the polymer material during heating process thus causing a weak understanding of the material behaviour for research purposes. Similarly, Unwin et al. (2005) reported the implementation of two blended polymer materials, Polystyrene (PS) and High Impact Polystyrene (HIPS) in their study of thermoforming a simple food container. These two studies present an excellent method of polymer combination to gain the material strength of the part but fail to understand the material behaviour of a certain polymer material when subjected to elevated temperature during thermoforming process. To provide an understanding of the material behaviour for a functional part, this thesis will present a singular polymer material implemented for producing a functional product.

Part designs are crucial in the production of any manufacturing productions. Similarly, with thermoforming, the general components of any part design must be initially defined. By defining the general components, it is then determined whether thermoforming process would be the best means of process to produce the part. Refining the designs must be worked out after factoring the general limitations of the forming process (Throne, 2008). The dimensions of the part are also dependent on the polymer shrinkage, warpage and dimensional tolerance. In addition to that, aspects such as corner dimensions are relevant in providing a good surface quality and specific design. A study conducted by Kommoji et al.(2014) shows the implementations of these part designs.

Five different moulds were designed with different mould design parameters which are corner radius, draft angle, depth of draw, top radius and slant of length. These mould design parameters are important in relation to study the wall thickness distribution and uniform stretching of the material. From their study, they found that with an increase in draft angle, the effect of non-uniform stretching of the material caused by the slant length of the positive mould could apparently be minimised. As to that, to produce a thermoformable part, this study proposes to implement the part design guidelines described.

2.5.1 Design Protocol

The primary importance in industrial design of a certain part is commonly the geometrical shape of the final part. A specific shape is used to classify various types of polymer process. For example, extrusion process is the main method in producing linear or areal shape parts, whereas blow moulding is often used in the production of hollow shape parts. Injection moulding on the other hand is mainly used to produce bulky shape parts with rapid wall thickness variations, while thermoforming process is the method commonly used for producing extremely thin-walled shapes with near-uniform wall thickness (Throne, 2008).

2.5.2 Design Characteristics

A significant engineering approach for designing a shape of a desired part is to identify the primary design characteristics of each part such as the shape limitations, maximum size, the complexity of the shape, wall thickness tolerances, whether it is an open or closed hollow shape or the relative size of the part and whether it needs accoutrements such as threads, inserts or moulded-in holes (Throne, 2008). This is to ensure the design of the part satisfies an engineering approach whereby also satisfying the ability of the part to be manufactured in a specific process, in this case thermoforming process. By applying the design characteristics examples described by Throne (2008), the truncated-shape positive mould used in this study is therefore factorised.

The limitations in shape are defined to be that it has a slant length which attributes to the stretching of the material during forming and may be minimized by increasing the draft angle. The shape of the mould however represents a certain complexity on the top and bottom region whereby drastic variation of depth occurs. Figure 2.7 shows an illustration of a schematic diagram of a truncated-shaped positive mould designed by (Kumar et al., 2013). The top region shows a diameter D_t and has a severe slant length, BA and XZ. The draft angle is denoted as θ. The bottom region is denoted as ZA. As to this, the truncated-shape positive mould fabricated in this study will generally apply the features of the mould in Figure 2.7 to imitate produced shape and feature of the thermoformed part.

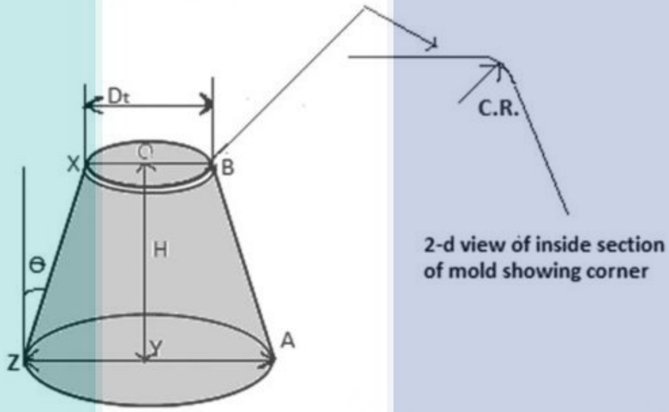


Figure 2.6 Schematic diagram of truncated shape positive mould

Source: Kommoji et al. (2015)

2.5.3 General Product Design

Thermoforming produces parts by differentially stretching a thermoplastic sheet against a mould surface thus resulting a part characteristically with a non-uniform wall thickness (Throne, 2008). Studies conducted by Ayhan & Zhang (2000); Chen et al., (2008); Erdogan & Eksi, (2014); Kommoji et al., (2015); Kumar et al., (2014) proves this matter. In these studies, positive or negative moulds are individually used to investigate the variation in wall thickness during by thermoforming a polymer material. The basic mould shape used were similarly truncated shapes of cups or cylindrical food containers.

However, despite the difference of type of mould used, whether positive or negative, variation in wall thickness still occurs. It is acknowledged that the moulds used does not incorporate any vent holes or air evacuation lines to assist in avoiding wall thickness variation. Thus, the thermoformed parts produced by positive mould in this study is predicted to have similar stretching behaviour but with better material distribution on the surfaces of different heights.

The duration of replication of the polymer sheet against the mould surface is dependent on the differential pressure used. This is mainly because different types of pressure force results in different extension of replication. Pre-stretching is a method of inflation whereby using plug assists to make changes to the local part wall thickness hence stretching the sheet in one area that affects the final wall thickness in every region of the part. A schematic diagram of basic plug-assisted thermoforming is shown in Figure 2.8. The plug is initially positioned above the polymer sheet, then it is forced into the mould where the polymer sheet is then inflated.

The study of plug-assisted thermoforming have been studied by numerous researchers in the recent years in which Aroujalian et al. (1997) and Harron et al. (2003) were the early few. In their studies, they presented the use of plug-assist in pre-stretching the polymer sheet against a negative mould. Although the method was found to be a great success in achieving near uniform wall thickness and provide an excellent replica of the surface on the mould, the results shows that plug velocity has a great influence in wall thickness distribution that requires to be numerically controlled. This however would not be a necessity in the use of positive moulds as the polymer sheet will be directly pressed against the mould surface by contact. In this study, however, only man power is implemented in providing pressure to the polymer sheet instead of other mechanical forces.

Figure 2.8 shows a schematic diagram of basic plug-assisted thermoforming process of food package adapted from McCool and Martin (2011). The schematics begins as the sheet is fitted on top of the opening of the negative mould while the plug is positioned to be on top of the plastic sheet. Forming of the plastic sheet occurs when the plug is drawn into the negative mould allowing the deformation of the plastic sheet into the shape of the mould and blowing occurs to inflate the plastic sheet. This simulation method is used as reference in developing the simulation of thermoforming process in this thesis, whereby the negative mould is replaced to be a positive mould and the plug is not utilised.

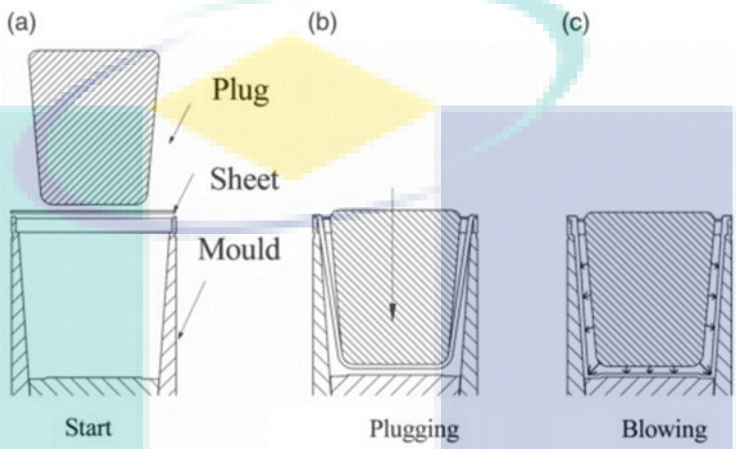


Figure 2.7 Schematic of basic plug-assisted thermoforming process

Source: McCool & Martin (2011)

2.5.4 Draft Angles

In thermoforming of female or negative moulds, the parts can be produced with zero draft angles which mean that the walls are 90 degrees or right angles to the base of the part (Throne, 2008). As a one-sided thermoforming process, this enables the thermoplastic sheet to form on the negative side of the mould and replicate the shape. Subsequently, when the part starts to cool, the density is increased and the dimensions of the part are decreased causing the part to shrink away from the mould surface and allowing the part to be released from the mould. This mechanism, however, was found to be an ineffectively way in producing high quality thermoformed parts due to the lack of pressure on the thermoplastic sheet when vacuum is applied to force the sheet into the mould. Therefore, studies show that in order to produce high quality thermoformed parts using female or negative moulds, plug assistance is required (Aroujalian et al., 1997; Ayhan & Zhang, 2000; Hosseini et al., 2006; Klein & Ph, 2006; Erdogan & Eksi, 2014). However, as plug assist thermoforming was found to be of higher cost and required more tooling involved compared to positive thermoforming in producing the same part, a study on using positive thermoforming is relevant to investigate its efficiency.

In positive thermoforming, drafts are used to enable the part to be released from the mould. The polymer, during the cooling phase, shrinks to the mould, and with a certain draft angle, is released from the mould. Positive mould draft angles are between one to 5 degrees, with an average of 4 degrees. For plastic productions that are required to be stacked, draft angles are a crucial part design of the part (Throne, 2008).

2.5.5 Draw Ratio

One of the basic functional features identified when a thermoforming mould stretches onto a thermoplastic sheet is the draw ratio (Tam & Chan, 2007). The draw ratio of a thermoforming mould is the ratio of maximum mould depth to a minimum across open mould face at given location. In thermoforming, the pliability of the thermoplastic sheet or draw-ability (depth of draw or maximum draw ratio) increases with increasing temperature (Of, Thermoforming, Of, Society, & Plastic, 2012). For pressure forming the draw ratio considered the best is <1:1, (Leidschendam, 2008). Maximum draw ratio is generally 3 to 1 ratio (“Thermoforming Design,” n.d.). High “draw ratio” are caused by shape features such as steep depressions and sharp edges, which is highly undesirable and difficult to form compared to low “draw ratio” of thermoforming features. Generally, to avoid these undesirable features, the thermoforming moulds chamfer the sharp edges, add fillets or fill up deep depressions. The equation below shows the formula to calculate draw ratio:

$$Draw\ Ratio, R_A = \frac{Depth\ of\ mould}{Width\ of\ mould} \tag{2.1}$$

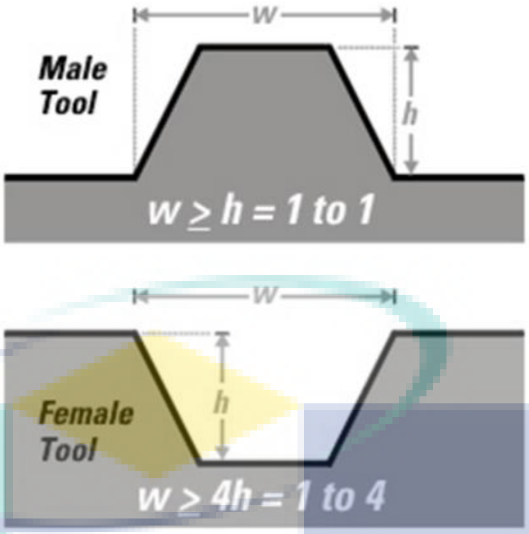


Figure 2.8 Schematic diagram of draw ratio features for a male(positive) and female (negative) mould.

Source: Saudi Basic Industries Corporation, (2015).

2.5.6 Moldability

The mould-ability of a plastic sheet to be shaped into a desired part is dependent on the mould design is termed as moldability. Several factors including wall thickness, sharp edges, warpage concerns, draft angles, bosses and ribs, types of core-cavity used, and undercut if using a sort of cam or finger cam. Figure 2.10 shows examples of diagrams with correct and incorrect part features. Sharp edges as seen in the diagram categorised as incorrect part design in which presents zero draft angle will be difficult to be produced. During the forming phase in positive thermoforming, the plastic sheet will be unable to attain precise conformation of the edges. When the plastic sheet it cooled, the thermoformed part will shrink onto the mould, thus causing difficulty to be released from the mould. On the other hand, the correct part features is a mould presented with a draft angle. This is to encounter the forming phase when the plastic sheet shrinks onto the mould and could be easily released. This study uses this feature in order to allow the thermoformed part to be easily removed from the mould.

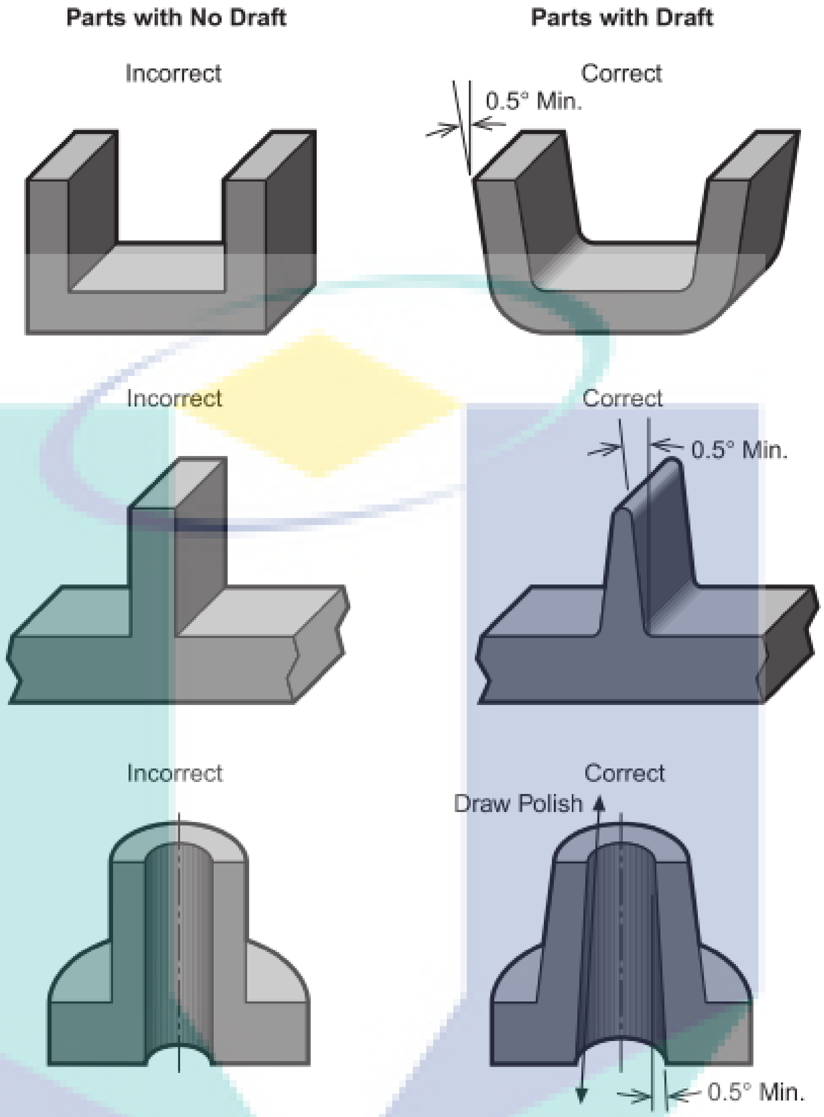


Figure 2.9 Shows another example of a part design of (a) undrafted and (b) drafted part. For negative moulds, guidelines from thermoforming industries suggest that draft angles are presented as one of the part design of the mould to provide a smoother production. The releasing of the thermoformed part from the mould with presented draft angle also prevents from any ruptures.

Figure 2.10 Diagram of an undrafted and drafted part

Source: Design of Moldability, Proto Labs, Inc. 5540 Pioneer Creek Drive, Maple Plain, MN 55359 USA

2.5.7 Guidelines for Successful Part Design

- Webbing or wrinkling typically occurs at the outside three-dimensional corners on male or positive moulds or on male or positive portions of female or negative moulds.
- Any draft on a mould surface is better than zero draft angle.
- Chamfers should be considered if any radius cannot be designed into the part.
- Half to three-quarters of part shrinkage occurs before the part temperature has fallen to the polymer heat distortion.
- For vacuum forming, the minimum radius in a two-dimensional or three-dimensional corner should be greater than the local sheet thickness. Otherwise, the sheet will buckle as it is drawn into the corner.
- Plastic sheet thins in proportion to the reduction in radius of the three-dimensional corner.
- Sharp corners can cause parts to be brittle or tear apart leading to part failure when impacted.
- Parts having internal angles of less than 90 degrees may be brittle regardless of the polymer.

(Throne, 2008)

Table 2.3 shows general guidelines in mould design that are applied in the designing and fabrication of the mould. A detailed methodology of how the guidelines are applied is in section 4.3.

Table 2.3 General guidelines in Mould Design

Properties	**Descriptions**
Draft Angles for Positive Mould	A minimum of 5^{o} of external draft angle is required
Radii and Chamfers	The deeper the part, the larger the radius or chamfer is required
Undercuts	Undercuts should be avoided but if necessary should be a maximum of 0.500 inch
Sharp corners or edges	Sharp edges should be avoided by radius or chamfer

2.5.8 Computational Simulation of Thermoforming

Trial and error methods are well employed in thermoforming industries today to design and develop new plastic products. These methods, however, use up a high amount of time and are highly cost consuming (Dong et al., 2006 and Karamanou et al., 2006). Therefore, a Computer-Aided Engineering software, ANSYS POLYFLOW was used to solve the issues. By using this software, the behaviour of the plastics are determined during the process in which thinning wall areas were able to be identified. Due to the increasing complications in material processing technologies, researchers have made significant the advances of simulation these processing techniques such as injection moulding. However, compared to thermoforming, the corresponding body of work is small and have not yet achieved benefits as other process simulations seen in other areas.

Advances in process simulations of thermoforming have been reported by a vast amount of studies since the early 90s due to the demand in thermoforming productions in industries. Bourgin et al. (1995) reported a simple vacuum forming process in terms of preliminary models in which a heated sheet was formed by air pressure, the material was treated as a membrane element and no interaction with a moving plug was discernible. Meanwhile, a vacuum forming study published by Wang et al. (1999) of an acrylonitrile butadiene styrene (ABS) square cup have reported a good correlation between experiment and simulation of the part. In most cases, simulations have employed finite element techniques for modelling the process components and in an early work, the assumption of isothermal conditions was considered as a standard procedure. As a result, these simulations generally employed membrane elements to represent the sheet during thermoforming while tooling surfaces were modelled as rigid surfaces as in the study conducted by (Karamanou et al., 2006).

In a different study, O'Connor et al. (2013) conducted a simulation of a plug-assisted thermoforming of polypropylene polymer to investigate the thickness distribution of the thermoformed part. The research done by O'Connor describes the solution taken in order to solve the fluid mechanic problem in venting systems. The research done suggests the use of uniform mesh refinement algorithm in a defined adaptive region domain by using a typical industrial process condition whereby the behaviour of a 1.23 mm thick polypropylene is simulated during the forming phase using a 3-node thick axisymmetric thermo-mechanically coupled shell elements that allow in-plane deformation and temperature gradient. A total of 0.70s was covered for the thermoforming process from the start to the end of the plug's displacement into the clamped sheet and then takes a further of 0.40s for the final application of air pressure.

2.6 Thermoplastic Material used in Thermoforming Process

Thermoplastic materials are commonly used in the thermoforming process of polymer materials. This is due to its molecular structure that enables it to deform when heated and hardened when cooled ("A Vacuum Forming Guide," n.d.). Although amorphous polymer materials such as Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), PVC, and PVC/Acrylic blends are able to form easier as they have zero critical forming temperature, semi-crystalline polymer materials such as Polyethylene (PE), Polypropylene (PP) and nylon are the most used polymer materials for thermoforming as they have narrower forming temperature (Incorporated & Guidelines, 2009). Both Schmidt et al. (2003) and Sadighi et al. (2008) used thermoplastic materials for their study in thermoforming processes. Polypropylene (PP) polymer material was used as a base material by Sadighi in the study of the deformation in thermoforming by laminating thermoplastic composites. Polypropylene (PP) polymer material was characterised and used in this study as the material of the thermoformed part.

2.6.1 Fourier Transform Infrared Spectroscopy (FTIR)

Laroche et al. (2013) in their studies of thin films, conducted an experiment to characterise thin films on polymer foils using Fourier transform infrared (FTIR) spectroscopy in the attenuated total reflectance mode. The FTIR method is able to identify unknown materials, which is able to determine the quality or consistency of a sample and to determine the number of components in a mixture (Thermo Nicolet Cooperation, 2001). This provides a solution technique to characterise the polymer material used in this study.

2.6.2 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) observes heat effects related with phase transitions and chemical reactions as a function of temperature whereby heat flow differences of the sample and a reference at the same temperature, is recorded as a function of temperature (Colby College, 2012). The melting behaviour of a semi-crystalline polymer was characterised using DSC by O'Connor in 2010, for thermoforming applications. Later in 2013, he performed another laboratory test that included DSC to identify the process timings, forming speeds and thermoforming window of the polymer material used in his study. As to this, the DSC technique is used to provide melting temperature of the polymer material used in this study.

2.7 Polypropylene

Polypropylene (PP) used by most researchers in the study of the deformation of polymer materials presents a wide range of applicability in its use, especially in plastic deformation process, namely thermoforming. The material has a semi-crystalline molecular structure that enables it to take the shape of a load pressed against it when heated to a certain temperature. With a density of 910 kg/m^3, it is a generally low-cost polymer material. It is known for its high melting temperature, excellent chemical and moisture resistance, and good impact strength. It has a melting temperature in a range of 165^{o}C – 175^{o}C, in which means that the molecular structure of the polymer material will begin to vibrate and restructure in a specific period. This is termed as the thermoforming window (Throne, 2008).

The thermoforming window is the temperature range over which the polymer is adequately pliable for stretching and shaping into the desired form (Throne, 2008). The region is determined by the need for the polymer to have sufficient structural integrity to maintain the shape after forming. It assists in monitoring the accurate period to when the polymer sheet would be able to be deformed.

Polymer films when reached a certain temperature, will primarily reduce in strength and is unable to sustain any applied stresses without extensive plastic deformation thus will then abruptly fracture like fluid. The transitions in amorphous polymers are gradual and occur within a temperature range near to the softening point. Semi-crystalline polymer, however, does not undergo any transitions into the rubbery phase as it will remain deformed until it reaches the melting point of the crystal. Therefore the thermoforming window for semi-crystalline polymers is expected to be much narrower compared to amorphous polymer (Of et al., 2012).

2.8 Material Distribution of Thermoformed Part

The stretching of a heated plastic sheet onto positive moulds induces a variation of material distribution on the thermoformed part. This is due to several factors that have been previously studied by numerous authors namely (Klein & Ph, 2006; Kumar et al., 2013; Kommoji et al., 2014). Klein, (2006) conducted a study to compare the difference of wall thickness distribution between using a male mould and a female mould. He designed a method of constructing gridlines on the plastic material to measure the stretched areas after forming. In his encounter with the male mould, he demonstrated that the highest wall thickness of the thermoformed part was at the bottom area in which the thermoplastic initially contacts and decreases through the sides and that a deformation defect known as “webbing” in the form of wrinkles are formed on the sides of the thermoformed part whereas using a female mould, the highest thickness wall distribution was at the side area and the bottom part was the thinnest.

