STRUCTURAL ANALYSIS OF THERMOFORMED ELECTROLUMINESCENT PRINTED LIGHTING

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABREAVIATION

EL	Electroluminescence
PET	Polyethylene Terepthalate
PC	Polycarbonate
SEM	Scanning Electron Microscopy
CAD	Computer Aided Design
EDX	Energy Dispersive X-ray
T_g	Glass transition temperature
q	Heat flux
q_c	Temperature independent heat flux
α	Heat convection coefficient
T_α	Reference temperature of the convective heat exchange
T	Temperature at the boundary
σ	Coefficient of radiation
T_σ	Reference temperature for radiative heat exchange
T_0	Non-zero reference temperature

ABSTRAK

Elektronik bercetak ialah teknologi baru yang mencetakan peranti elektronik ke atas pelbagai jenis substrat. Fleksibiliti elektronik bercetak telah membolehkan pembentukan peranti elektronik yang tercetak pada substrat yang fleksibel. Proses termopembuatan telah diperkenalkan ke dalam proses pembentuk bahan electroluminasi(EL) yang tercetak pada substrat plastik. Objektif utama projek ini adalah untuk mengkaji kesan termopembuatan pada termoplastik bercetakan electroluminasi dengan menggunakan simulasi ANSYS Polyflow dan mikroskop elektron pengimbas. Simulasi proses termopembentukan telah dijalankan pada lembaran polietilena tereftalat(PET) untuk mendapatkan taburan ketebalan pada lembaran polietilena tereftalat yang disimulasikan. Pada masa yang sama, produk yang dibentuk telah diuji menggunakan mikroskop elektron pengimbas untuk mendapatkan taburan ketebalan produk tersebut. Hasil daripada kedua-dua pendekatan ini telah menunjukkan perbezaan dalam ketebalan di kawasan yang berbeza. Bagaimanapun, perbezaannya boleh diterima disebabkan reka bentuk acuan yang rumit dan berlengkung. X-ray tenaga bersebar telah dijalankan untuk menentukan komposisi elemen dalam produk yang terbentuk. Keputusan menunjukkan bahawa taburan bahan EL adalah tidak merata selepas proses termopembuatan tetapi lapisan bahan electroluminasi masih boleh dikesan dengan menganalisiskan komposisi elemen. Kesimpulannya, proses termopembuatan ialah proses yang sesuai untuk membentuk elektronik bercetak pada substrat termoplastik.

ABSTRACT

Printed electronic is an emerging technology which the electronic devices are printed on various type of substrates. The flexibility of the printed electronics have enabled the shaping of these flexible electronic if they are printed on flexible substrate. Thermoforming process has been introduced into the shaping of printed electroluminescent(EL) on the plastic substrate. The main objective of this project is to study the effect of thermoforming on the EL printed thermoplastic by utilising ANSYS Polyflow simulation and Scanning Electron Microscope(SEM). Simulation of the thermoforming process was done on a polyethylene terephthalate(PET) sheet to obtain the thickness distribution on the simulated PET sheet. At the same time, the thermoformed product was experimented using SEM to obtain the thickness distribution of thermoformed product. The result from both approach showed that there were different deviations in thickness at the different area of the thermoformed product. However, the difference was acceptable due to the complex and curvature design of the mold. Energy dispersive X-ray was done to determine the composition of element in the thermoformed product. The results showed that the distribution of EL materials were uneven after thermoforming process but the layers could still be detected by analysing the composition of element in the layers. In conclusion, thermoforming process is a suitable process for the shaping of printed electronics on the thermoplastic substrate.

CHAPTER 1

INTRODUCTION

1.1 Background

Recently, printed electronics have became an emerging technology in the electronic industry. According to “Flexible, Printed and Organic Electronics 2019-2029” researched by IDTechEx in 2018, the total market for printed, flexible and organic electronics in 2018 is $31.6 Billion[1]. Among these technologies, printed electronics is considered as a potential field that can replace current traditional lighting such as light emitting diode and light bulb.

Printed electronics is fabricated by printing the electronic device on a variety of substrates. The printing methods use the functional ink with traditional printing methods such as screen printing, inkjet, offset lithography, and gravure. By utilising these printing techniques, electrically functional electronic and nanopowder ink can be deposited onto the various substrates like paper, plastic film or metal.

Printed electronics are being applied in various fields. In display field, printed electronics is utilised to produce flexible screen. In labels and information fields, printed electronics is used in the radio frequency identification(RFID) labels. This enable the information of consumers to be stored electronically in a small tags. In smart packaging industry, printed electronics labels help in the inventory management. Moreover, printed electronics are being applied as lighting fixtures in automotive and medical fields.

Printed electronics is cost effective as the printing methods only requires low cost. At the same time, these methods are easy to be implemented for production and integration purpose. The printed materials are also very thin, light and flexible which means less weight and more flexibility. Therefore, these technology have been widely applied for mass production and certain non conventional electronic device like flexible displays.

Electroluminescent(EL) is one of the category of the printed electronics. EL material will emit light when an electric field is applied. EL materials is screen printable and has long-time stable light emitting. It also has low power consumption and low heat generation. Thus, it is used in electronic equipment, advertisement and decorative purpose.

As EL material is screen printable on various substrate, it can be shaped into any type of design. This unique characteristic of EL has introduced the printing electronics technology with thermoforming process. During the process, the substrate will be heated to a forming temperature and then followed by the shaping process. The final products will be substrate sheet with printed EL materials in desired shape. This technology is an area of interest to be explored and developed.