Similarly, a research study conducted by Kumar et al. (2013) on thick PP sheets also found that the highest wall thickness after the stretch in forming was found on the first contact area of the plastic sheet on the positive mould. Figure 2.12 shows a schematic diagram of a thermoforming process using positive and negative moulds. In the thermoforming process using a positive mould, the first section the plastic sheet is in contact becomes the thickest part and decreases as the thermoplastic sheet is drawn down the mould. While in the thermoforming process using a negative mould, the thickest wall is on the side of the mould and decreases as the thermoplastic is drawn down the mould. In these two distinct process, a non-uniform thickness is obtained. Kumar et al. (2013) designed an approach in which they constructed identical ring shapes on the plastic sheets to observe the stretched areas after forming. In both studies, they designed a method to observe the stretched areas on a thermoformed part. This idea is applied in this study to determine the material distribution of the thermoplastic material during forming.

Figure 2.11 A schematic diagram of male or positive and female or negative forming.

2.8.1 Stretching Behaviour of Thermoplastic Sheet on Positive Mould

When the heated thermoplastic sheet is drawn onto the male mould, stretching of the material occurs at the region of drastic height difference. Figure 2.13 shows a schematic diagram of sheet drawing onto the mould during positive forming. The first region the sheet contacts which is the OB region shows that the sheet freezes and is stretched the least. This is because the OB region is flat.

As the sheet draws onto the side regions of the mould, BP, it is stretched between the mould corner B and the clamping frame P. When vacuum is applied, and the air is removed, the sheet over BP gradually comes into contact with the mould surface, curving inwards and stretching further during the process. The slant length BA of the part is formed, along with the section PA, which is then trimmed off.

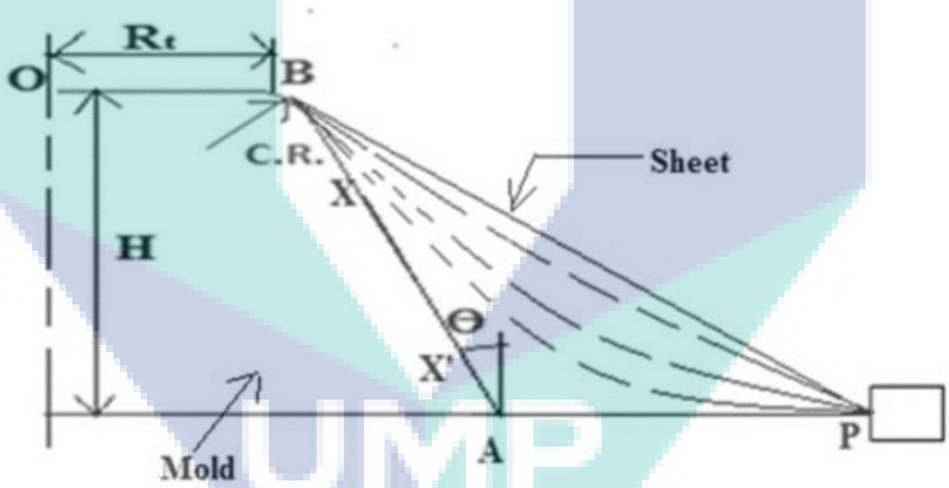


Figure 2.12 Schematic diagram showing one-half of the truncated positive mould during forming in vacuum forming process

Source: Kommoji et al. (2015)

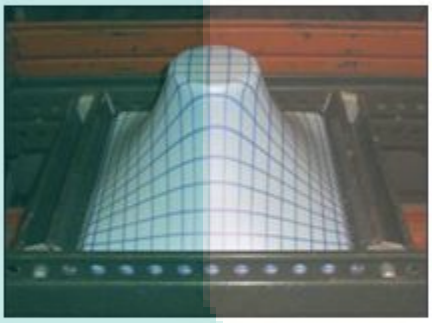
2.8.2 Parameters Affecting the Material Distribution of Thermoformed Part

Aroujalian et al. (1997) showed that material distribution of a thermoformed strawberry container using high-impact polystyrene is highly influenced by the processing parameters, explicitly plug velocity, plastic sheet temperature and plug temperature. Apart from processing parameters, Ayhan and Zhang, (2000) found that the material distributions in thermoformed parts are not only influenced by the processing parameters but also by the wall location, container side and their interactions during the thermoforming process. These findings suggest that the material distribution of a thermoformed part is not only affected by the processing parameters but also by the tooling design of the process.

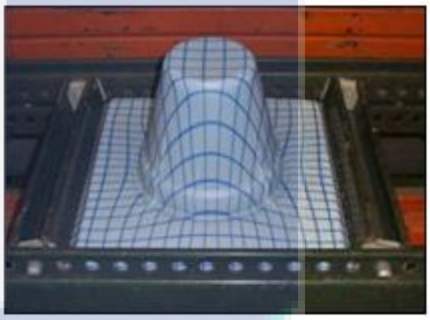
In a study by Azdast et al. (2012), an optimum combination of a two-step forming process consisting of plug-assisted and free forming was proposed to attain uniform material distribution of thermoformed part. Other factors such as the geometry of clamping frame, uniformity in plastic sheet temperature and mould geometrical shapes are also studied in previous research (Collins et al.,2000; Collins et al.,2001; Monteix et al., 2001; Martin et al., 2002; McCool et al., 2011). Basically, as observed from prior studies, material distribution during thermoforming is mainly influenced by processing parameters such as plug temperature, plastic sheet temperature, and the pressure applied. However, there are very few studies present regarding the venting system of thermoforming moulds that contributes material distribution during the process.

2.9 Grid Marking

The process of printing line patterns on the surface of the area of interest on a sheet metal blank is called grid marking (Hariharan et al., 2009). It is one of the commonly used strain measurement methods for strain analysis in sheet metal forming processes due to the relative simplicity (Kim et al., 1996). In thermoforming thermoplastic sheets, gridlines are commonly printed or constructed to observe and analyse the stretching and material distributions that occur during the forming phase. In metal forming, grid markings are utilised to effectively solve problems by analysing the strain produced. A practical method of strain analysis by grid marking has been utilised effectively to solve problems in metal forming in which wrinkling and fractures are normally formed on the metal part (Carasusan et al., 2003). Grid marking methods include silk-screen printing or serigraphy, electrochemical etching, photochemical etching, and laser etching (Ozturk et al., 2009) . Klein and Ph, (2006) used gridline sheets in their study of vacuum forming a thermoformed pot, while (Kommoji et al., 2014) constructed circular and gridlines onto their thermoplastic sheet prior to the forming process. Although these studies use different shapes to visually analyse the stretching behaviour of the thermoplastic sheet during forming, not much difference is observed in terms of which shapes are better to be used as both types of experiments show a high concentration of stretching in the same regions. As selecting the shape of the grid on the thermoplastic sheet has been categorised as least significant, gridlines are used as the simplest form of visual observations in this study.



(a)



(b)

Figure 2.13 Gridline plastic sheet stretched onto positive mould
Source: Klein & Ph, (2006)

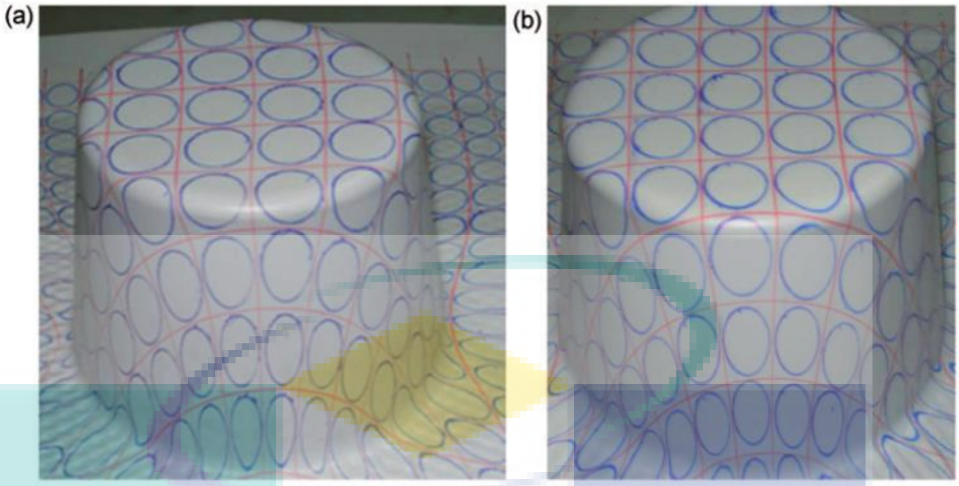


Figure 2.14 HIPS thermoformed parts with grid markings on positive mould at (a) 130ºC and (b) 140ºC. HIPS: High Impact Polystyrene

Source: Satish Kommoji et al.(2015)

2.10 Summary of Chapter 2

This chapter introduces the fundamental components there is to know about the thermoforming process. It relates to the earliest studies to the recent studies of this plastic manufacturing process. A general perspective of the thermoforming process of plastic products and its application is introduced. The categories of the process are also explained in which it is dependent on the functionality of the product itself. The designs of the earlier thermoforming equipment and the recent are shown to provide an explicit comparison in terms of mechanical structure, electrical components and size. A brief explanation of the basic components of a thermoforming equipment is described. The previous studies in the thermoforming process of plastic products and parts are reviewed and problems related to the study were diagnosed to determine the major problem faced in the thermoforming process of plastic parts and products and to determine the problem statement of this research.

CHAPTER 3

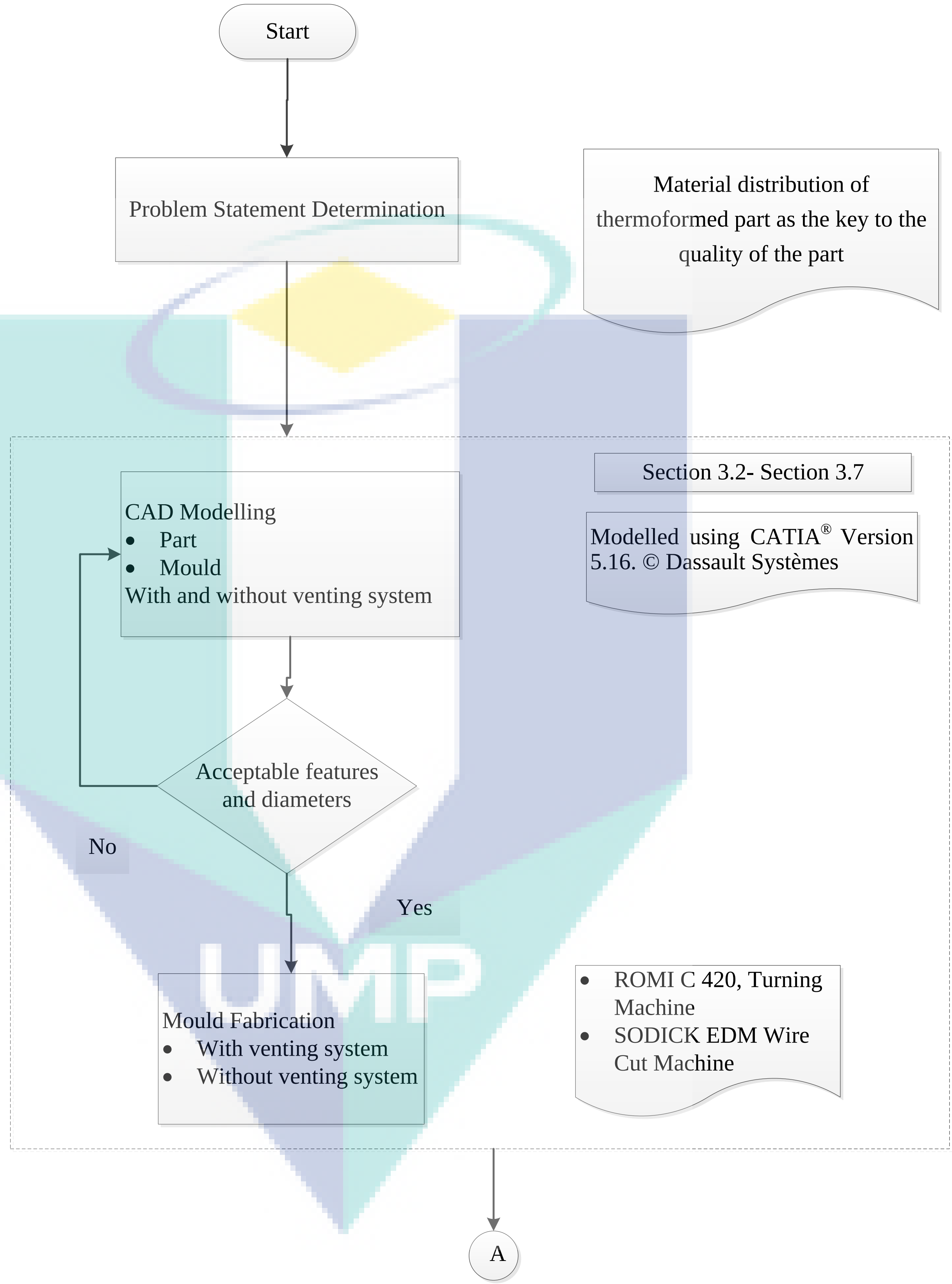
METHODOLOGY

3.1 Introduction

This chapter explicitly explains the activities and work done throughout the study. A process flow chart is presented to provide a brief view of the work flow, whereby it is divided into three segments; design and fabrication, material characterisation and computational simulation.

3.2 Process flow of activities in study

Initially, the problem statement of the study is determined to obtain objectives. The first stage of the study is the mould and part design and fabrication. The specifications of the mould design and fabrication are explained in the following sections. The thermoplastic material is then characterised to obtain polymer character and melting temperature that is relevant for the study. The thermoforming process is then conducted and a simple simulation study is conducted.


Start
Problem Statement Determination
Material distribution of thermoformed part as the key to the quality of the part
Section 3.2- Section 3.7
CAD Modelling
• Part
• Mould
With and without venting system
Modelled using CATIA® Version 5.16. © Dassault Systèmes
Acceptable features and diameters
No
Yes
Mould Fabrication
• With venting system
• Without venting system
• ROMI C 420, Turning Machine
• SODICK EDM Wire Cut Machine
A

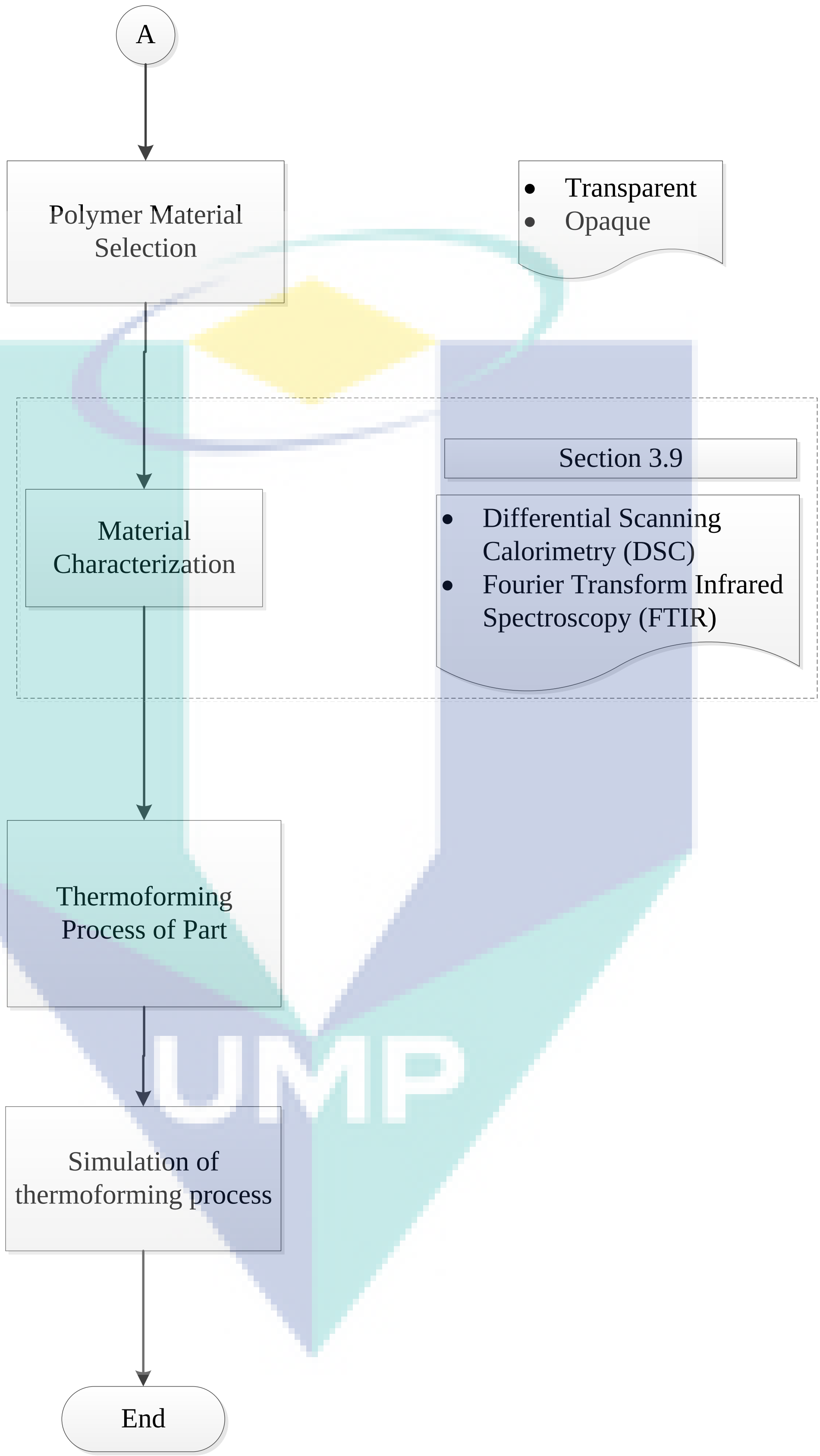


Figure 3.1 Process flow of main activities in the study

3.3 Mould Design

The part design is based on market requirements whereby the engineering specifications follow the guidelines in part designs for thermoforming process. The designing of the part and the mould was conducted initially by drafting the model of the part and the mould design via computer-aided design software, CATIA® Version 5.16. © Dassault Systèmes. The part and the mould without venting systems and with venting systems were modelled according to the mould-ability guidelines provided from industrial magazines and websites. The mould design selected was based on the commercial 7 -eleven plastic cup. However, the design does not approximately follow the geometrical dimensions as simplifications in the geometrical structure was made. The purpose was to apply the basic structure of the plastic cup into the mould design. The mould was fabricated in-house using a high-end turning machine facility provided in the Milling Laboratory of Faculty of Manufacturing Engineering in Universiti Malaysia Pahang. The details of the mould fabrication will be explained in the following subsections.

Figure 3.2 shows the geometrical structure of the part which is designed to comply with the mould-ability guidelines for a mould for thermoforming process. The features of the part and mould design consists of draft angle, radius, edge fillets and depth of draw. The CATIA Mechanical Design feature was employed in the preparation of the 3D model of the part and mould. The operation part design selected as the platform to design the models and drafting is used for the constructions of the 2D drawings. The mould with a height of 73.4mm and width of 75.7mm, giving rise to a draw ratio of 0.96. The draft angle is 15.23^{o} and the volume of the mould is $229879.4mm^{3}$. The label A and B in Figure 3.2(a) is the separation positioning where the venting system is located. Table 3.1 tabulates the geometrical details of the designed mould.

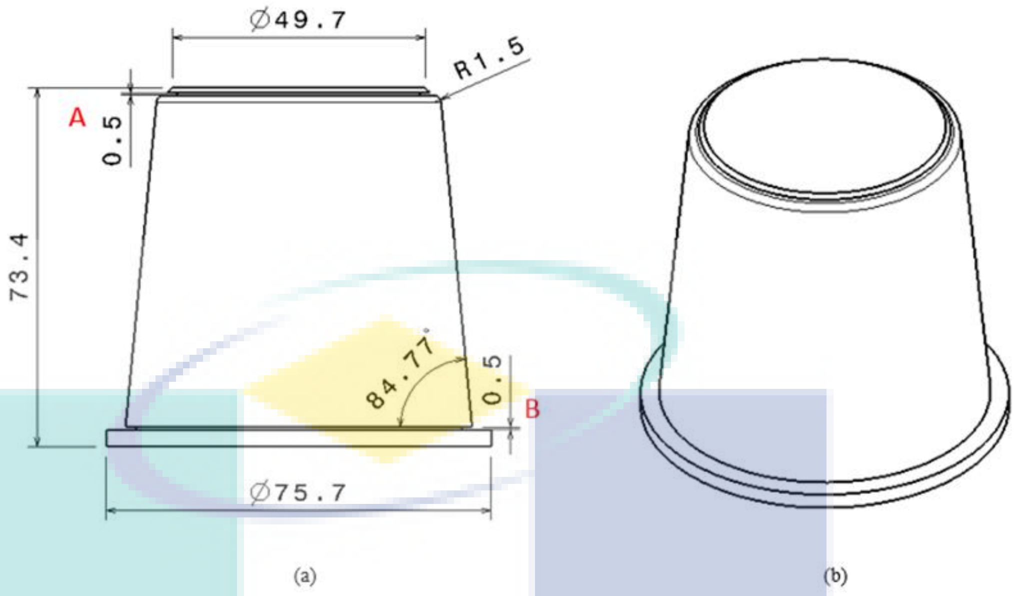


Figure 3.2 Schematics of positive mould with venting system

Table 3.1 Features of mould

Features of Mould	Measurements (SI units)
Volume (mm^3)	229879.4
Height (mm)	73.4
Draft angle (^{o})	15.23
Draw ratio	0.96 ~ 1.00
Corner Radius (mm)	1.5
Top Radius (mm)	24.85
Bottom Radius (mm)	37.85
Slant length (mm)	66.84
Dimension of gap for venting system (mm)	0.500

In which the volume is calculated using the formula;

$$V = \frac{1}{3}\pi[(r^1)^2 + (r^1 r^2) + (r^2)^2]h \qquad 3.1$$

V: Volume

r: Radius

h: Height

3.4 Mould Fabrication

Two axisymmetric positive moulds were developed. A simplified mould without venting system (Mould A) and a complex mould with a venting system (Mould B). A cylindrical aluminium billet was prepared by cutting it into size using a bend saw. In surfacing process, the ends of the billet were machined to obtain uniform flat surface using a ROMI C 420 Turning Machine. The design in Table 3.2 is computed and boundary conditions were set. Sodick VZ300L Electrical Discharge Machine Wire Cut was then used to trim the undesired part of the mould. Table 3.3 shows the boundary conditions applied in the turning process. Mould A is a truncated shaped positive mould. Mould B has a more complex geometrical structure and can be described as a dome shaped positive mould.

Table 3.2 Boundary condition of Turning Process for Truncated Shape Positive Mould

Parameters	**Numerical Value**
Spindle Speed (rpm)	1000
Feed Rate (mm/rev)	0.8

Figure 3.3 shows the turning process of mould A. The billet was held as shown to avoid damaging the mould during turning. Mould A was machined without a venting system. Similar to the machining the truncated shaped mould, an aluminium billet is first faced prior to machining. The sketch drawing is computed into the turning machine computer system along with the boundary conditions. The mould is manually fabricated. Table 3.3 shows the boundary conditions used during the machining of the mould in Figure 3.4.

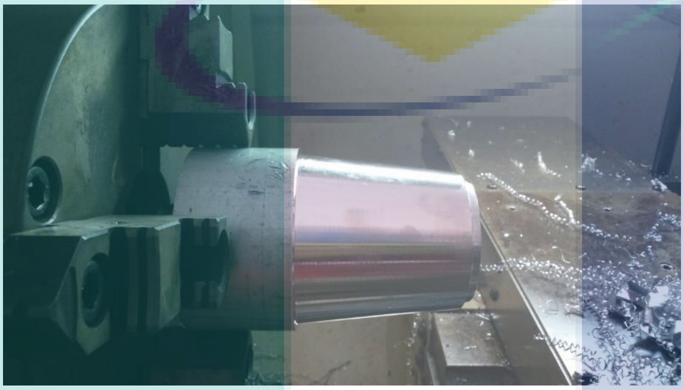


Figure 3.3 Mould A during turning process

Table 3.3 Boundary condition of Turning Process for Truncated Shape Positive Mould

Parameters	**Numerical Value**
Spindle Speed (rpm)	1000
Feed Rate (mm/rev)	0.200

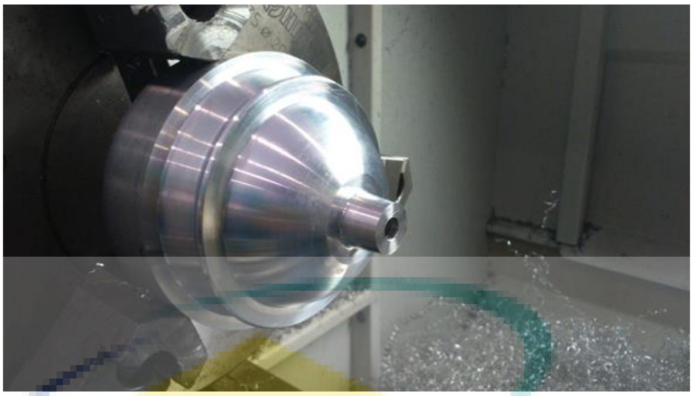


Figure 3.4 Turning process of mould B fabrication

3.4.1 Machining Process

The truncated positive mould without a venting system was fabricated using milling machine 3-axis Makino KE55 CNC Milling Machine and Sodick ROMI C420 Turning Machine. Figure 3.5 shows the fabricated mould without a venting system. The draw ratio for this mould is 0.96 ~ 1.00 whereby satisfies the guidelines for positive mould draw ratio explained in Chapter 2 section Draw Ratio.

Figure 3.5 Fabricated mould without venting system.

Figure 3.6 shows the fabricated mould with constructed venting systems allocated between two distinct draft angles. The venting systems are allocated in the relative positions to allow air trapped between the distinct to be evacuated. A custom designed aluminium mesh is fitted between the mould pieces to provide a gap that would allow air flow during forming stage with the assist of a vacuum system.

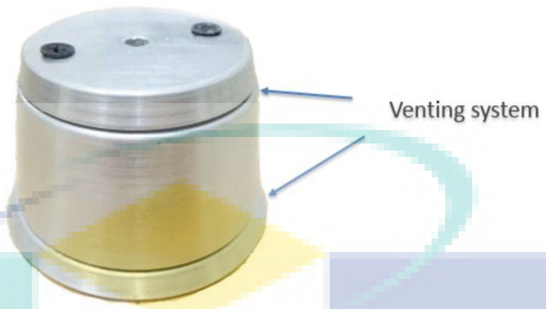


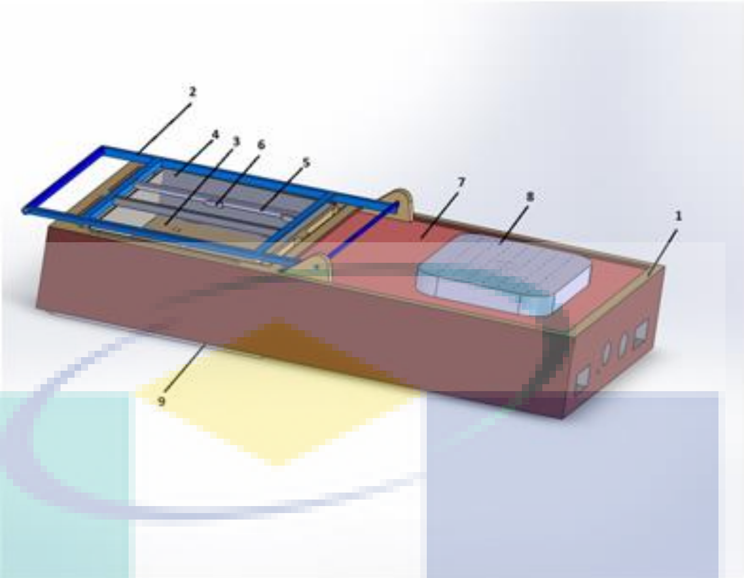
Figure 3.6 Fabricated mould with venting system

Table 3.4 Properties between a mould with a venting system and without a venting system

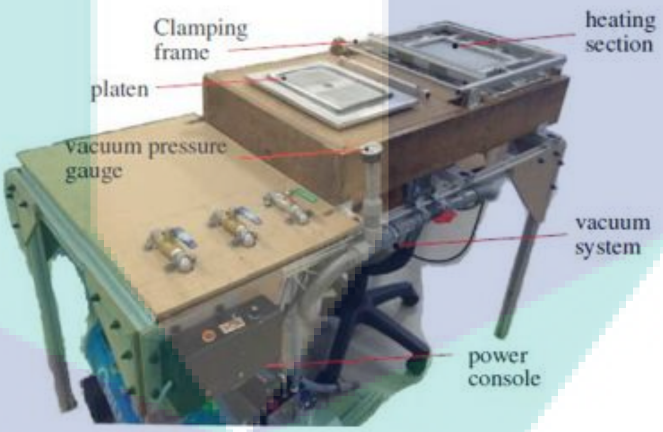
Properties	Advantages	Disadvantages
No fillets	Able to evacuate air properly	Venting size depends on local material distribution
Venting system with adjustable height	Convenient to manufacture and assemble	Venting size depends on the initial material thickness
Holding system	Convenient in maintenance	
Venting system in centre		

3.5 Thermoforming Equipment

The thermoforming equipment as shown in Figure 3.7(a) and (b) consists of several components and sections. This includes, the heating element, forming sections and vacuum system.



(a)



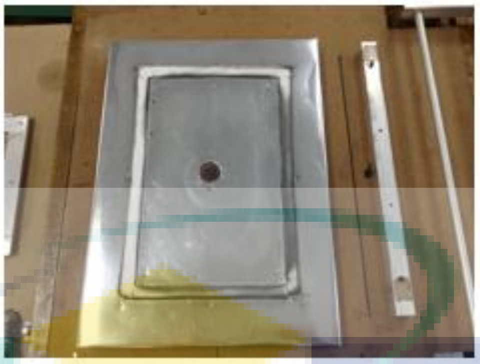
(b)

Figure 3.7 (a) Initial CAD design of thermoforming equipment (b) Pictorial image of thermoforming equipment

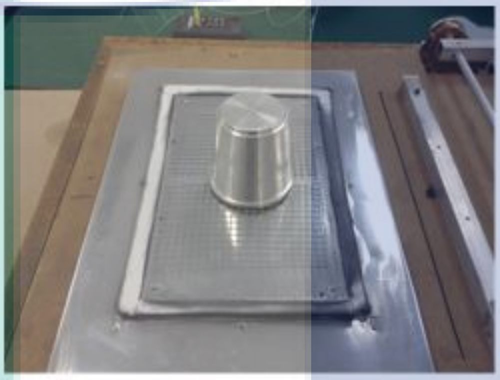
Table 3.5 Components of Thermoforming Equipment

	Component	Material
1	Wood part	Wood
2	Pivoting frame	Steel rod
3	Insulator board	Insulator board
4	Oven box	Galvanised steel sheet
5	Clamp frame adapter	Steel
6	Adapter bars	Aluminium
7	Top cover	Particle board / plywood
8	Platen	Particle board with Aluminium foil covering
9	Bottom cover	Aluminum sheet Pegboard

The platen, an aluminium material covered wood and an aluminium foil is placed on top of the thermoforming equipment in the forming section as shown in Figure 3.8. Through-holes are incorporated on the platen to assist in air evacuation during the process. Trapped air is transferred out through the through-holes and into the vacuum pipes with the assistance of pneumatic air pressure in which enables the softened plastic sheet to take hold firmly onto the mould and replicate its shape. Aluminium mesh is placed on top of the platen during forming process to allow air flow between the mould and the platen. The mesh is required during forming because without the mesh the thermoplastic sheet does not conform the shape of the mould as it provides air flow between the mould and platen. However, when the shape of the mesh is reproduced, it can affect the forming area.



(a) Venting system setups for platen



(b) Placing the mould

Figure 3.8 Design of thermoforming process – step 1 and step 2 in thermoforming process.

The heating element system as shown in Figure 3.10 is one of the crucial components of a thermoforming equipment. The heating element which consists of a coil positioned in a contour rectangular spiral shape uses an amount of current and voltage of 8 amps and 240 volts respectively. During the experiment, the experimental current and voltage were taken, which are 7.4 amps with the amount of 200 volts. The experiment was set in an air-conditioned room whereby the amount of time taken to heat the plastic sheet exceeded 120 seconds depending on the thickness and type of plastic material. This explicitly depends on the type and thickness of the thermoplastic.

The power of heating element was dissipated by convection, radiation and conductions. Placing aluminium foils around the plastic sheet while heating would allow a higher rate in increase of temperature of the plastic sheet, thus, shortening the cycle time.

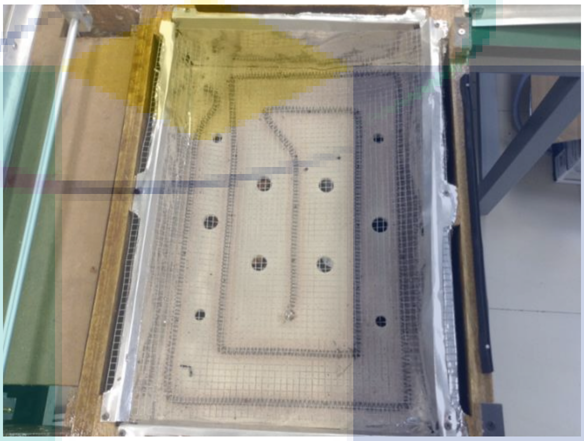
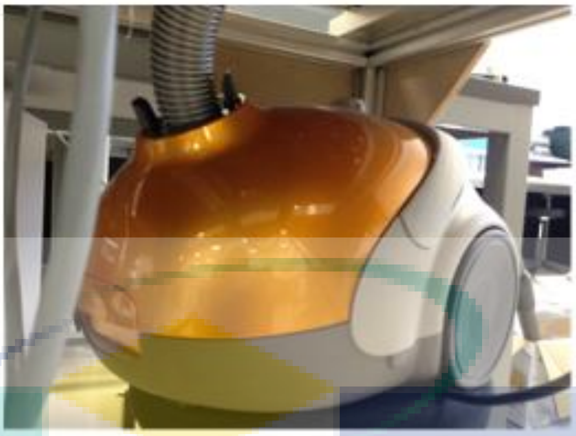
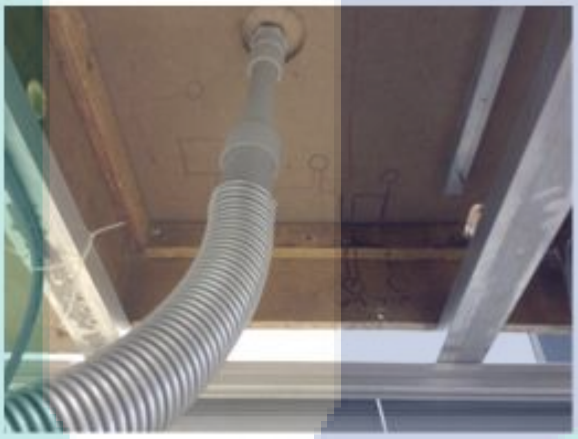


Figure 3.9 Oven section of thermoforming equipment

The vacuum system is installed in the thermoforming equipment to remove air from between the mould and the thermoplastic sheet during the forming phase. A high power domestic vacuum cleaner with a maximum pressure of 20 kPa is used for this purpose. A PVC pipe is used to connect the vacuum hose with the platen hole. An analogue vacuum pressure gauge is used to measure the maximum pressure used when the vacuum is switched on to remove the air. Figures 3.10 and 3.11 shows the image of the vacuum system and pressure gauge. The vacuum cleaner was placed onto a chair for as the platform for the component.



(a)



(b)

Figure 3.10 Pictorial of (a) Vacuum section of the specific built thermoforming equipment and (b) Installation of flexible hose and piping fixture to the platen

Figure 3.11 Analogue vacuum pressure gauge from RS Component Sdn Bhd (product model type : SMC GZ46-K-01)

The clamping frame installed, as shown in Figure 3.12 (a) and (b) is a hollow aluminium based material with a rectangular shape. It is hinged on the cylindrical aluminium to function in a rotation motion when transferred from the oven (heating section) to the platen (during forming phase) and vice versa. The thermoplastic sheet is secured onto the clamping frame using aluminium stationary clips.

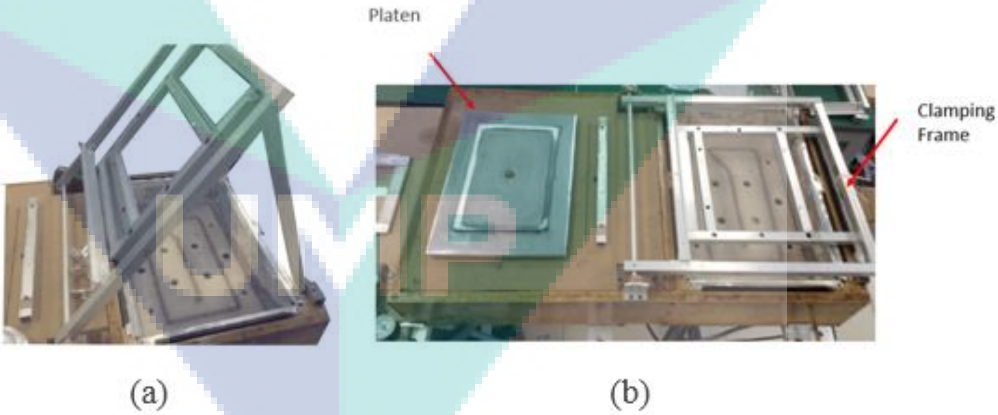


Figure 3.12 Pictorial of (a) Clamping frame of thermoforming equipment and (b) Positioning the clamping frame during the heating stage

3.6 Polypropylene Polymer Material

Polypropylene thermoplastic material in the form of a sheet was obtained from Scienfield Expertise PLT in Selangor. Polypropylene is characterised as a viscoelastic material whereby its mechanical properties are significantly dependent on time, temperature and stress. Consisting of both amorphous and crystalline molecular structures, the semi-crystalline characteristics of polypropylene allow the material to exhibit both viscous and elastic behaviour when undergoing deformation. The following are the properties of Polypropylene whereby are sufficient for the thermoforming process with the designed mould.

a) High stiffness
b) Low-density material
c) Heat resistance
d) Chemical inertness
e) Steam barrier properties (for food protection)
f) Good transparency
g) Able to stretch (for film applications)
h) Good impact and rigidity balance
i) High gloss (for appearance)
j) Good hinge property (for one-piece lid and box design)
k) Recyclable

Source: The Essential Chemical Industry. (n.d).

3.7 Material Characterisation

For documenting purposes, the thermoplastic material was subjected to two material characterisation tests. The tests were Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR). Both the test exhibit different characteristics of the material in terms of thermal and molecular components.

3.7.1 Differential Scanning Calorimetry (DSC) of Polymer Sample

The DSC experiments presented in this study is performed using a modulated DSC Q1000 (TA Instruments, New Castle, DE, USA) with an accuracy of ±0.1^{O}C and a temperature range from -180 to 725^{o} C. Figure 3.13 shows a schematic diagram in which the samples were encapsulated in standard aluminium sample pans and referenced with an empty pan with a 50ml/min nitrogen stream. The samples were cut into small pieces to form a uniform shape and spread as thinly as possible across the bottom of the sample pan to minimise the temperature gradients. The weight of the sample was kept very low (2–3 mg). A DSC measurement of 35 to 350 ^{o}C is carried out with a heating rate of 10 ^{o}C/min. The sample characterisation was conducted at the Analytical laboratory in the Faculty of Chemical & Natural Resources Engineering, Universiti Malaysia Pahang.

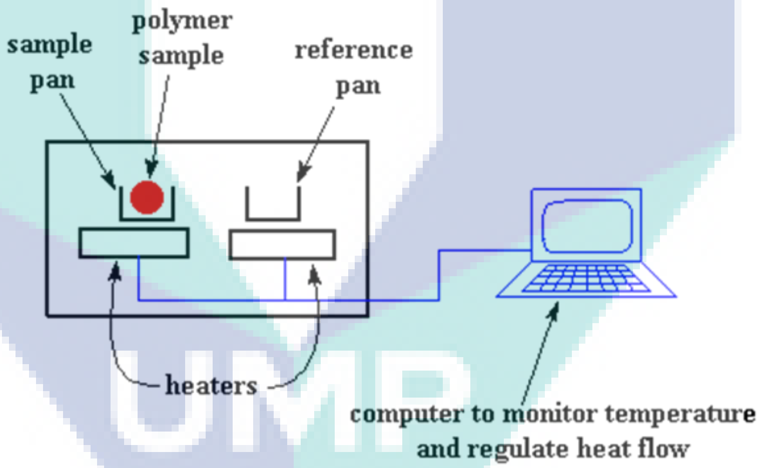
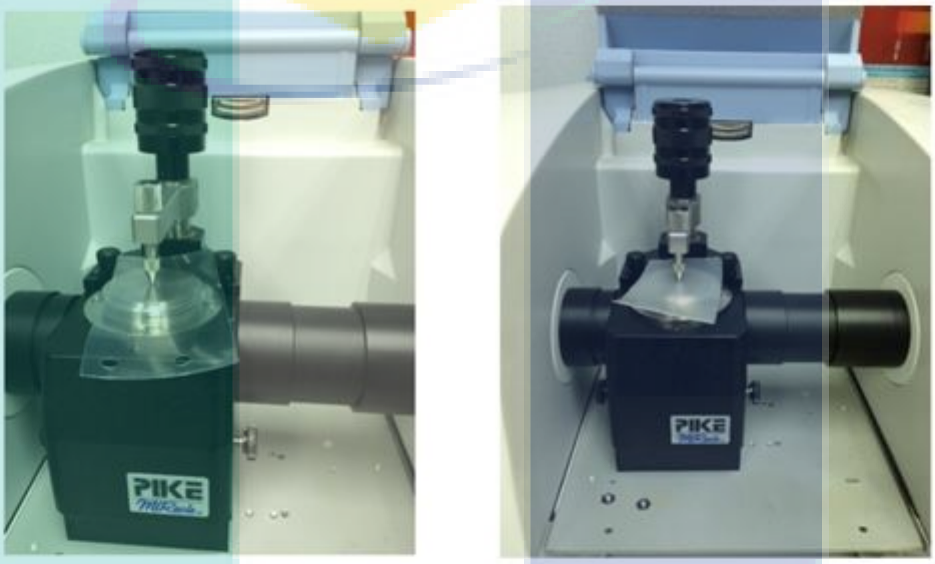


Figure 3.13 Schematic of Different Scanning Calorimetry Process Flow

3.7.2 Fourier Transform Infrared Spectroscopy of Polymer Sample

Figure 3.14 shows the electromagnetic-waved absorption based device used in the characterisation of the thermoplastic sheet. The facility used was carried out in the laboratory of the Faculty of Industrial Sciences and Technology (FIST), Universiti

Malaysia Pahang, Gambang Campus. Attenuated Total Reflectance (ATR) technique was employed which requires the sample to be placed in a close contact with an internal reflection element (IRE) in which the IR beam from the spectrometer is directed onto the sample and produces reflection and evanescent wave. Figures 3.14 shows the polymer material during FTIR test.



(a) (b)

Figure 3.14 Testing the polymer (a) sample A and (b) sample B by means of FTIR method

3.8 Pre-Thermoforming Process of Polypropylene Polymer Sheet

Prior to thermoforming process, several procedures are conducted before the process is able to begin. Temperature assessment of the heating element in the oven is run to determine the uniformity of heating. This is to allow even heating of the thermoplastic sheet and avoid over-heating at certain regions of the heating element. Another procedure is stamping the thermoplastic sheet with gridlines. This is to observes changes of the material distribution on the mould during forming.

3.8.1 Temperature Assessment

The experimental facility previously shown in section 3.5, Figure 3.5 (b) shows a Hobby-Vac 12X18 vacuum forming equipment with low vacuum pressure system, both alternately powered by a 240V 13A 50 Hz single phase AC power supply. During the use of the facility, an analogue vacuum pressure gage with a computer controlled and data acquisition system is incorporated with the equipment.

Three distinct experimental configurations were designed to analyse the temperature response during the heating stage in the thermoforming process. The first setup referred to as the full-configuration is constructed by using four different type-T fast response thermocouples from Omega Engineering Inc. Each thermocouple was projected to a height from the open coil heating element through an orifice fitted to a ceramic bed. The arrangement of the thermocouples is symmetric from the centre plane of the heating section to accommodate the working area of the plastic heating. Figure 3.15 (a) shows a schematic representation of natural convection of air through the orifices during the heating stage. The plan view and pictorial image of the full-configuration are shown in Figure 3.15 (b). The figure also shows the coil layout over the ceramic bed. For convenience, the numbering of the thermocouple is given to identify the number of the sensor being used and its quadrant. For example, T1-1 corresponds to the first sensor in quadrant 1. Temperature values were acquired during heating and cooling for a prescribed amount of time, of t 2000 s.

The second setup referred to as the quadrant-configuration was constructed by using nine different thermocouples. Each thermocouple was attached to a stainless-steel mesh in the 3rd quadrant at a typical heating plane. The thermocouples were fitted to the mesh in an arrangement of 3 by 3 to accommodate better spatial resolution of measurement than the full-configuration setup. Figure 3.15 (b) shows the plan view and pictorial image of the quadrant- configuration setup for thermocouple arrangements. For convenience, the numbering of each thermocouple was given to identify its row and column position relative to the centre of the heating plane. The T11 located at the centre and correspond to the first sensor in the 3rd quadrant. Three different types of commercial grade thermocouples from RS components were used; type T, K and N. Temperature values were acquired during heating for a prescribed amount of time t 2000 s.

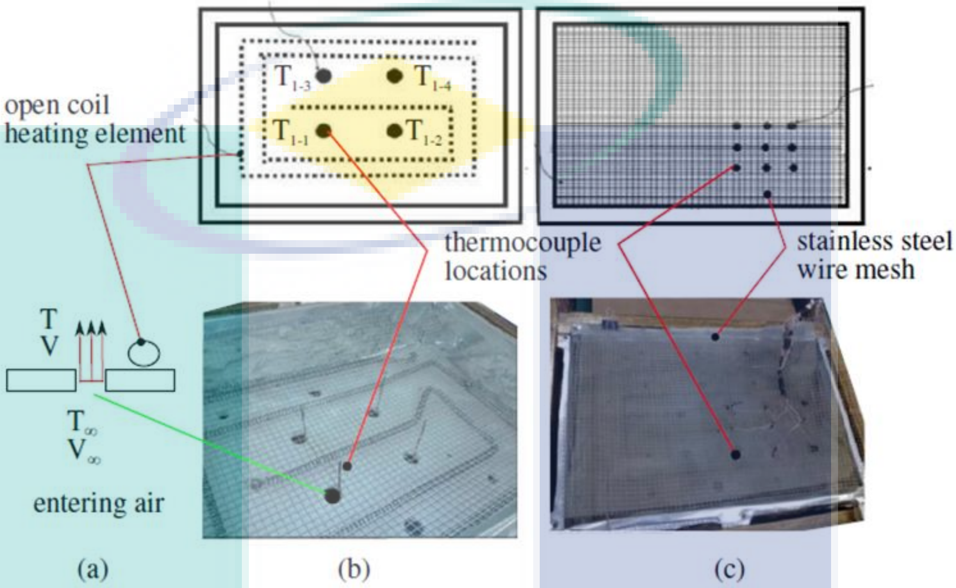


Figure 3.15 Schematics and physical arrangement of thermocouples for full- and quarter-configurations experimental setup. (a) Natural convection of air through the orifices during the heating stage (b) plan view and a pictorial image of the quadrant-configuration setup for thermocouple arrangements and (c) thermocouples allocated on one quadrant of the mesh.

The third setup referred to as the full-plate-configuration was constructed by using nine different thermocouples fitted to a model of blank material. The instrumented aluminium plate was clamped and positioned to cover the working area at a typical heating plane. Nine holes were drilled and the thermocouple junction was bolted temporarily to the plate. The thermocouples were placed in an arrangement of 3 by 3 to accommodate better spatial resolution of measurement than the full-configuration setup. Figure 3.16 (a) shows a schematic representation of natural convection of air through the orifices during the heating stage. The plan and bottom views of thermocouple locations are shown in the pictorial image of Figure 3.16 (b). For convenience, the numbering of each thermocouple was given to identify its row and column position relative to the centre of the heating plane. The T22 located at the centre of working area and was used as the reference temperature. Only type-K thermocouple was used in the experiment. The daily room temperature T1 varies between 10 to 15°C and was measured using a type-K thermocouple. However, the temperature was virtually constant throughout the experiments.

A specific purposed built graphical user interface is shown in Figure 3.16 (c) was also designed using LabVIEW for heating performance calibration of quadrant- and full-plate configurations. All thermocouples during the experimental setup were connected to a signal conditioning block of a Data Acquisition device (DAQ) for monitoring purposes.

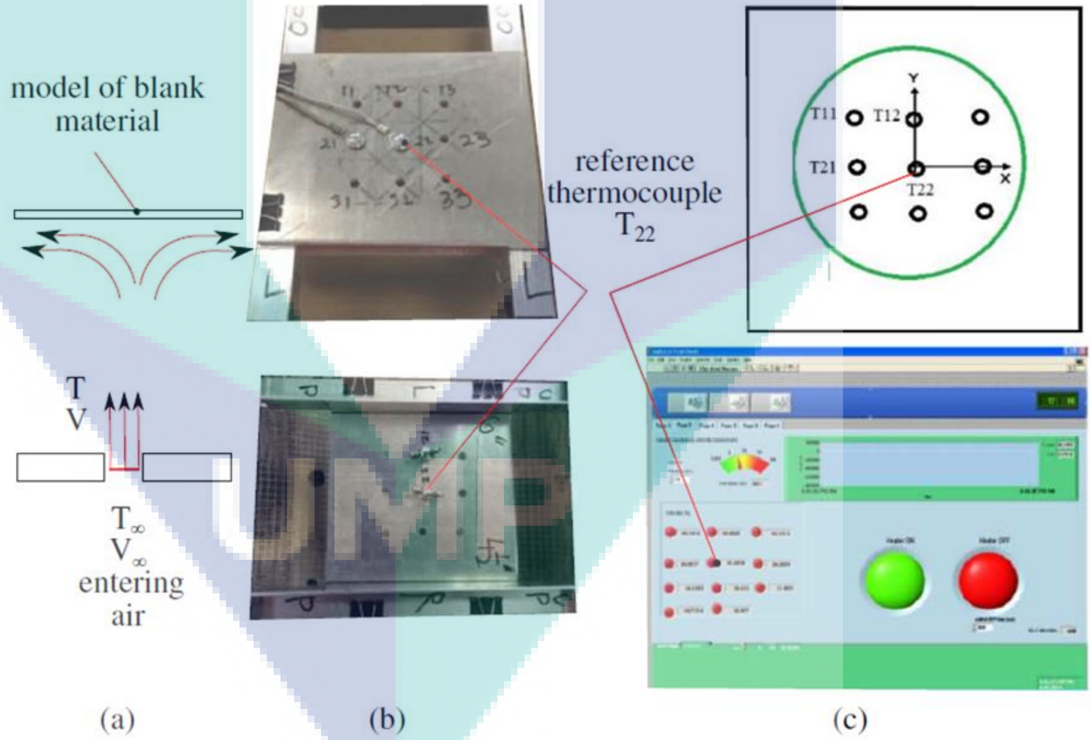
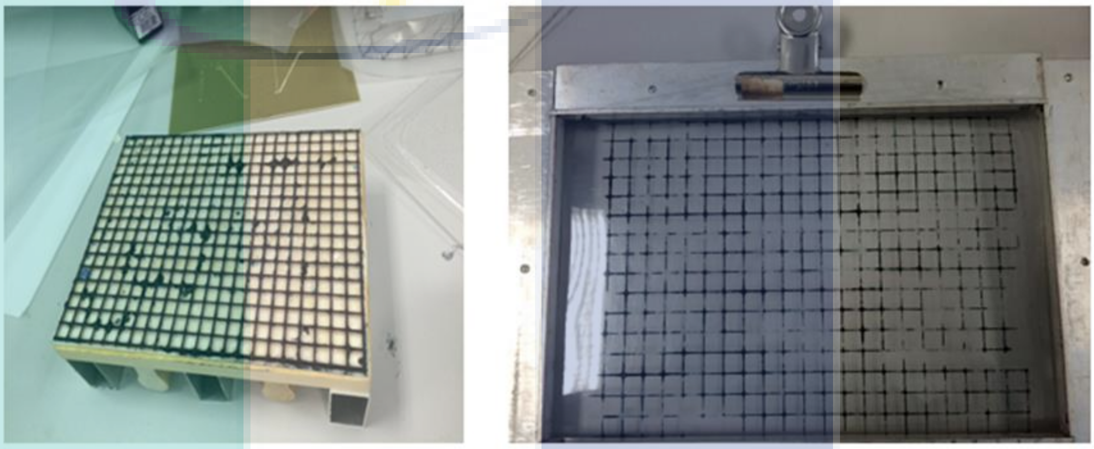


Figure 3.16 Physical and monitoring arrangement for full plate-configuration experimental setup

3.8.2 Preparations Prior to Thermoforming Process

The Polypropylene sheet is stamped with a grid stamp as shown in Figure 3.17(a) which is fabricated from an elastomer material. The stamped sheet is then left to dry for 20 ~ 30 minutes before it can be used for thermoforming to allow the ink from melting when heated. The polypropylene sheet is then clamped on the clamping frame and is ready to be heated as shown in Figure 3.17(b). Table 3.6 shows the properties of the grid stamp used.



(a) (b)

Figure 3.17 (a) Rubber grid stamp (b) Clamped thermoplastic sheet

Table 3.6 Properties of grid stamp

Properties	Description
Material	Elastomer
Size	1 inch x 1 inch
Ink	Indelible Ink

3.9 Thermoforming Process of Polypropylene Part

Figure 3.18 shows the flow chart of thermoforming process conducted in this study. The process starts with heating the thermoplastic sheet until the thermoforming window is reached. When the thermoforming window is reached, it is then formed onto the mould and let to cool. The thermoformed part is then trimmed to obtain the desired thermoformed part.

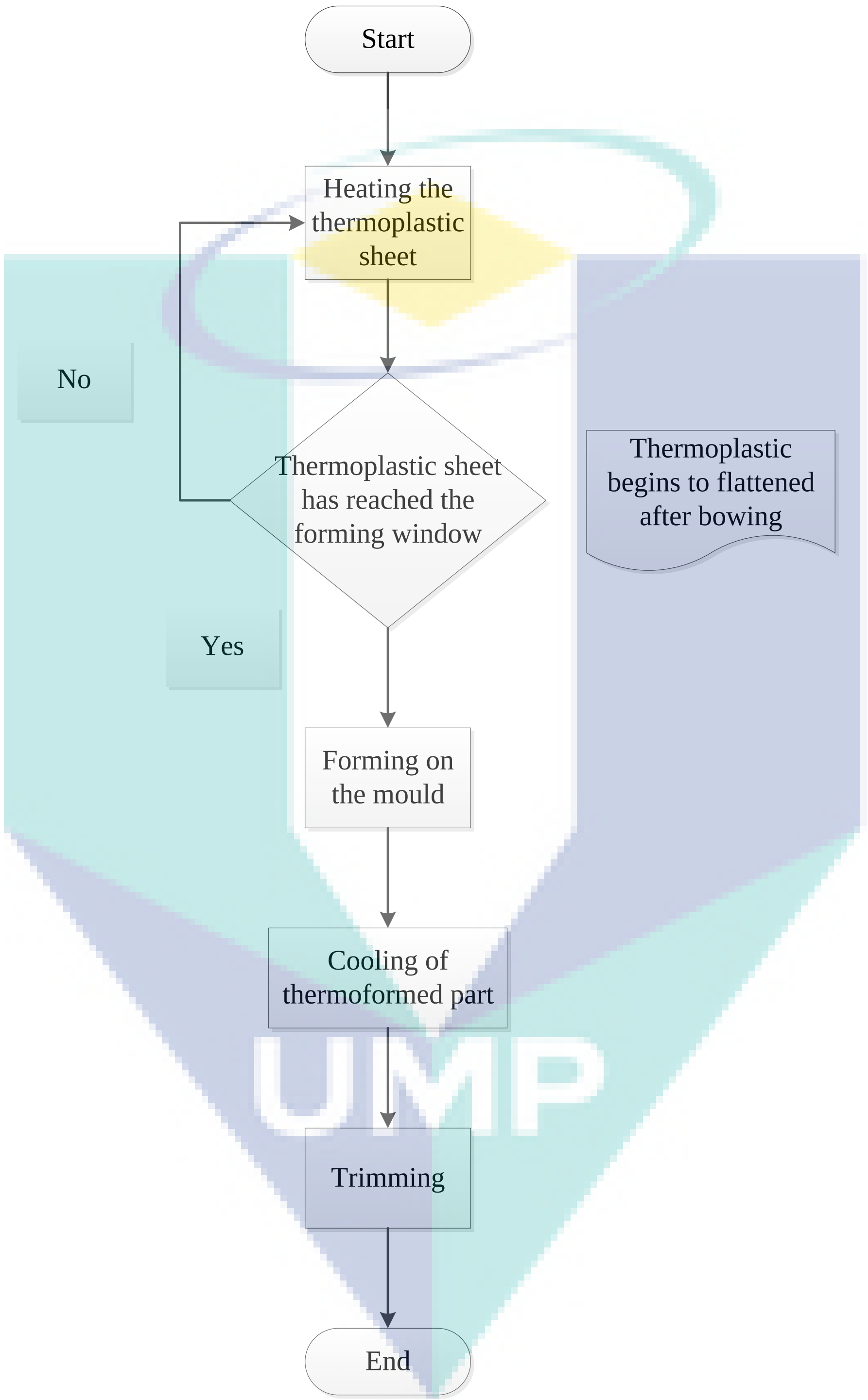


Figure 3.18 Process flow of thermoforming process of Polypropylene sheet using drape forming technique

Referring to the process flow in Figure 3.19, the thermoplastic sheet is initially prepared by cutting into A4 size and stamping grid lines on the surface. The sheet is then secured to the clamping frame while the mould is placed on the platen. The oven is switched on and the thermoplastic sheet begins to be heated with a constant temperature of 180^{o}C with a pressure of 20kPa. The temperature of the thermoplastic surface is measured by using the pyrometer as well as the characteristic of the thermoplastic sheet. Once the temperature of the thermoplastic sheet has reached within 160^{o}C ~ 170^{o}C, the clamping frame holding the thermoplastic sheet is transferred onto the forming section in which the heated thermoplastic sheet is drawn onto the positive mould. The vacuum is switched on to allow air evacuation between the thermoplastic sheet and the mould. The thermoformed part is left to cool for 5 ~ 15 minutes before it is then removed from the mould and trimmed. Figure 3.19 shows the flow of the thermoforming process in the heating phase and forming phase.

The thermoforming mould used in the process has a constant temperature which is room temperature. Therefore, the mould does not need to be heated prior to the thermoforming process. Table 3.7 shows test rig properties that are used in the thermoforming process.

Table 3.7 Test Rig Properties in Thermoforming Process of Polypropylene

Properties	**Value**
Initial Thickness (mm)	1.5
Vacuum pressure (kPa)	20
Thermoforming window of Polypropylene(^{o})	160-170
Mould temperature	Room temperature (Constant)
Temperature of laboratory	Room temperature (Constant)

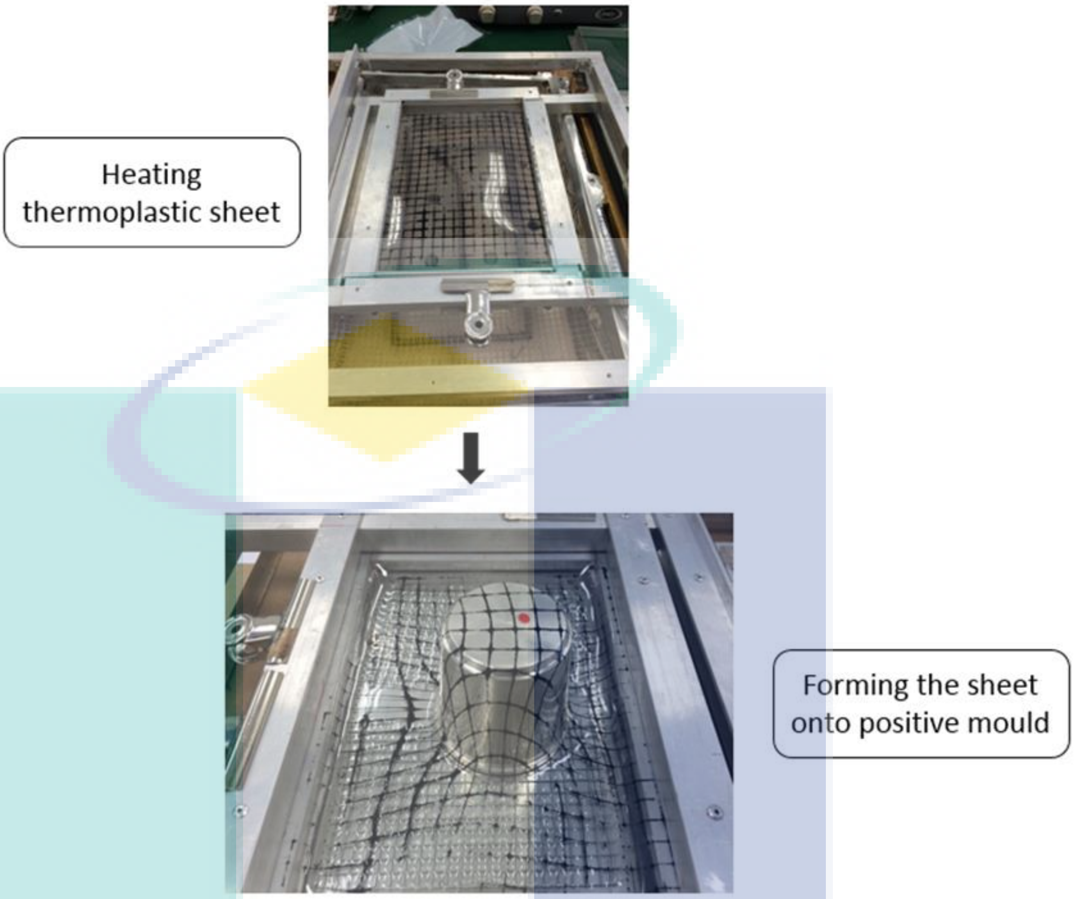


Figure 3.19 Process flow during heating and forming phase in thermoforming process

3.9.1 Behaviour of Thermoplastic Sheet during Heating

During heating, the polypropylene sheet begins to bow. Bowing of thermoplastic sheets during heating are sheet curvatures which appear from the results of thermal expansion of the solid sheet before softening (Baek, 2014). In Figure 3.20 sheet curvatures appear during heating of the thermoplastic sheet which determines that it is bowing. This thermoplastic behaviour during heating is significant as it allows predictions of uniform temperature of the thermoplastic sheet (Michaud & Giacomin, 2011). After the sheet bows, it then returns to a slightly flat state and begins to soften and sag as shown in Figure 3.21. However, the thermoplastic sheet is drawn onto the positive mould just before it begins to sag to avoid webbing of the thermoplastic sheet during the forming phase.

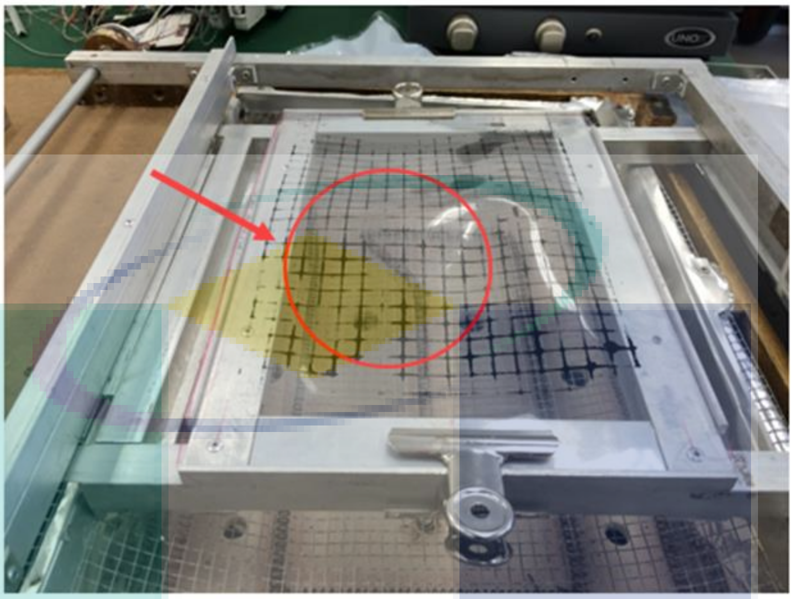


Figure 3.20 Sheet bowing during heating phase in thermoforming process

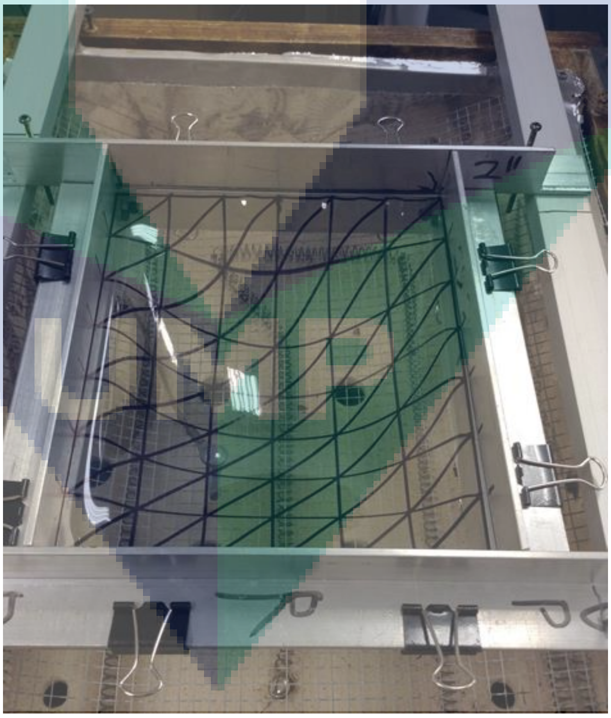


Figure 3.21 Sagging of thermoplastic sheet during heating phase

3.10 Computing Thermoforming Using ANSYS® Polyflow

A flowchart presenting the stages in computer simulation of the thermoforming process is shown below. The mould is initially sketched using Design Modular, then mesh is applied. Polydata is used to compute the boundary conditions whereby the solutions are generated and is analysed.

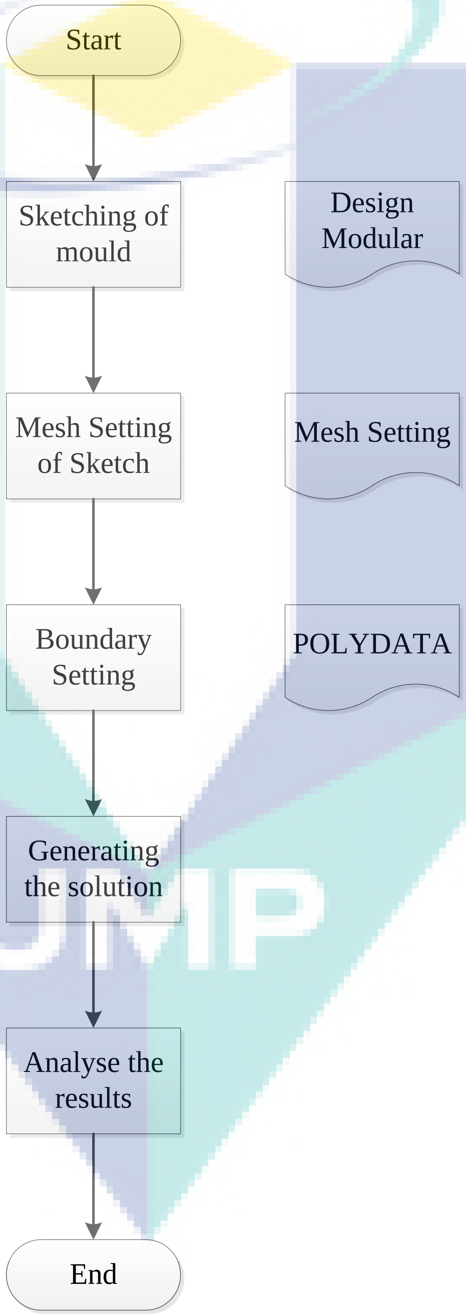


Figure 3.22 Flow diagram of Computing Thermoforming Process

Referring to the process flow in Figure 3.22, the mould model is initially designed in the Design Moduler in which the drawing and geometries of the mould design are constructed. During sketching of the mould, the mould features such as draft angles and radius are applied. The mesh is then developed from the drawing to the mould design. In the POLYDATA window, numerical parameters and boundaries are set to provide a suitable domain to the simulation. Results are then displayed subsequently with the solution appointed.

A typically truncated shape disposal product was chosen as the principal part design for constructing the process simulation. This is illustrated in the dimensioned drawing of the mould shown in Figure 3.23. The part design was selected from a range of disposal products currently being manufactured by industrial firms. The part consists of a volume of 229879.4 mm^3 which is used for liquid containers and is very similar in design to the deep-draw food packaging that is produced by thermoforming. It may be manufactured from various grades of either Polystyrene (PS) or Polypropylene (PP), but in this case, the sheet material chosen for the study was a PP, which has an initial sheet thickness of 1.5 mm. The normal processing conditions for the part were obtained from the ANSYS® Polyflow user guide. The mould tool was manufactured from an aluminium alloy, which is the mould material of the choice in the industry due to its excellent combination of mechanical and thermal properties. It was maintained at 20^{o}C in all tests.

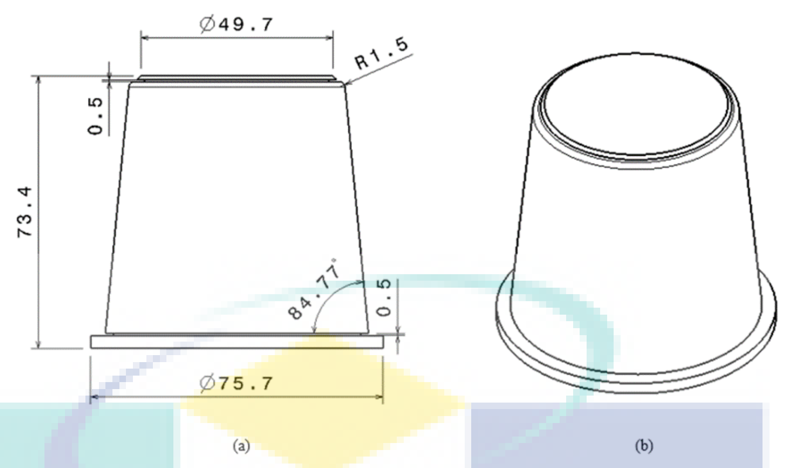


Figure 3.23 Schematic diagram of positive mould (a) with major dimensions (mm) and (b) perspective view of mould design.

As a basis for part quality evaluation, the engineering assumptions for the blank material and mould are briefly given as follows:

- The thermos-mechanical properties of a generic thermoformable material are evaluated at near-melt states and are assumed constant and isotropic.
- Rigid, adiabatic and smooth contact surfaces.
- Isothermal and rapid forming process.
- Aspect of mould design such as draft, vent and surface textures are implemented.

3.10.1 Preparations and Blank Material Behaviour

The mould is positioned at the centre of a platen and such arrangement introduced 2- and 3- plane point transition corners and forming surfaces. The area of both the platen and the pre-cut blank material are (A_i =) 140 x 160 mm^2 and the flat free surface (A_0) of 100 x 120mm^2. Due to symmetrical properties, the computational model is $\frac{A_i}{4}$ (= 70 x 80mm^2). The initial thickness of the blank material (h_i =) is 1.5mm. The origin of the solution domain (x = 0, y = 0, z = 0) is located at a point where symmetry planes in x and y- directions intersect with z = 0 planes. The behaviour of the blank material is represented by the Generalized Newtonian fluid material model such that **T** is defined as:

$$\mathbf{T} = 2\eta\mathbf{D} \tag{3.2}$$

Where η is the zero shear rate viscosity and take the value of 10^5 Pa.s. In the absence of contact, the kinematic conditions is given by

$$v_i = \frac{\delta x_i}{\delta t} \tag{3.3}$$

when the contact is established between two different surfaces, deformable-to-rigid contact is assumed whereby the local reaction force is modelled by a penalty method algorithm. The parallel and normal components of the local surface force are respectively given by;

$$f_s = C_s\,[v(s,t) - w(s,t)] \tag{3.4}$$

$$f_n = C_n\,[v(n,t) - w(n,t)] \tag{3.5}$$

where C_t and C_n are known as slipping and penalty coefficients respectively and took the value of 10^{10} Ns/m. Details of the numerical implementation for solving the algebraic governing equations is given in ANSYS® Polyflow user guide. The numerical boundaries of blow moulding simulation was implemented for the thermoforming process simulation of this part as it was assumed that the material behaviour of both the blank materials were similar during inflation process.

3.10.2 POLYDATA

ANSYS® Polyflow is used to compute the permeability of the blown part in which shell elements are used to solve 3D blow moulding models. The permeability is known to be inversely proportional to the local thickness, h. Given the permeability coefficient π , the permeability per unit area can be evaluated as

$$p = \frac{\pi}{h} \quad 3.6$$

Source: Calculation of the Permeability of the Blown Product. (n.d).

If the material involves several overlapping layers, the permeability per unit area is computed from

$$\frac{1}{p} = \sum_i \frac{1}{p_i} = \sum_i \frac{h_i}{\pi_i} \quad 3.7$$

Source: Calculation of the Permeability of the Blown Product. (n.d).

Where h_i is the thickness of the i^{th} layer, and π_i is the corresponding permeability coefficient. The total permeability of the blown product is computed from:

$$P = \int_A p \, dA \quad 3.8$$

Source: Calculation of the Permeability of the Blown Product. (n.d).

The permeability coefficient denotes a given amount of water passing through a sheet of material with a given thickness and area, during a given time. Typical values for are on the order of 10^{-11} to 10^{-12} g-mm/s/mm^2. The finite element model used to solve the forming simulation is membrane element. This type of solver was used as it was similar to 3D blow moulding and was suggested by ANSYS® Polyflow. The blank material is assumed to behave as generalised Newtonian fluid in which is similar to blow moulding. Other properties such as density and viscosity are the general properties of the polymer. The slipping coefficient and penalty coefficient took the value of 10^{10} Ns/m in which the equations are adapted from ANSYS® Polyflow user guide. Two relative speed of the blank material drawn onto the mould was simulated which are 50 mm/s and 100 mm/s. Table 3.8 and 3.9 both consists of the numerical and boundary conditions in POLYDATA, while Table 3.10 and 3.11 shows the transition velocity of the mould for both simulations in which distinct only in the Z-direction.

Table 3.8 Condition and properties of Domain

Properties	**Description**
Finite element model	Membrane element
Assumption	Generalized Newtonian fluid
Topology	Quadrilateral
Density	900 kg/mm^3
Viscosity	100 000 x E^5 Pas
Boundary Contact	
• Slipping Coefficient	1.0 x E^10
• Penalty Coefficient	1.0 x E^10
• Penetration accuracy	0.05
Pressure applied	100 000 Pa
Relative speed between mould and sheet	50 mm/s , 100 mm/s

Table 3.9 Numerical Parameters and Boundary Conditions for Polydata for Velocity of 100 mm/s

Properties	Value
Initial time value	0
Upper time limit	1
Initial value of the time-step	0.001
Min value of the time-step	1 $e^{-}006$
Max value of the time-step	0.001
Tolerance	0.01
Max number of successful steps	1000

Table 3.10 Translation velocity of mould

Translation velocity of mould	Velocity (mm/s)
Velocity in x-direction	0
Velocity in y-direction	0
Velocity in z-direction	100

Table 3.11 Translation velocity of mould with Z-direction 1000mm/s

Properties	Value
Initial time value	0
Upper time limit	0.28
Initial value of the time-step	0.001
Min value of the time-step	1 $e^{-}006$
Max value of the time-step	0.001
Tolerance	0.01
Max number of successful steps	400

The assumptions made for the simulation are that the blank material does not sag, the mould does not conduct heat or increase in heat, the blank material moves according to the design of kinematic function. Besides that, the thickness of the blank material does not change when contacting the flat surface of the mould. The external air pressure and air pressure between the blank material and mould is about 100kPa (atmospheric pressure).

3.11 Simulation of Thermoforming Process of 1.5mm Polymer Sheet

The simulation starts with a thin, uniform 1.5mm thick flat polymer sheet resting above a positive mould surface as shown in Figure 3.24. A fine mesh as shown in Figure

3.25 is used to provide sufficient details of the truncated mould as it draws into the corner of the mould. The polymer sheet which initially contacts the top region of the mould which is flat, remains the same thickness but as the sheet draws to the sides of the mould, the thickness decreases. After pre-stretching, vacuum pressures are applied to inflate the sheet onto the adiabatic mould. As the sheet touches the mould's side in which referring to the ramp function, the shape immediately freezes. The total forming time is about t=2.61s. The thermoformed truncated part is left for 5, 10, 15 minutes to cool.

Table 3.12 Conditions and properties during simulation of 1.5mm Polymer Sheet

Conditions	**Value**
Mould Velocity (mm/s)	50
Initial Thickness (mm)	1.5
Total period of time (s)	2.61

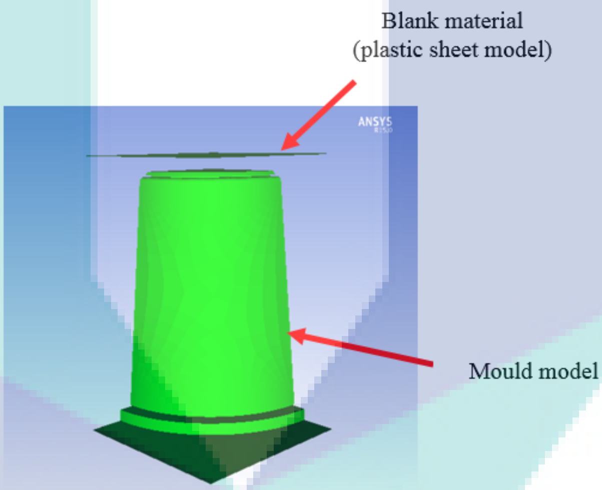


Figure 3.24 Blank material (plastic sheet model) resting on top of positive mould model.

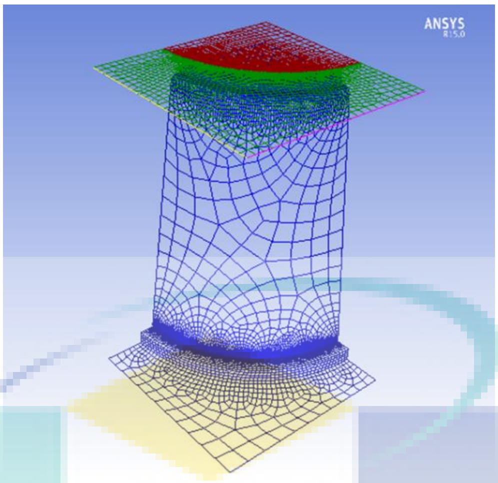


Figure 3.25 Blank material and mould in mesh structure.

Figure 3.26 shows the blank material and positive mould with different coloured regions. The red region indicates the flat surface of the mould in which the thickness of the sheet remains the same when formed whereas the green region indicates the side part of the mould in which the thickness of the sheet decreases when drawn onto the mould.

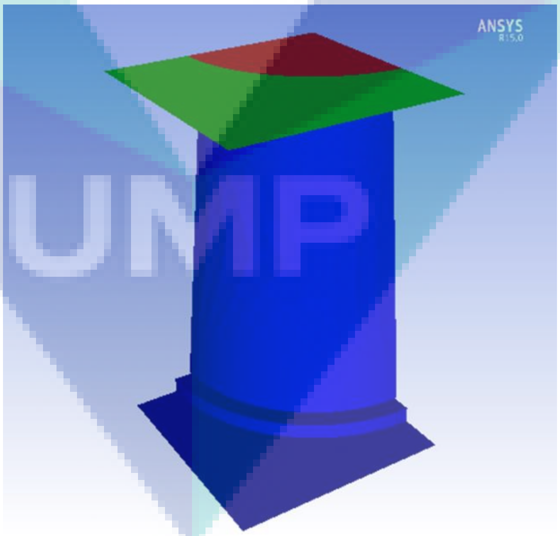


Figure 3.26 Different regions of blank material and mould.

3.11.1 Simulation of Thermoforming Process using Adaptive Meshing

Adaptive mesh refinement (AMR) is implemented during mesh refining in this study. This is to enable an improved solution calculation. The program automatically estimates the mesh discretization error for certain types of analysis and refines the mesh. To implement adaptive meshing technique in POLYDATA, the instructions below are done in the following sequence:

1. Numerical Parameters
2. Adaptive meshing
3. Activate adaptive meshing for contacts
4. Criteria on mold 1: Contact along mold; Disabled
5. Remesh based on angle and curvature
6. Upper level menu
7. Adaptive meshing
8. Enable mesh conformation which ensures that the mesh only contains conform elements
9. Modify the parameters
   - Modify maxdv = 3
   - Modify Nstep (time-step)= 4-5
10. Save& exit
11. Next series
12. Accept

3.12 Summary of Chapter 3

This chapter intends to provide a comprehensive view of the methods and of the work done in this study. The method of producing the CAD mould is explained within this chapter. The process of mould fabrication is then constructed. The method of material characterisation of the polymer material used in this research is also explained to provide a solid evidence of the polymer characteristics. Experimental procedures of the thermoforming process of the designed part are shown to provide a clear view of the thermoforming process of the part. A detailed design of the simulation conducted for the thermoforming process of the designed part is presented in this chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter shows and discusses the results of all the conducted studies mentioned in chapter 3 of this research. This chapter is divided into three main sections in which the first section shows the results in fundamentals of thermoforming while the second section shows the results in conceptual work in experimental measurement of thermoforming and the last section shows the results of computational simulation of thermoforming.

In the first section, the results of CAD of the mould, mould fabrication and material characterisations discussed. This is then continued with the results in conceptual work in measurement of thermoforming which includes the experimental setup, thermoforming process of the part, and measurements taken on the thermoformed part. The last section shows the results of the computer simulation of the thermoforming process using ANSYS® Polyflow.

4.2 CAD of Mould

A commercial engineering software, CATIA 5VR16 was used in the designing of the part and mould. The designs were drawn in accordance to the mould features such as draft angles, radii and draw ratios. Guidelines were followed during the sketching of the design to obtain effective mould features. The table shows the guidelines during the designing of the mould.

4.3 Design of Positive Mould

The moulds are design based on the guidelines in for a thermoforming mould. Draft angles of 5^o are constructed on the external structure of the positive mould. The radius of the mould on the upper region is constructed according to the thickness of the thermoplastic material which is 1.5mm. The sharp edges of the bottom region of the mould are improved by constructing a venting system that allows air to be evacuated within the region.

4.4 Material Characterisation

According to the tests conducted by the Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared Spectroscopy (FTIR) method, the results are shown in the following sections.

4.4.1 Differential Scanning Calorimetry (DSC) Test Results

Figures 4.1 shows the results analysed by conducted Differential Scanning Calorimetry (DSC) tests a polymer sample. From the Figure 4.3, it shows that the polymer material begins to melt at a temperature peak of 299.54^{o}C and continues to melt until it reaches the summit of the melting peak at a temperature of 310.76^{o}C. The DSC curves shown below are found to contain partially crystalline polymer materials. The test results show that the polymer material will begin to melt when heated to a temperature of 299^{o}C. It is found that to allow forming occur without sagging, the thermoplastic sheet temperature should be below 299^{o}C.

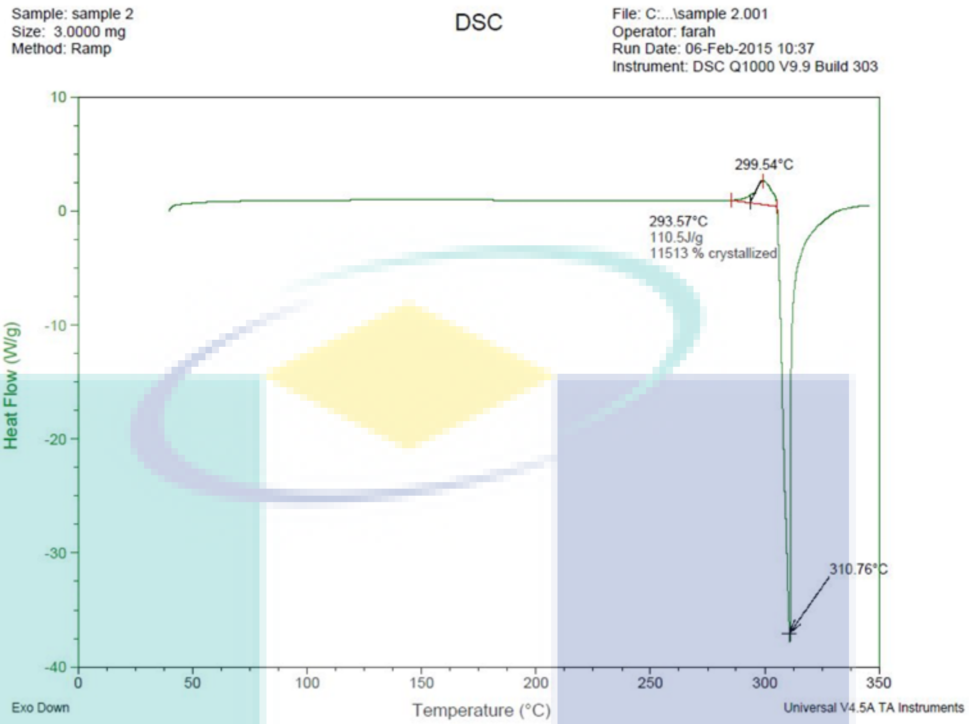


Figure 4.1 DSC curve of thermoplastic sample

Table 4.1 Properties of Polypropylene Polymer Sample

Properties	**Description**
Melting Temperature (°C)	299.54
Melting Peak Temperature (°C)	310.76
Forming window (°C)	250 ~ 299

4.4.2 Fourier Transform Infrared Spectroscopy (FTIR) Test Results

Figure 4.2 shows an illustration of the infrared absorption spectrum of the polymer sample tested by Fourier Transform Infrared Spectroscopy (FTIR) method. The spectrum consists of wavenumber and percentage of transmittance of the polymer sample. According to the analysis done by comparing the spectrum and a library sample in Figure 4.3, the polymer samples shows that the polymer sample consists components similar to Polypropylene.

The advantages of using Fourier Transform Infrared Spectroscopy (FTIR) method in material characterisation includes, a non-destructive technique, provides a precise measurement method in which requires no external calibration, does not require any chemical gas involved in the method, and is mechanically simple with only one moving part.

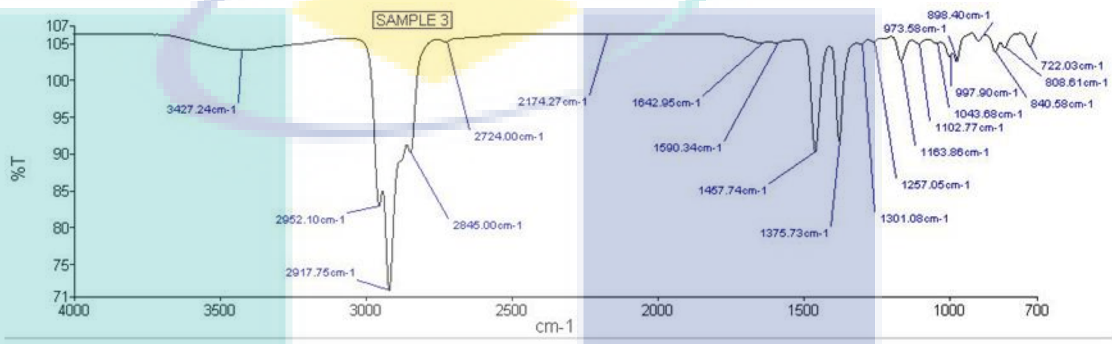


Figure 4.2 Infrared Absorption Spectrum of Polymer Sample

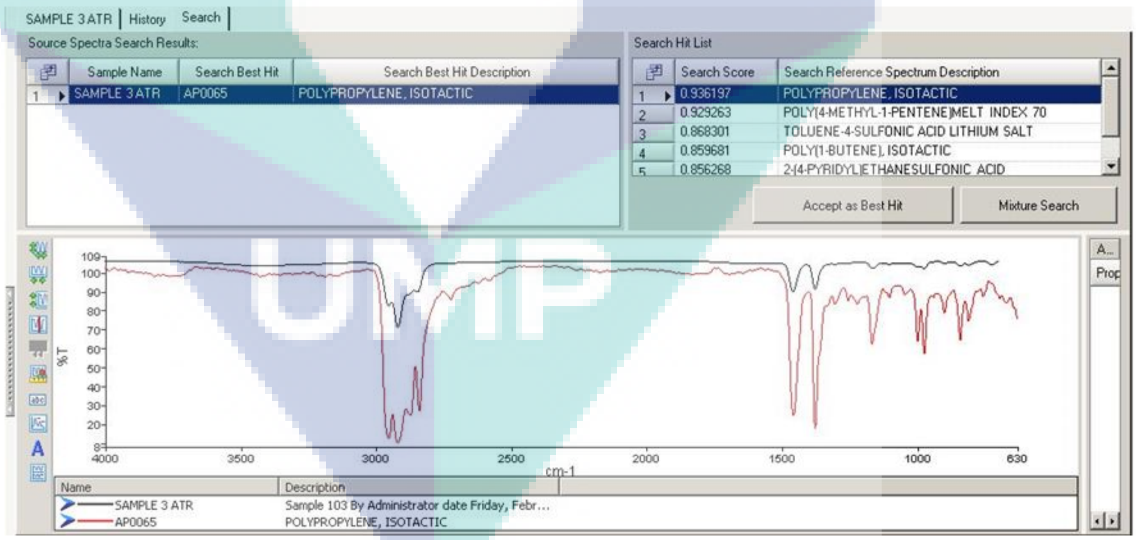


Figure 4.3 Comparison of Infrared Absorption Spectrum of Polymer Sample with Library Sample

4.5 Temperature Assessment of Heating Stage for a Thermoforming Equipment

Figure 4.4(a) and (b) shows the temperature history in the full-configuration setup to simulate the conditions at which the air temperature is not affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection over a blank sheet. It is shown that the temperature in the quadrant 1 and 3 given by T_{1-1} and T_{1-3} respectively are virtually equal and higher than T_{1-2} and T_{1-4}. However, the difference of measured values are relatively smaller during the cooling stage. It is expected as more net radiation heat transfer was produced by the pole of the heating element which is closer to the location of T_{1-1} and T_{1-3}. In heating, the actual thermoplastic sheet for sagging experiment is not reported, however, the sag geometry and material thickness distribution indicated that the plastic received more heat energy in these areas.

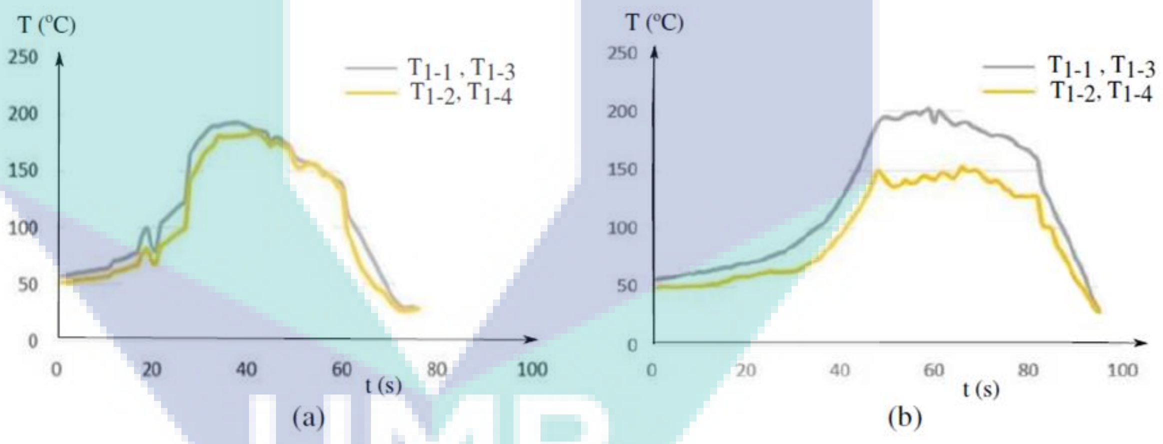


Figure 4.4 Temperature histories for full-configuration experiment using fast response type-T thermocouples

Figure 4.5 (a) and (b) shows the temperature history and growth respectively in the full-plate configuration setup to simulate the conditions at which the air temperature is affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection in the presence of the blank sheet. The measured temperatures on the bottom surface of the instrumented plate are transient and virtually increase exponentially. Visual inspection for comparison with Figure 4.5 shows that the commercial grade thermocouple has greater thermal inertia and provide much greater uncertainty in the actual surface temperature of the heated plate. Figure 4.5(b) shows that the uniformity of temperature distribution in the work virtually takes around one minute if the heating begins when the air temperature between 20 to 50^{o}C. High starting temperature shown in the figure implies that the experiment was carried out at the end of a cooling experiment.

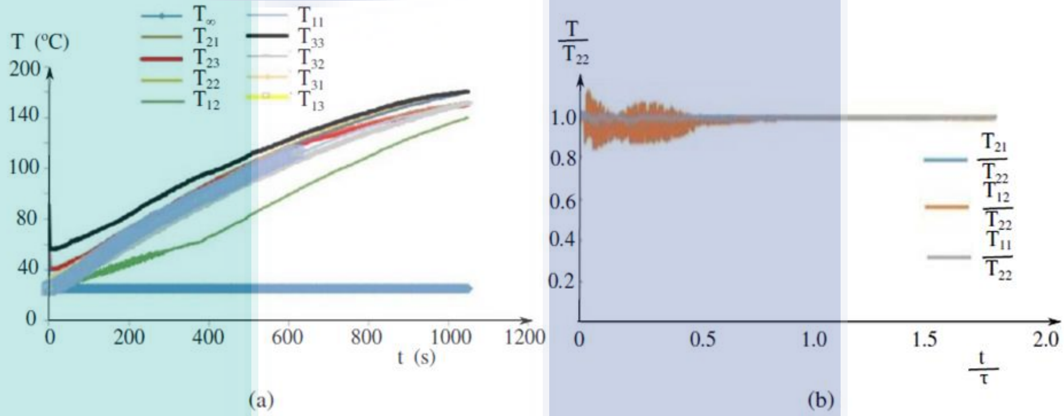


Figure 4.5 Temperature histories for full-plate-configuration experiment using commercial grade thermocouples

Figure 4.6 shows the temperature histories in the quadrant-configuration setup to simulate the conditions at which the air temperature is not affected by the net radiation heat transfer from the heated blank sheet and characteristics of convection over a blank sheet. Figure 4.6 (a) compare the spatial distribution of measured temperature using commercial grade gas thermocouple at two different time stamp to indicate the effects of daily room temperature, T1. It is shown that T1 has a weak influence on the temperature variation across the working area compared to the measured temperature rise. Visual inspection for comparison with Figure 4.6 shows that the thermal and geometrical properties of thermocouple junction are important to determine the actual air temperature. However, not much variation can be seen between magnitude and characteristics of air temperature between full-plate and quadrant-configurations experiments given in Figure

4.6 (a). Figure 4.6 (b) shows that the temperature rise is less than 10% at the end of after 500 seconds of heating.

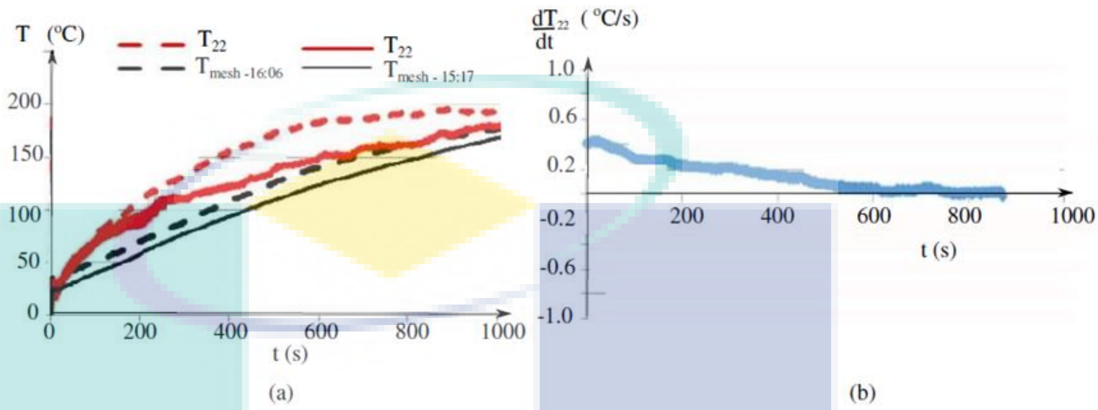


Figure 4.6 Temperature measurement on mesh profile using aluminium plate

4.6 Thermoforming Process of Polypropylene Polymer

4.6.1 Thermoplastic Behaviour during Heating Phase

A thermoplastic sheet, when heated, changes from one phase to another under a period of time. According to Michaud and Giacomin (2011), in a work of thermoforming a plastic sheet, plastic sheets undergo three consequence phases before they are sufficiently draped onto a mould; bowing, softening and sagging. These three phases are essential in the study as it dictates the forming window of the thermoplastic sheet for the forming process to take place.

4.6.2 Stretch Marks on Thermoformed Part

As expected from the theoretical hypothesis, the stretch marks on the top region of the male mould (flat surface) in Figure 4.7 stretches the least. The gridlines shows a slight deformation in which indicate material distribution when the sheet first comes into contact with the mould surface. As the sheet draws onto the side region of the mould, stretching occurs along the slant length of the mould. Webbing or wrinkling also occurs on the bottom edges of the thermoformed part. Several causes of webbing or wrinkling that is discussed by thermoforming manufacturers include the spacing between the male mould and the clamping frame (as shown in Figure 4.8) , sheet sag, high draw ratio and sharp edges (Albert et al., n.d.; Guides & Processing, n.d.; “A Vacuum Forming Guide,” n.d.).

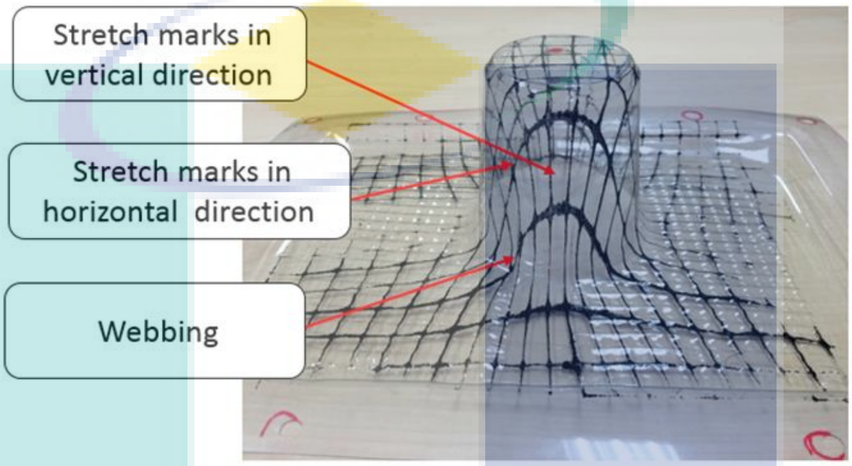


Figure 4.7 Stretch marks on front view of thermoformed part

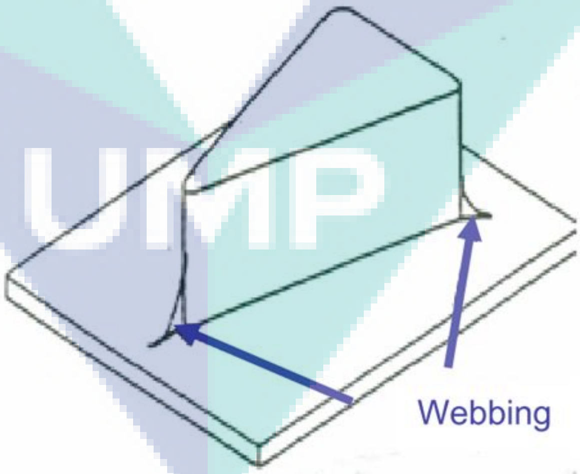


Figure 4.8 Webbing defects on positive mould
Source: Klein & Ph, (2006).

Air in the empty space near the clamping ring has been detected to be trapped between the thermoplastic sheet and mould with the platen as the base as shown in Figure 4.9 side B. Compared to side A, the thermoplastic sheet is observed to conform more than in side B whereby trapped air is detected to have occurred. The mould is nearer to the clamping frame in side B compared to side A which is farther away from the clamping frame. The distance of the mould placed between the clamping frame is found to become a contributing factor in webbing and stretching of material. Thus, to improvise stretching behaviour and to obtain a uniform material distribution, the distance of mould and clamping frame should be increased.

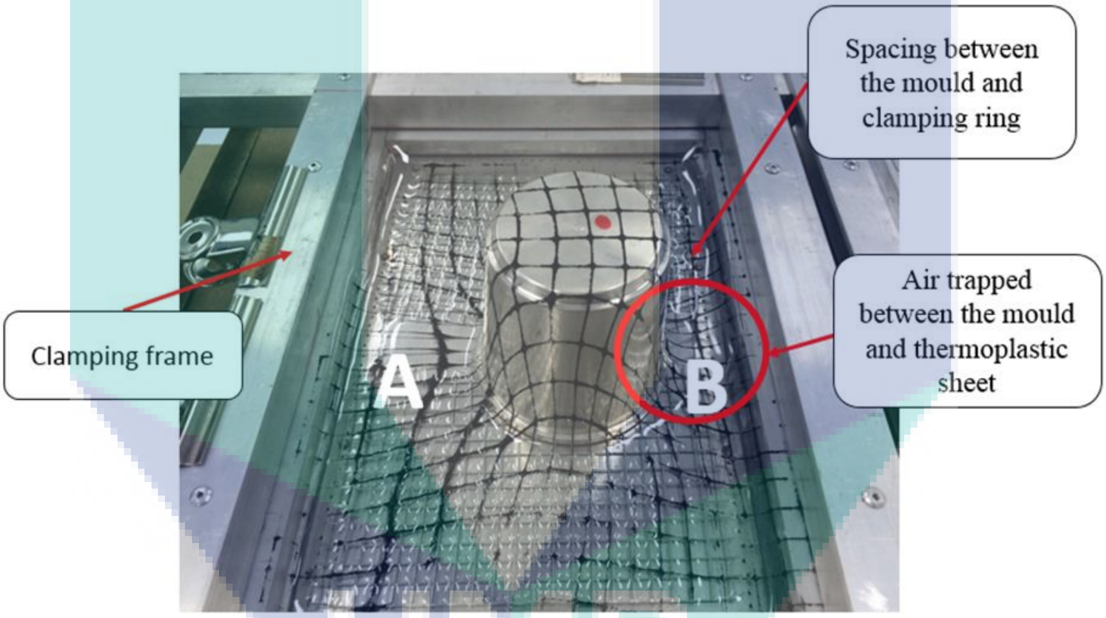


Figure 4.9 Thermoplastic sheet drawn onto mould

The high distortion of stretch marks shown in Figure 4.10 in the bottom region shows non-uniform material distribution in the bottom region of the thermoformed part. The spacing between the clamping frame and draw ratio may be a contributing factor of the non-uniform stretch marks that occur. Table 4.2 provides several solutions to webbing or wrinkling that occurs on positive moulds.

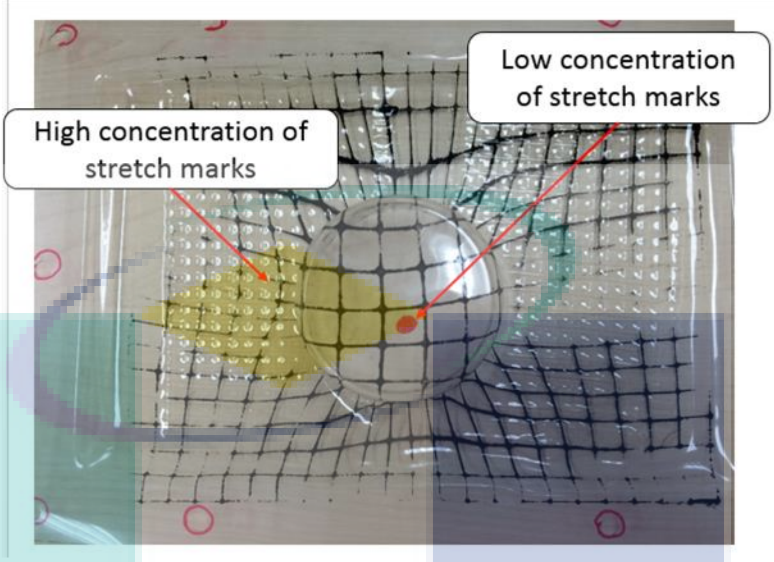


Figure 4.10 Stretch marks of plan view of thermoformed part

Table 4.2 Solutions in webbings of thermoformed part

Forming Defects	Solution
Webbing or wrinkling	• Place stretch blocks on the corners of the mould • Prevent sheet from sagging • Use a negative plug assist • Re-design mould with lower draw ratio • Re-design the clamping frame with a shape suitable for the shape of mould • Increase the spacing between the mould and the clamping frame • Increase the draft angle or radii in the webbing area • Use appropriate size of thermoplastic sheet suitable for mould size

Source: "A Vacuum Forming Guide," n.d.; Thermoforming-, n.d. ; Albert et al., n.d.; Outline, (2014a)

4.6.3 Part Removal from Positive Mould

After the thermoformed part is left to cool, it is then removed from the positive mould. In this study, part removal was difficult for the positive mould without a venting system. This may be due to many reasons, mainly the structural design of the mould, shrinkage of the thermoplastic sheet onto the mould and lack of openings on the mould. According to Klein and Ph, (2006), the thermoplastic expand when heated and shrink when cooled. As indicated in Table 4.3, some polymer materials have a shrink rate as high as 5% when cooled from thermoforming temperatures while others have low as 0.35%.

Table 4.3 Typical Shrinkage Range for Several Polymer Materials in Thermoforming

Polymer Material	**Shrinkage Range Percent**	**Shrinkage Normally Used Percent**
ABS	0.3-0.8 %	0.5 %
Acrylic	0.3-0.8 %	0.6%
Butyrate	0.2-0.5%	0.35%
HDPE	2.0-3.5 %	2.5%
HIPS	0.3-0.8%	0.5%
Polycarbonate	0.6-0.8%	0.7%
Polypropylene	1.2-2.2%	1.8%

Source: McConnell, (1995).

According to McConnel, (1995), approximately 50% of the shrinkage occurs while the thermoformed part is on or in the mould. During cooling, the thermoplastic sheet shrinks and “grips” the mould which makes the part removal very difficult. A suggested solution for this matter is by increasing the draft angles and re-designing the mould structure to improve part removal. The thermoformed part was removed from the mould using compressed air. Figure 4.11 shows the image of thermoformed part during cooling and after it has been removed from the mould.

Figure 4.11 Thermoformed part (a) during cooling (b) after removal

4.7 Simulation of Thermoforming Process of Polypropylene Polymer

4.7.1 Simulation of Thermoplastic Sheet with Velocity of 50mm/s and 100 mm/s

Figure 4.12 presents an illustration of the contour results of a computer simulation of a thermoforming process using ANSYS® Polyflow. The numerical parameters and boundary conditions applied are discussed in Chapter 3. From the simulation conducted in Figure 4.12 with a mould velocity of 50 mm/s the material distribution on the flat surface of the mould to the sharp decrease shows that the material does not conform entirely to the mould surface. The wrinkling region indicates the appearance of trapped air between the blank material and the mould. As the blank material draws down the sides of the mould, the thickness continues to decrease until the bottom edge of the mould. Wrinkling or webbing also appears on the bottom edge of the thermoformed sheet due to sharp edge design of the mould.

Figure 4.13 presents an illustration of the same simulation but with a mould velocity of 100mm/s. The wrinkling of blank material between the flat top surface and the sharp decrease appears to be lesser compared to in Figure 4.12. Similar with the wrinkling or webbing in the bottom edge of the mould, a lesser amount is seen. Wall thick- ness distribution became more uniform with an increase in the plug velocity and a decrease in the stretching time. From the two mould velocities (50 mm/s and 100 mm/s) the latter develops a more uniform wall thickness distribution compared to the first. This shows that an increase in mould velocity increases the uniformity of material distribution of thermoformed part (Aroujalian et al., 1997). A faster rate of forming also means that the stretching time is decreased. Therefore, a higher speed in forming and a less amount of time during stretching develops a more uniform wall-thickness distribution.

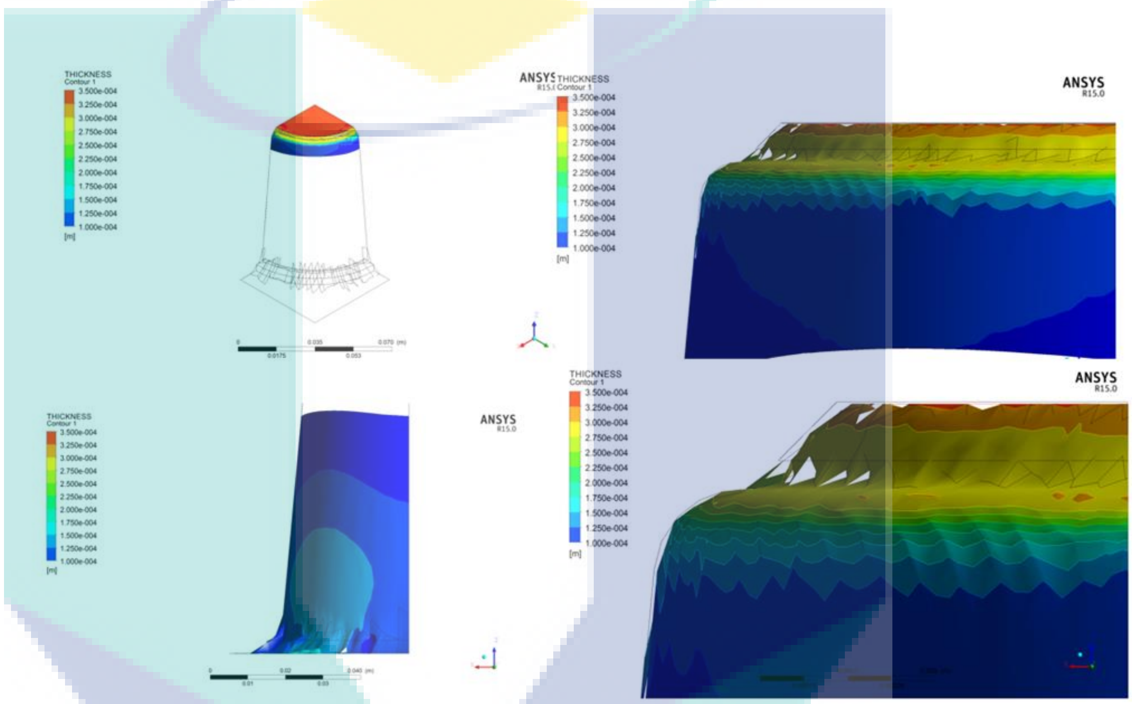


Figure 4.12 Material distribution with mould velocity of 50mm/s

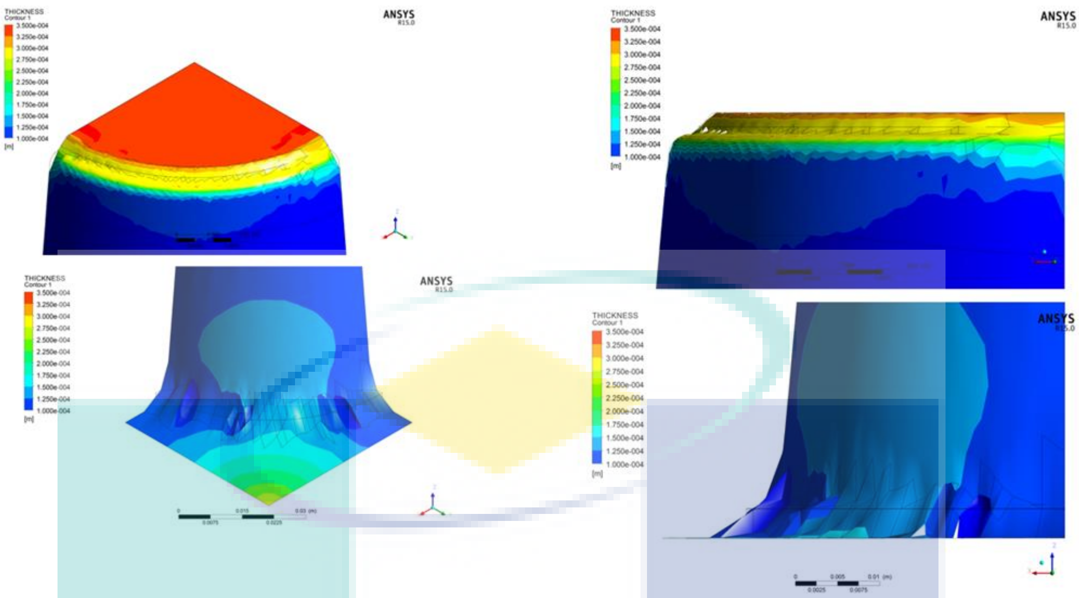


Figure 4.13 Material distribution with mould velocity of 100mm/s

4.7.2 Simulation of Thermoplastic Sheet using Adaptive Meshing

Figure 4.14 shows the computer simulation for a domain of a thermoforming of a thermoplastic material with implementing adaptive meshing technique. An additional parameter is modified to obtain a finer mesh problem which is discussed in Chapter 3. From the figure, the variation in colours of the contours shows variation in the wall-thickness distribution of the simulated thermoformed part as similar to previous simulations without adaptive meshing technique.

As similar to the previous simulations, the thickest wall-thickness developed is on the flat surface whereby the first region the blank sheet contacts. Then, the thickness decreases as the blank material is drawn down the sides of the mould. In this case, the region between the flat surface and the side of the mould develops a smoother surface or much less wrinkling compared to the previous simulations that use not use adaptive meshing technique whereby the thickness is in the range of 0.25mm-0.35mm. This is due to the finer mesh structure developed when using the adaptive meshing method. The blank material is able to conform to the mould surface almost entirely, therefore having less to zero air trapped from the results of the venting system.

Webbing due to excess material is still seen on the bottom part of the thermoformed sheet whereby the mould corners are sharp. However, compared to without using adaptive meshing technique, the amount of wrinkling is less visible. Sharp vertical corners are proven to cause webbing and thinning of material ("A Vacuum Forming Guide," n.d.). This is an undesirable feature of thermoformed part as it will weaken its mechanical properties. As explained by Tam and Chan, (2007), design features, such as sharp edges and steep depressions, will lead to a high ''draw ratio'' in which makes the thermoforming features difficult to form compared to a low draw ratio. Sharp edges are suggested to be avoided in thermoforming moulds by chamfering the design or adding fillets to corners. Nonetheless, the venting systems which are located on two sections of the mould provide assistance in removing trapped air between the mould and sheet.

A substantial change occurs along the contour of the mould model in which, the region turns to a yellow colour indicating the decrease in wall-thickness. The edge fillet of the mould model incorporates a venting system in which a minimal orifice that functions to evacuate air at a faster rate. In Figure 4.15, the region of the allocated venting system shows a conformed thermoformed part on the mould model. This shows that the venting system in the mould model is able to allow air evacuation without leaving any air trapped between the thermoplastic sheet and the mould.

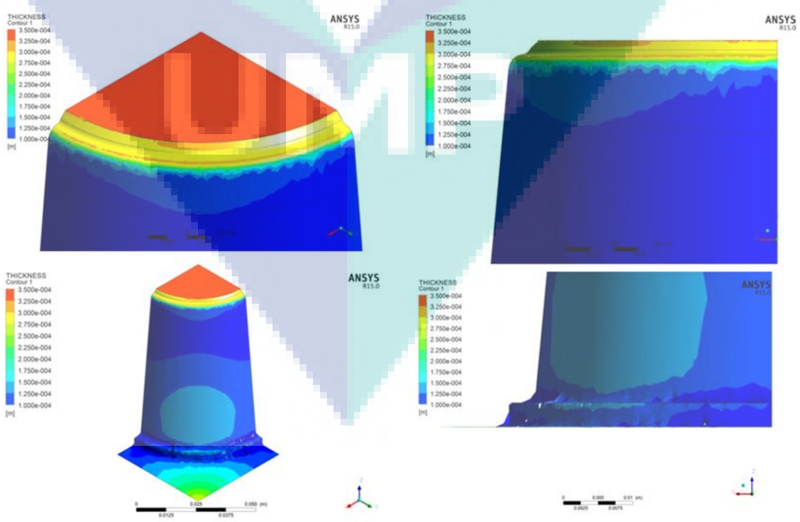


Figure 4.14 Material distribution of thermoplastic sheet in sections

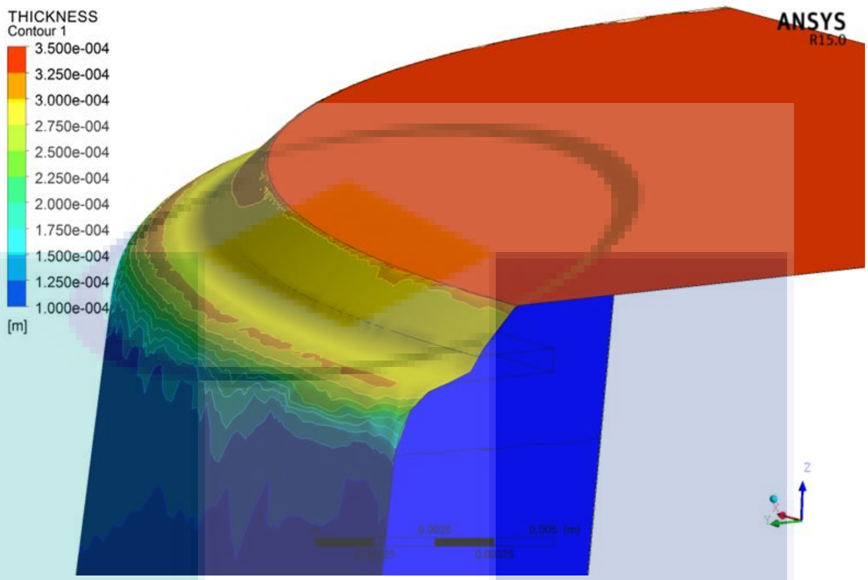


Figure 4.15 Macro view of material distribution on contour area

4.7.3 Simulation of Thermoforming Process with 1.5mm Thickness of Thermoplastic Sheet

The thermoforming process illustrated in Figure 4.16 and 4.17 shows the phase from start to end of the sheet displacement into the positive mould, which covers a total period of 1.7s, and then the final application of air pressure in which the sheet is then inflated, which takes a further 0.90 s. In the figures, reductions in the local sheet thickness are indicated by increases in the relative brightness of bands in the walls of the partially formed parts. The sheet is seen to effectively wrap around the positive mould as it progressively deforms and draws into the mould during its traverse into the lower recesses of the mould until time t = 1.7s. Once the pressure is ramped during the pressure cycle at t > 1.7 s the sheet is seen to billow and inflate and ultimately touches the positive mould, whereupon it cools and sets forming the final thermoformed shape. The successful step reached is 300 steps. Adaptive meshing technique was also implemented and a mould velocity of 50mm/s is used. Table 4.4 shows the specifications used in the simulation.

Table 4.4 Specifications during simulation of thermoforming of 1.5mm thickness blank material

Specifications	**Descriptions**
Initial thickness (mm)	1.50
Inflation period (s)	0.90
Maximum successful steps	300
Mould velocity (mm/s)	50

At t=0s, the blank material rests above the mould. During this stage, the sheet thickness is initially 1.5mm. Once the sheet contacts the flat surface of the positive mould at t>0s, and begins to draw on the edges of the mould, the thickness decreases. At t=0.43s, the sheet stretches which is indicated by the increase in the band brightness. The sheet stretches and decreases in thickness to a maximum thickness of 1.35mm. The local sheet thickness continues to decrease as the sheet draws until t=1.7s. At t>1.7s, the inflation occurs and the sheet is conformed onto the mould edges until t=2.61s in Figure 4.17. At this stage, the range thickness of the local thickness of the sheet on the sides of the mould is between 0.45mm- 0.60mm thick.

The region close to the top surface of the mould appears to be thicker compared to the region close to the bottom of the mould. This is due to the sharp decrease sheet stretching from a flat surface to the slant sides which shows non-uniform material distribution. As explained by Kommoji et al., (2014), an increase in draft angle will increase will allow the thickness in the slant length to become less sharp. Therefore, a generous value of the draft angle is required for greater values of wall thickness and less extreme thinning on the region of a sharp decrease of the slant length.

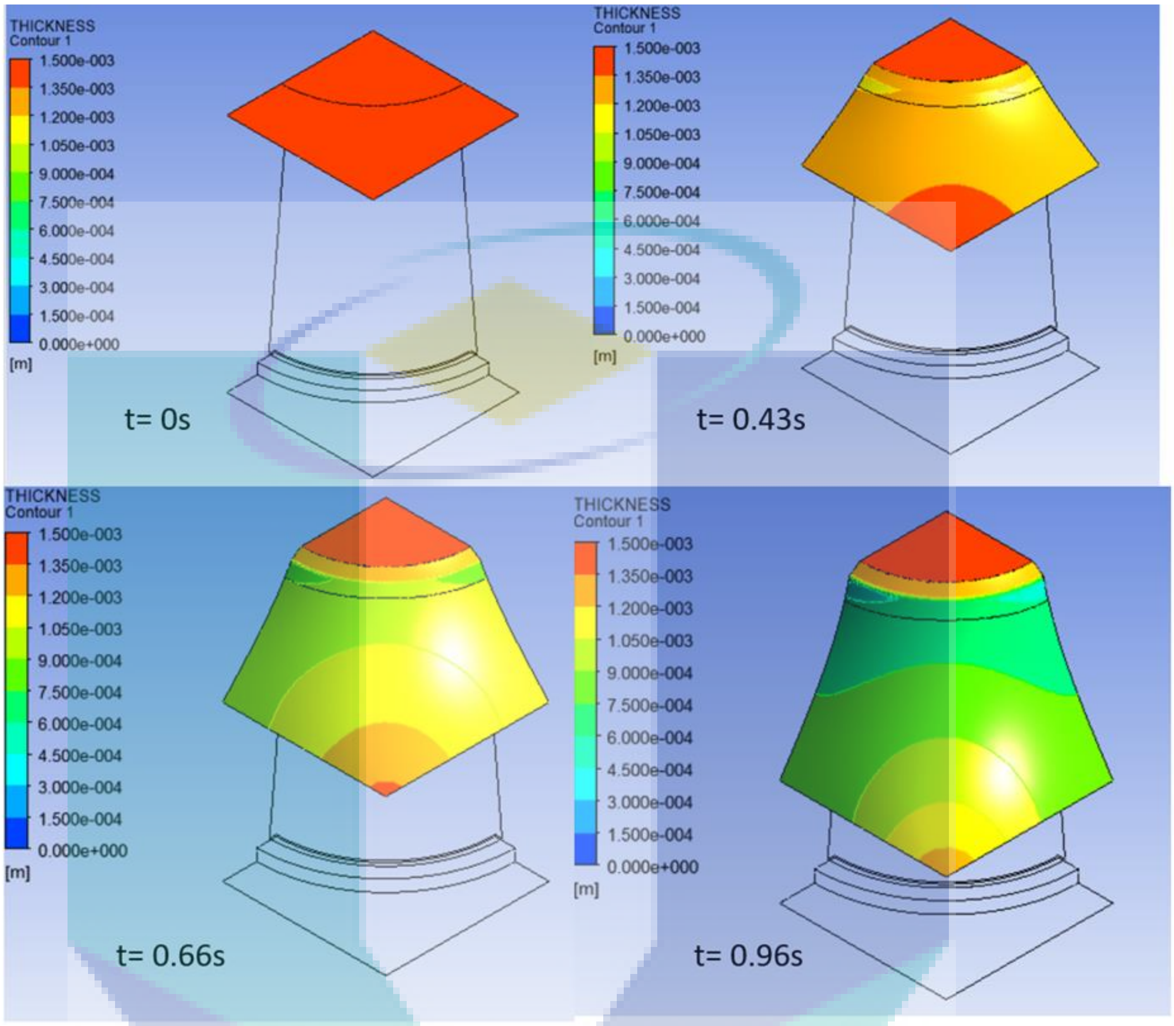


Figure 4.16 Material distribution of thermoplastic sheet from t=0s to t=0.96s

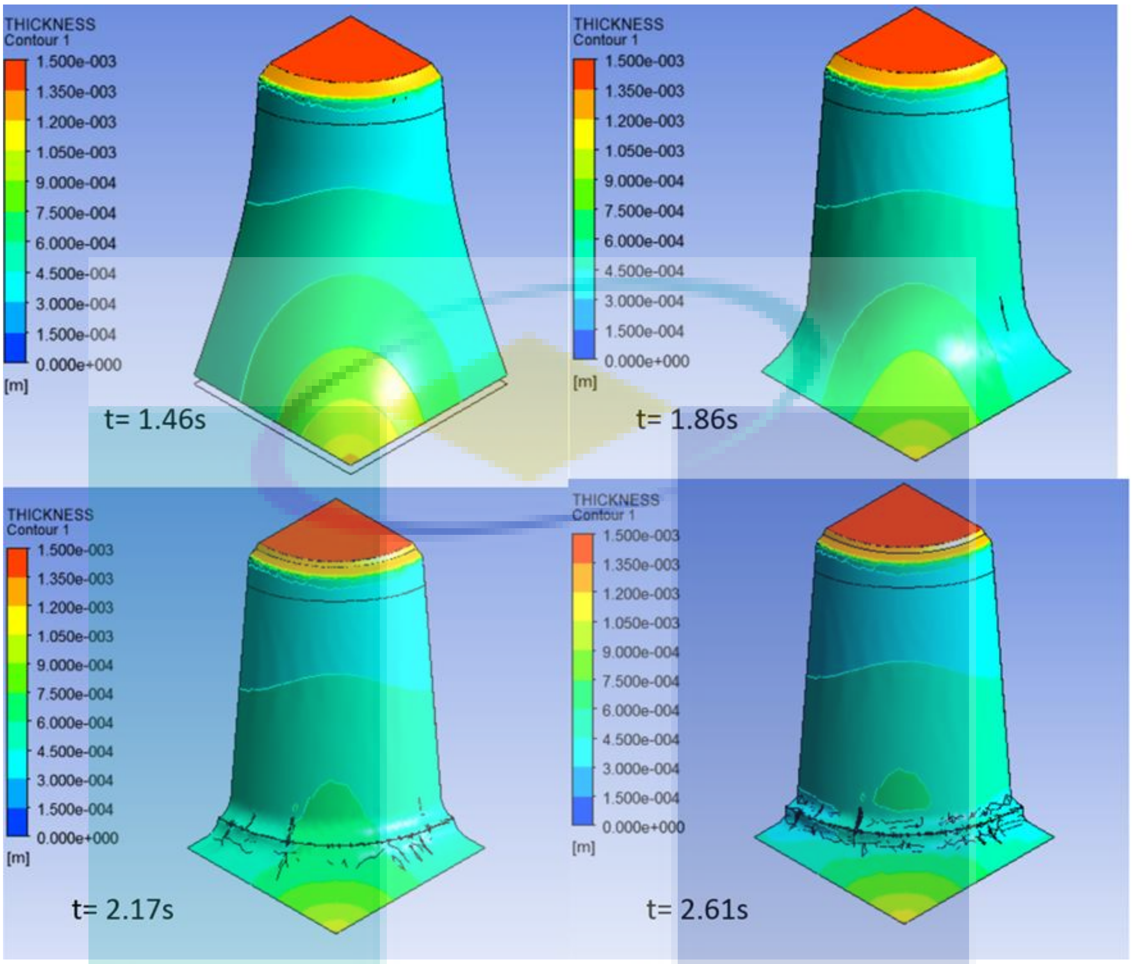


Figure 4.17 Material distribution of thermoplastic sheet from t=1.46s to t=2.61s

4.8 Calculations of Final Thickness of Thermoformed Part

From the simulations conducted, the thinning percentage of polymer sheet can be calculated using the formula:

$$\text{Thinning percentage}=(\text{Initial thickness} - \text{Final thickness}) \times 100 \tag{4.1}$$

Referring to Table 4.5, the thickest wall-thickness is in region A in Figure 4.18, in which the blank material first touches the mould. As the blank material is drawn onto the mould sides in region B, the wall-thickness decreases 22.4% more. The change in slope proves a decrease in wall-thickness as explained by Satish Kommoji et al., (2015).

The region BC extends from the mould corner up to a short distance along the slant length whereby an extreme change in slope appears. In this region, the wall thickness decreases sharply with a thinning percentage of 97.5%. Compared to BC, the thinning percentage in CD is much lower which is 82.5%. This is due to a wider angle of slope. In region DE, the thickness was found to be decreasing but the magnitude is lower compared to in CD with a percentage of 37.5% as it is less sharp compared to region CD. Also, in region DE, the formed plastic sheet appears to be wrinkling on the corner or the mould. This is due to the sharp design structure of the mould that makes the blank material unable to conform properly onto the mould. As reported by Kommoji et al., (2014), sharp corners are known to produce wrinkles.

Table 4.5 Percentage of thinning on the areas of the thermoformed part

Region	**Original Thickness(mm)**	**Final Thickness(mm)**	**Percentage of thinning (%)**
A	1.5	1.5	0.00
B	1.5	1.275	22.5
C	1.5	0.525	97.5
D	1.5	0.675	82.5
E	1.5	1.125	37.5

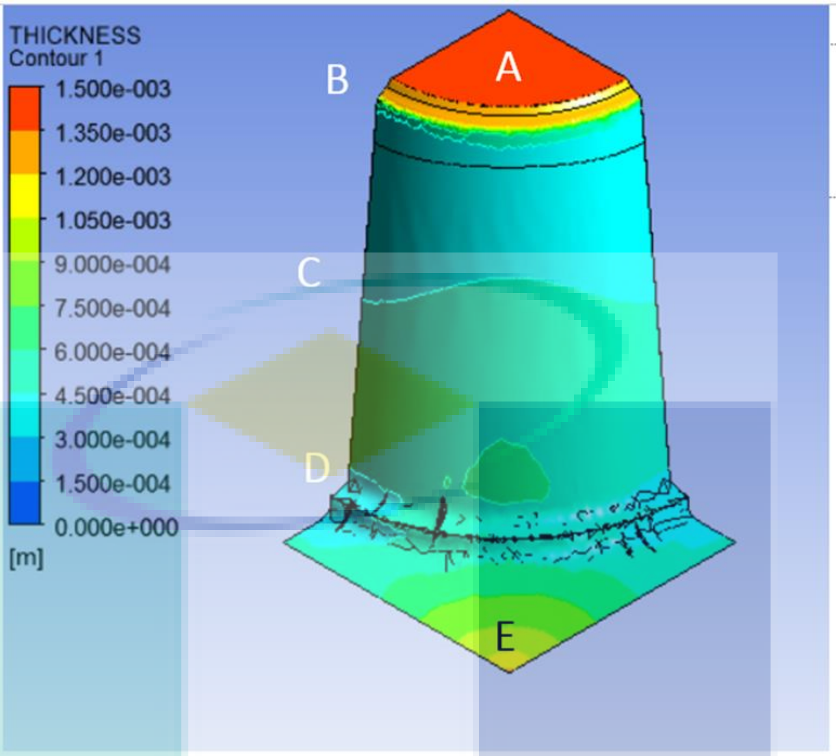


Figure 4.18 Thermoformed part with labelled regions of different wall-thickness

4.9 Summary of Chapter 4

This chapter provides a constructive presentation of results collected from the research conducted. A CAD model of the part and mould design is illustrated in which the guidelines features to mould modelling of a thermoforming process is implemented. The complete fabricated mould design is presented in order to provide a rigid view of the design and to also provide a visual illustration of the thermoforming process of the part in terms of geometrical structure and mechanical properties of the thermoformed plastic part. The computer simulation of the thermoforming process is shown and issues during and after the simulation are discussed.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The purpose of this study is to design a thermoforming process for a semi-crystalline polymer material. A brief introduction of thermoforming process is explained earlier in Chapter 2. The manufacturing process is explained with assisting examples and diagrams. Drape forming technique was implemented using an in-house specific purpose thermoforming equipment for producing thermoformed parts. The low-cost manufacturing equipment and aluminium moulds for qualitative measurements were used throughout the manufacturing processes. Numerical computations were carried out using Ansys Polyflow to assist better physical understanding of the behaviour of the thermoplastic sheet during the forming stage of the thermoforming process.

5.2 Summary of Research

A combined computational and experimental investigations were carried out in the design and development of thermoforming process. A drape forming technique whereby the heated thermoplastic sheet is formed onto a positive mould with the assistance of pressure is implemented. Literature reviews were chronologically made to identify the problem statement, hypothesis, research methods and scope of the investigation. These include the designs in the construction of the thermoforming process, the thermoforming equipment, guidelines of thermoforming mould designs, thermoforming mould fabrication, polymer materials used in the process, material distribution of thermoplastic sheet during forming, venting systems in mould and computational simulations for the process. Therefore, the thermoforming process of a semi-crystalline polymer material is investigated to provide a better understanding in the production of the thermoformed part.

Chapter 3 described the modern approach of designing the thermoforming process. The simulation of drape thermoforming process was carried out to determine the expected results assuming porous aluminium mould. A thermoforming equipment was then developed and the positive moulds were fabricated. Quantitative measurement was made on grid marks on the blank Polypropylene sheet. The process variables were measured using computer data and imaging acquisition system.

The primary concern in the investigation is the quality of the thermoformed part which is affected by the venting system of the thermoforming mould. As thermoformed part using truncated positive mould without venting system was found to have trapped air in extreme changing slope areas and sharp corners, a venting system is designed to improve this issue. The venting system is designed to remove trapped air between the thermoplastic sheet and the mould in extreme slopes and corners.

In this study, drape forming technique is implemented to generate thermoformed parts that do not require plug assistance. The technique uses a positive mould whereby the thermoplastic sheet is then pressed onto the mould to imitate the shape of the mould. In addition to that, by using this technique, the thermoformed part will have a more detailed interior structure design.

The results of thermoformed parts produced with using positive mould without venting system found that air is trapped in the slope and sharp regions. The changes in structure from horizontal to slope makes the material to be distributed much more difficult and traps more air. Venting system is designed to provide a solution in the removal of trapped air in these regions.

A modular type of positive mould is designed to provide an orifice between each segment as the venting system. The orifice provides an opening that enables trapped air to be removed once the thermoplastic sheet is pressed against the mould. The mould is designed in segments whereby the venting system is allocated horizontally as the distribution of material is exerted in the opposite.

From the computer simulation of thermoforming process conducted using ANSYS POLYFLOW, the positive mould with the venting system shows a drastic decrease in wall-thickness in the slant length region. Meanwhile, the material shows improved conformation in the region near the venting system.

5.3 Discussion and Implications of Findings

The process of designing and then developing a thermoforming process for a semi-crystalline polymer material has attained many relevant issues. The first concerns are in designing the thermoforming equipment. The type of thermoforming tools used is according to the suitability of the part to be produced. Thermoforming tools such as heating element, platen, clamping frame, thermoforming moulds and venting system is developed in accordance to the suitability of thermoformed part.

Redesign of the thermoforming equipment was done to obtain a productive thermoforming process. The platen, vacuum system, clamping frame and operating system was designed and redesigned to achieve good thermoforming process relating to the positive mould used. Initially, the former platen used to produce a leakage during the forming stage. By covering the former platen with aluminium foil and installing an aluminium mesh, the leakage issue was able to be solved. The clamping frame was also redesigned to fit the shape of the platen. A domestic high power vacuum cleaner was installed to provide high power suction.

Prior to thermoforming process, prerequisites such as material characterisation, temperature assessment and thermoplastic sheet preparations are also conducted. The temperature assessment is significant to attain uniform heating of the thermoplastic sheet during the heating process. Although simple, the fast response temperature sensors used in measuring the temperature of the heating element was found to be efficient in the temperature measurement process. As to that, temperature sensors are suitable to be used in measurements over a wide range of temperatures with in various applications.

In the computation of the thermoforming process, the material distribution and quality of the simulated part depends on the mesh distribution, processing parameters, material models, and boundary conditions. The simulation conducted by applying adaptive meshing developed profound results of the thermoforming process. By increasing the mesh quantity, the material was able to conform better onto the mould, especially on the venting areas.

5.4 Limitations of Research

During temperature assessment of the oven, the temperature sensors were only placed on one section of the oven. This was done as it is assumed that the heating element would provide similar temperature readings. During thermoforming process, an ideal room temperature environment was not available. Although the laboratory used to conduct the experimental tests was at room temperature, but the oven is closed during heating the thermoplastic sheet to avoid air contamination and heat leakage. An aluminium foil was used as a barrier of escaping heat from the oven. Comparative investigations on material models, polymer types, blank sheet thickness were not carried out as it is not part of the investigation.

5.5 Recommendations for future work

Certain improvements can be done for further research in this work. The mechanism of the forming process of the semi-crystalline material, instead of a rotation motion of the forming process, a vertical transverse motion can be applied. This is to investigate the uniformity of material distribution of the thermoplastic material onto the mould. The first contact region the thermoplastic material contacts are a significant factor that contributes the material uniformity. By investigating this process, both mechanisms can be compared to determine whether the material distribution of the thermoformed semi-crystalline is affected.

The conducted investigation shows that the semi-crystalline material undergoes conforming difficulties in sharp edges and steep slope regions as webbing occurs in these mentioned areas. Referring to the results in Chapter 4, although the draw ratio of the mould design is 1.00 and draft angle is >5^{o} which follows the moldability for a positive mould, the results, however, show non-uniform wall thickness along the slant length and especially on the sharp corner of the mould. The design of the positive mould can be further improved by applying geometries that follow the guidelines more accurately, by chamfering sharp edges and reducing draw ratios.

It is important that a thermoplastic material, semi-crystalline polymer is used in the thermoforming process as it consists of a molecular structure that is able to deform when heated to a high temperature. The basic characteristics of semi-crystalline, as mentioned in the literature, has vaguely excellent behaviour as it has a higher melting point. High melting points of the thermoplastic material enable it to remain solid until a given quantity of heat is absorbed as it does not gradually soften. Comparing to amorphous polymers, whereby, when heated, the plastic immediately begins to soften due to its randomly ordered molecular structure which softens gradually as the temperature rises.

Although some studies find that using amorphous polymer materials to be a suitable thermoplastic material for thermoforming, such as (Aroujalian et al., 1997 and Gilormini et al., 2012), as amorphous polymers have excellent stretching behaviour and wider forming window, other studies prefer using semi-crystalline polymer materials such as Polypropylene (PP), Polyethylene (PE) and Polyesters (PET) due to their high melting point and chemical resistance. Amorphous polymer material has a low melting point compared to semi-crystalline polymers. This causes the material to sag easily during heating phase when the temperature is poorly controlled. When using semi-crystalline polymer material, Polypropylene (PP), the material initially bows indicating that the molecular structure has begun to randomly disorient. After the bowing ends, the material begins to flatten indicating that it will then start to sag. The forming window of the material was experimented to be of best quality just before the material begins to sag. The selection of polymer material used in thermoforming process is highly crucial for the benefit of the quality of the thermoformed part. Starting from the heating phase, the thermoplastic sheet should provide a fraction amount of time given to allow molecular disorientation rather than gradually softens just as heating begins, to avoid over sagging.

The results in simulating thermoforming process using a modular approach mould design have profoundly proved enhancement of conformation of the thermoplastic material onto the mould. The Generalized Newtonian fluid material model used as the blank material property regulates the semi-crystalline material excellently throughout the simulation. The material formed in the venting areas shows conformation whereby proclaiming removal of trapped air between the blank material and mould. The venting system of the mould can be increased depending on the length of the slant. The venting system is therefore directly proportional to the length of the slant. This is due to the wider surface gap between the top and bottom area that will trap more air.

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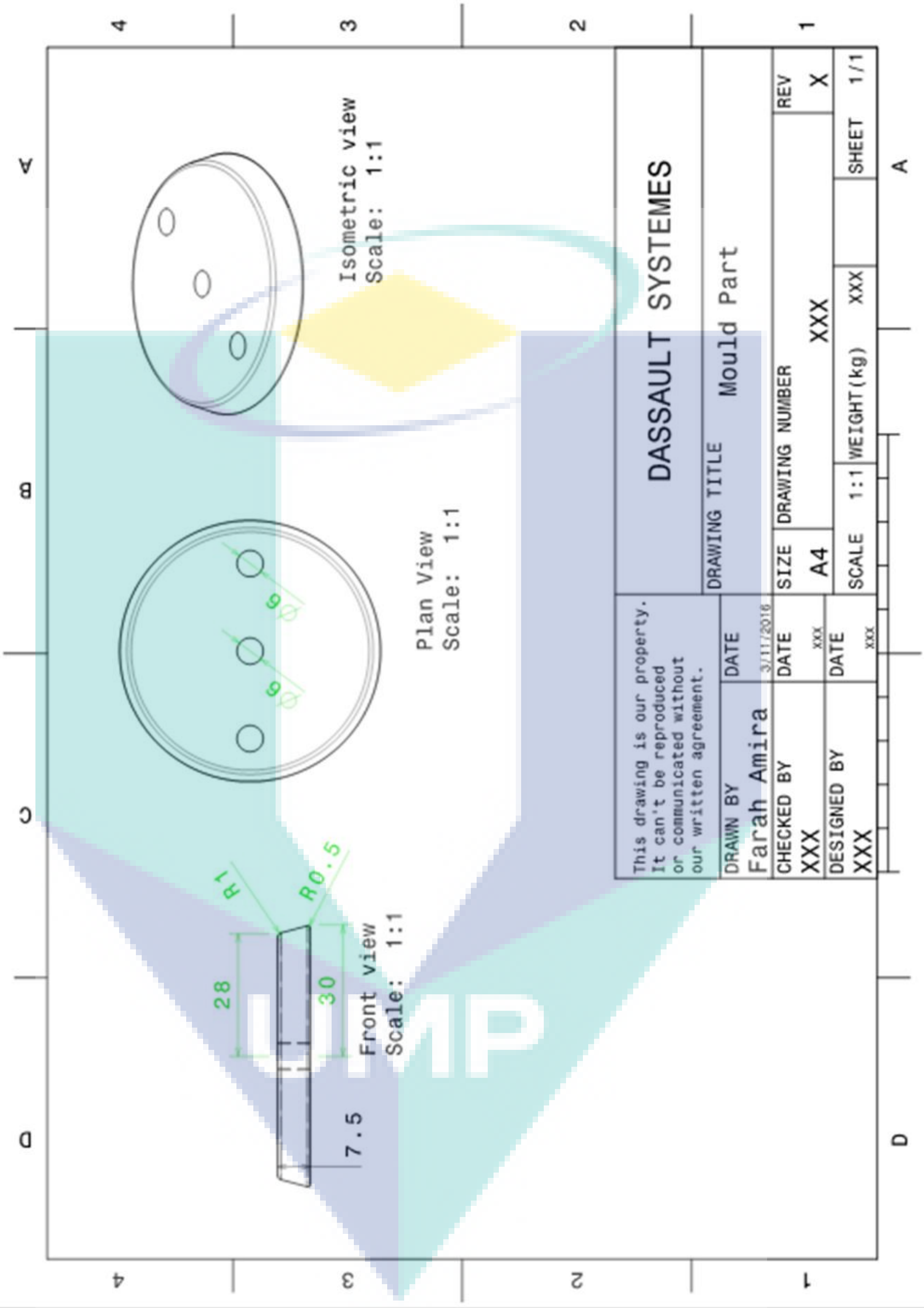
APPENDIX A

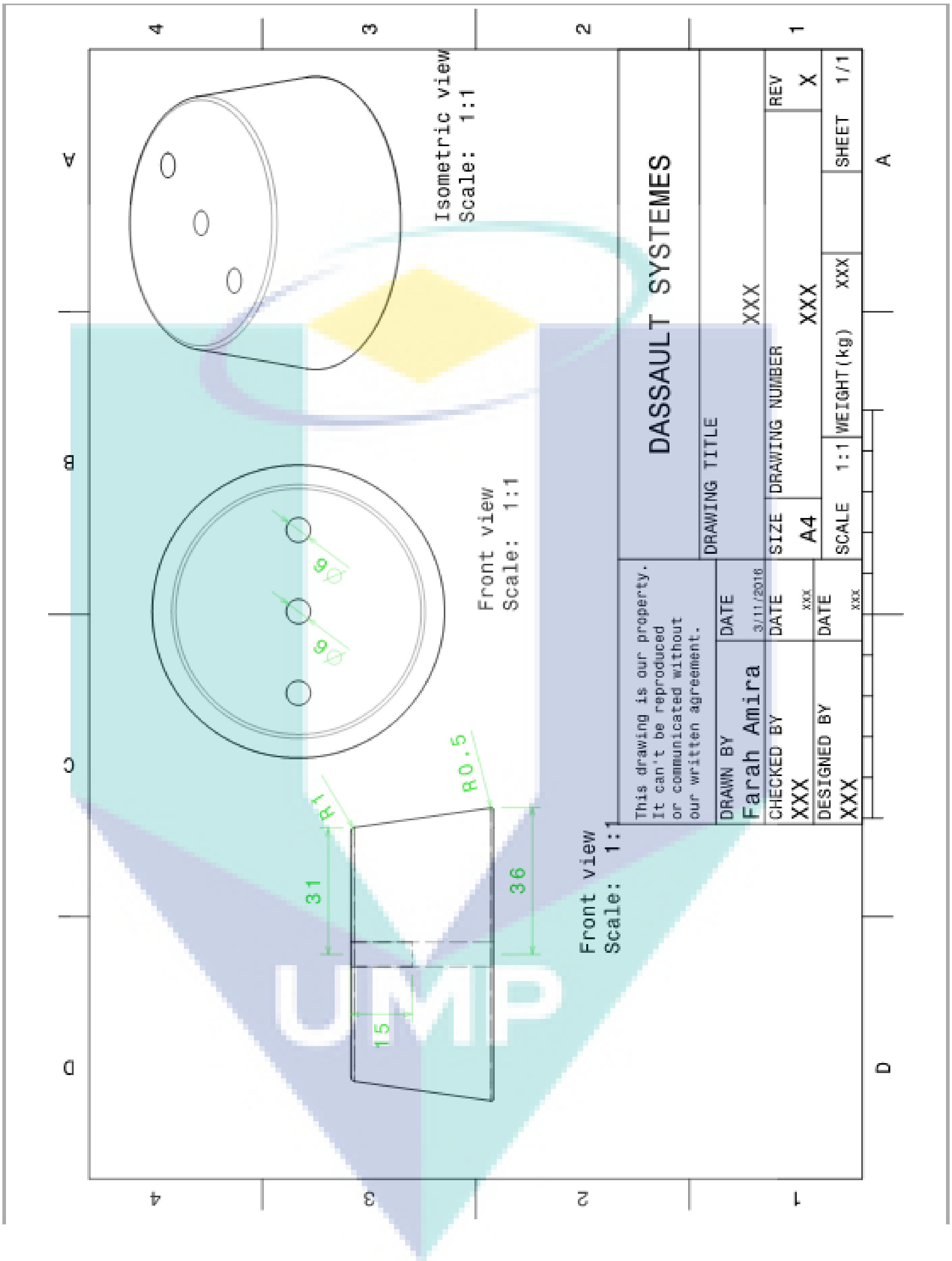
MOULD DESIGNS

Truncated-shaped positive mould

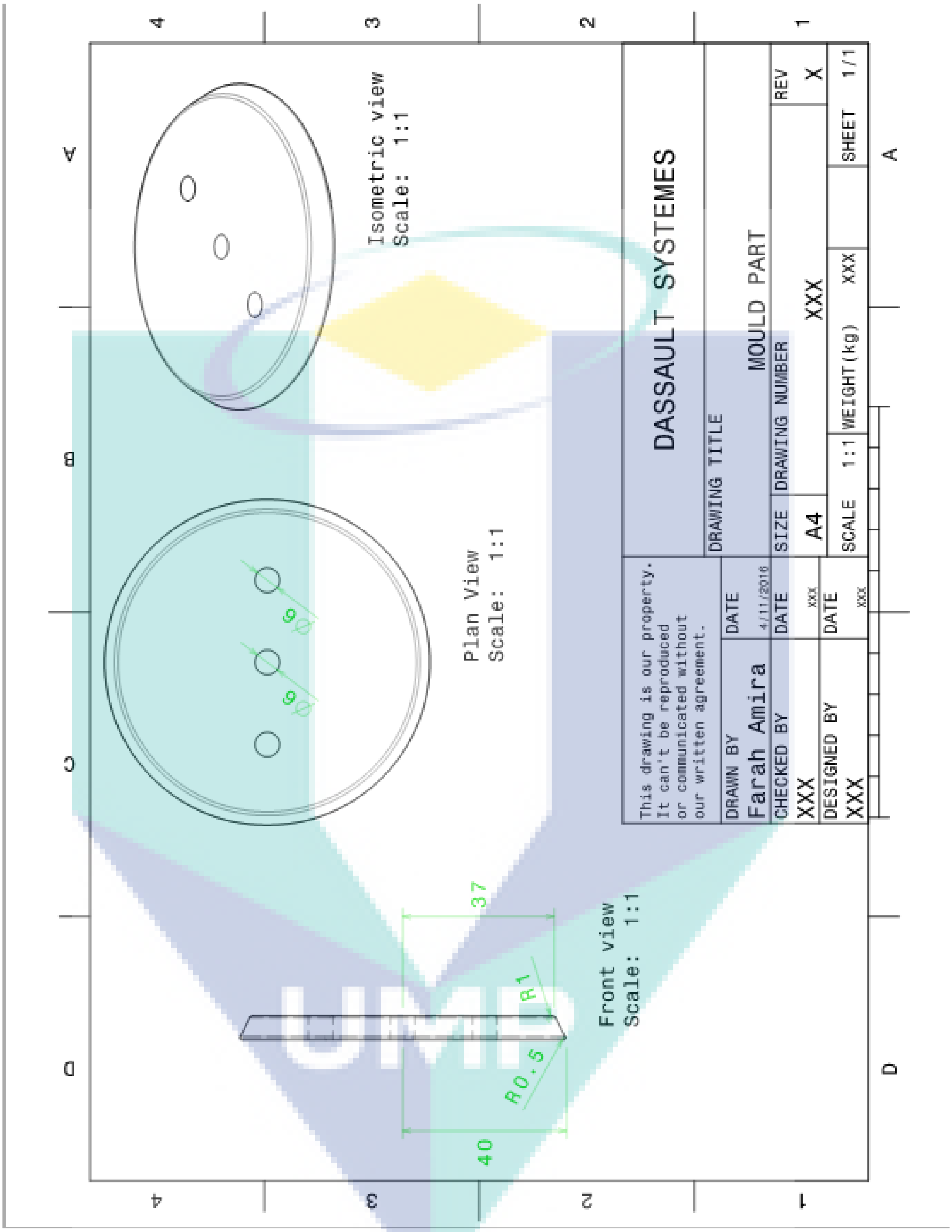
Dome-shaped positive mould



Two-dimensional drawing of upper part of truncated-shaped positive mould with dimensions

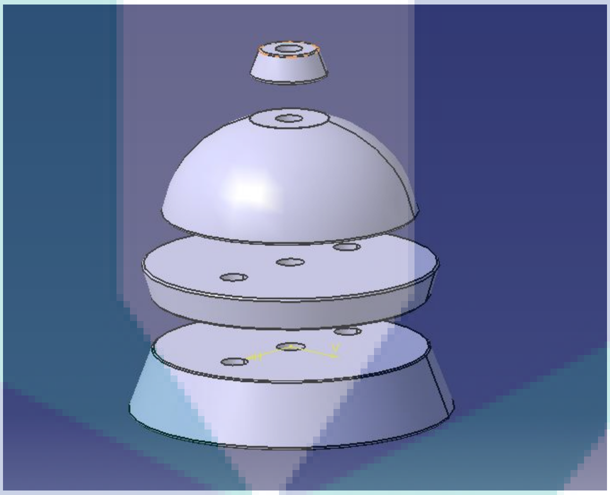


Two-dimensional drawing of body part of truncated-shaped positive mould with dimensions



Two-dimensional drawing of bottom part of truncated-shaped positive mould with dimensions

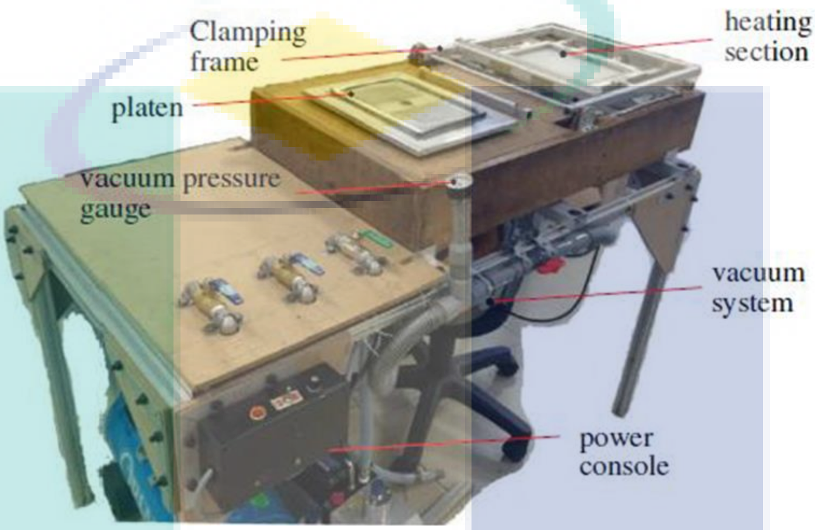
Disassembled modular design truncated-shaped positive mould



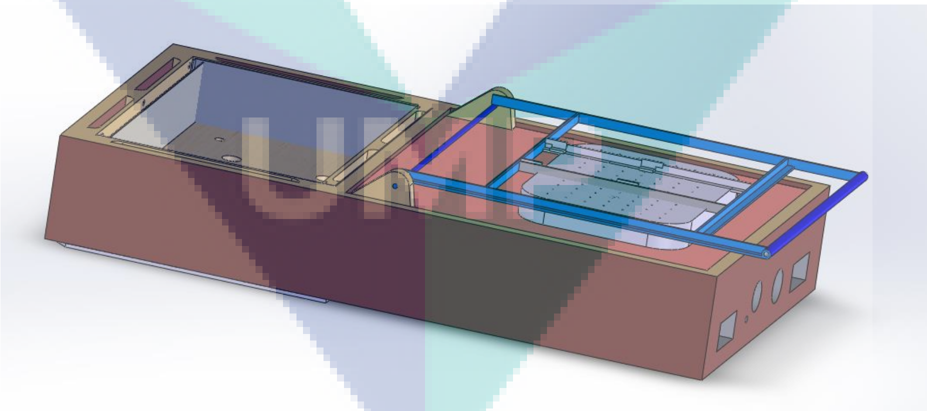
Disassembled modular design dome-shaped positive mould

APPENDIX B

THERMOFORMING EQUIPMENT



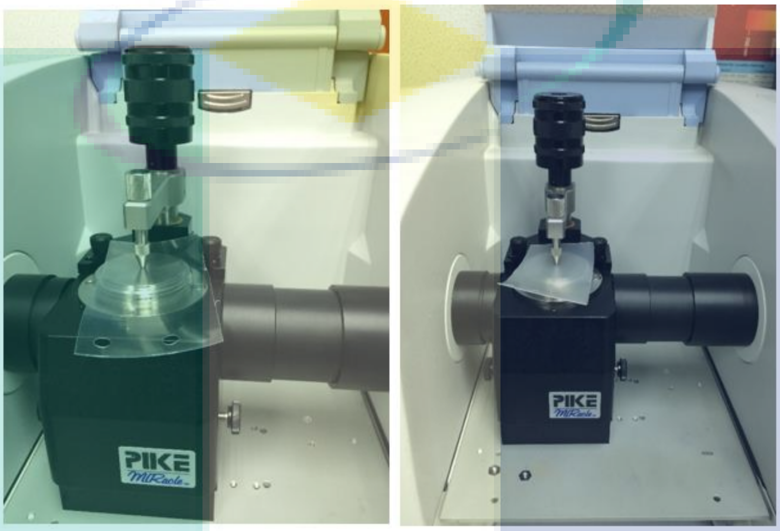
Thermoforming Equipment



CAD of Thermoforming Equipment

APPENDIX C

MATERIAL CHARACTERISATION AND EQUIPMENT

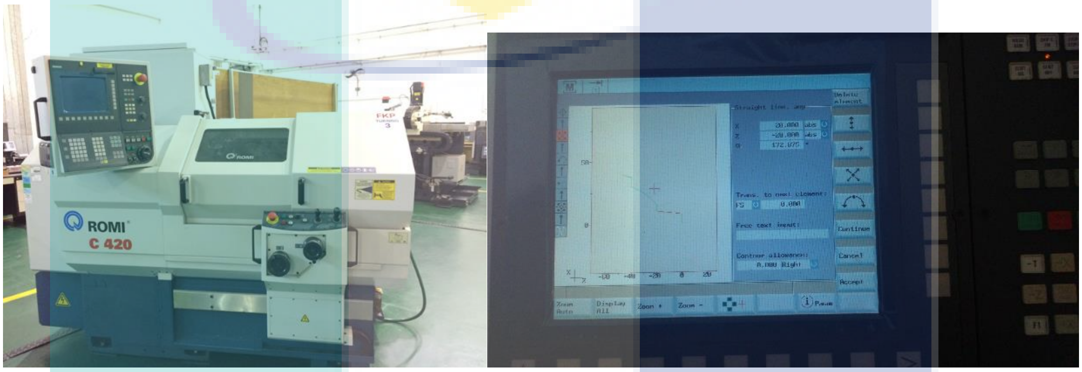


Testing of polymer sample using Fourier Transform Infrared Spectroscopy

Differential Scanning Calorimeter

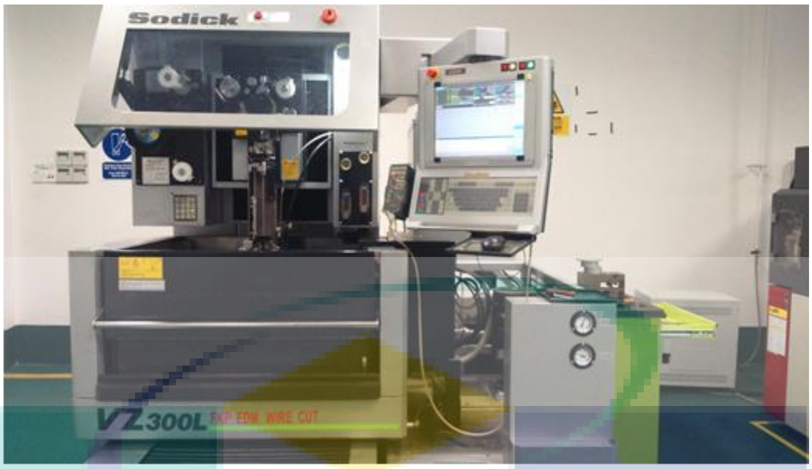
APPENDIX D

MOULD FABRICATION



ROMI C 420 Turning Machine

Mould fabrication process

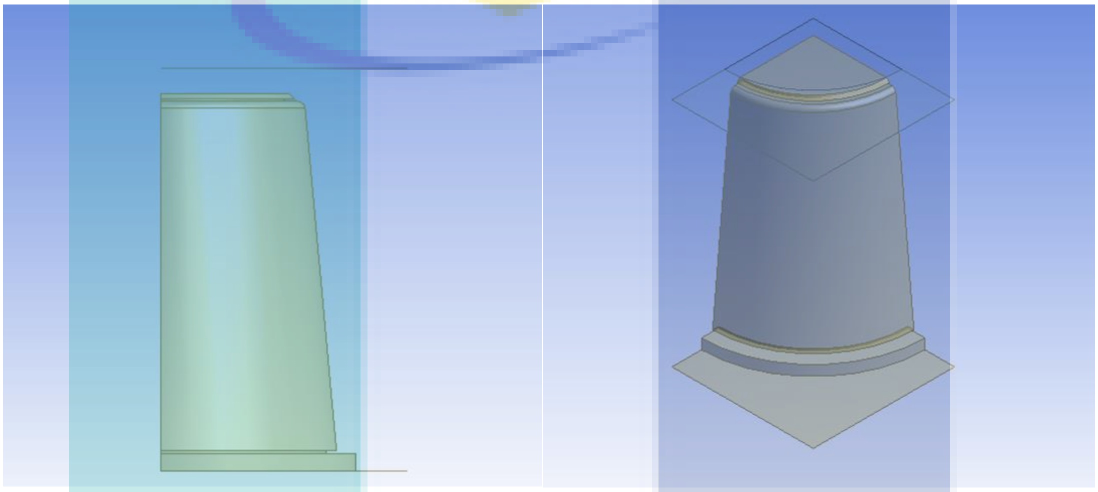


Sodick VZ 300L EDM Wire Cut

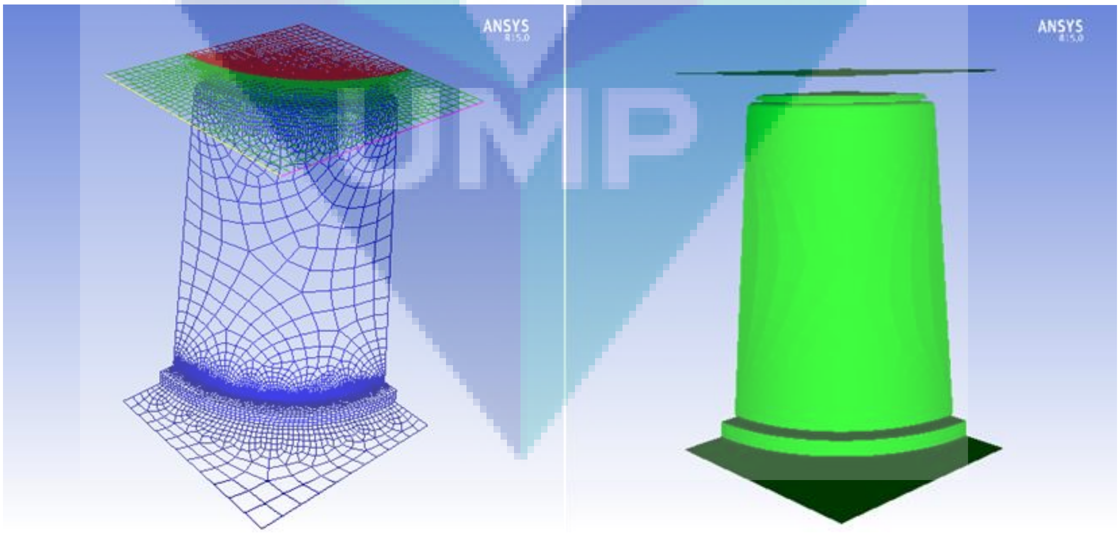
Mould fabrication process using EDM Wire Cut

APPENDIX E

COMPUTATIONAL SIMULATION



Sketching of the positive mould with venting system in Moduler Design



Mesh structure and model of positive mould in computation