1.2 Problem Statement

In the electronic industry, the current traditional lighting are the light emitting diode(LED) and light bulb. However, light bulb produce a lot of heat energy and LED is a spot light source which only suitable for small area. Therefore, printed EL technology is proposed to replace conventional light bulb in automotive industry.

EL material has the advantage of flexibility. It can be printed onto flat thin panels through screen printing. After screen printing, the EL materials with the substrate can be thermoformed into any desired shape. However, this process may affect the properties of the EL panel which consists of EL materials and thin panels. Therefore, experiments are conducted to investigate the effect of thermoforming on the EL printed thermoplastic sheet.

1.3 Objective

Objectives of this research are:

1. To simulate the thermoforming process on the printed electroluminescent film.
2. To compare the thickness distribution from simulation results with the experimental results.
3. To investigate the effect of themoforming process on the microstructure of the printed electroluminescent film.

1.4 Scope of work

In this research, the main focus is to determine the effect of thermoforming process on the printed EL film. Therefore, two methods are utilised in this process. Firstly, Scanning Electron Microscopy(SEM) is performed to determine the thickness distribution and microstructure of the printed EL film. The microstructure of EL film before and after thermoforming can be compared and analysed. The thickness at different sections of thermoformed EL film can also be compared. Secondly, ANSYS Polyflow software is used to simulate the thermoforming process of the printed EL film. The result of simulation is used to check the thickness distribution of the thermoformed EL film. The results from both methods will be utilised in determining the effect of thermoforming process on the printed EL film.

1.5 Thesis structure

There are five chapters in this thesis. In the first chapter, the background of printed electronics, problem statement, objective and scope of work of thesis are stated.

In the second chapter, literature studies on electroluminescent and thermoforming are discussed. The structures of EL film, working principles of EL substrates and procedures for thermoforming are discussed in details.

In the third chapter, the methodology approach are discussed. The experiment setup and thickness measurement of samples are explained. The simulation procedures for thermoforming are highlighted.

In the fourth chapter, the experimental results from SEM are compared to the results from simulation. The difference in the results are discussed.

In the fifth chapter, the conclusion are made based on the objectives and results. Some recommendations are suggested for future work purpose.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Printed EL technology is an area that is to be explored. The screen-printable EL materials can be printed on various substrate and this EL film can emit light once electric field is applied to it. Then, this EL film can be processed into any desired shape through thermoforming process. Therefore, further information on the EL materials, type of substrates and steps in thermoforming process should be investigated.

2.2 Electroluminescent

2.2.1 History of EL

Electroluminescence was first discovered by an English engineer Captain Henry Joseph Round in 1907. He discovered the generation of yellow light when electric current was passed through silicon carbide. In 1936, a French engineer named Georges Destriau had recorded another observation on emission of light from zinc sulfide (ZnS) powders when an electrical current was applied. He then coined the term "electroluminescence" for the phenomenon observed.

During World War II, a lot of research were done on phosphors and transparent conductive films but the research focused mainly on military purposes. During 1950s, research was done mainly on powder EL phosphors and a United States manufacturer of electrical devices named GTE Sylvania had created the first ceramic electroluminescent lamp. However, the product lifetime was too short (around 500 hours) and thus the commercialization of EL technology had failed.

In the late 1950s, Vlasenko and Popkov had fabricated the first thin-film EL(TFEL) structures. The luminance was much higher in thin film EL (TFEL) devices than the previous powder EL. In 1974, Toshio Inoguchi and his colleagues at Sharp Corporation introduced an alternating current (AC) TFEL display that consist of Zinc Sulfide doped with Manganese (ZnS:Mn) as the phosphor layer and Yttrium

Oxide (Y2O3) as the sandwiching insulators. This product was the first high-brightness long-lifetime electroluminescene display(ELD) made.

During that period, the main issue of ELD was that it could only display one colour. In 1981, Okamoto from Osaka University reported that Zinc Sulfide that was doped with rare-earth could be applied in the phosphor layer of a TFEL device to produce red, green and yellow colours. In 1984, William Barrow and his colleagues from Planar reported that the blue-green emissions can be obtained through strontium sulfide doped with cerium (SrS:Ce). In 1986, Shosaku Tanaka and his group introduced the concept of the ‘colour-by-white’ TFEL device. In this device, a broad-band (white) luminescence was produced and the three primary colours would then be extracted using passive striped filter. [2]

In 1990s, ELD field had achieved a major success. Planar International announced that a SrS:Ce/ZnS:Mn white phosphor deposited by atomic layer epitaxy achieves sufficient luminance and stability for use in color EL display products. The company was then commercialized the fullcolour ELDs in the form of active-matrix (AM) microdisplays. [3]

After that, more variety of ELD products were marketed. Thick dielectric EL(TDEL), organic light emitting diode(OLED) and active matrix EL displays were marketed as the technology of EL kept advancing. Today, ELD is still developing and contributing to the flat panel display market.

2.2.2 Working principle and structure of EL

Luminescence is the spontaneous emission of light from the excited electronic states of physical systems. This excitation can be produced by various different agents such as chemical, light and electric field. The excitation by an electric field is therefore known as electroluminescence. [4]

Electroluminescence is the non-thermal generation of light from a material when a high electric field is applied to it. Generally, the light emission happens due to the electronic relaxation process. When high electric field is applied, charge carriers are injected into the phosphor layer in the EL material and these energetic electrons will excites the luminescence centres of the phosphor layer. The luminescent centres will then undergo radiative relaxation and the phosphor layer will emit lights.

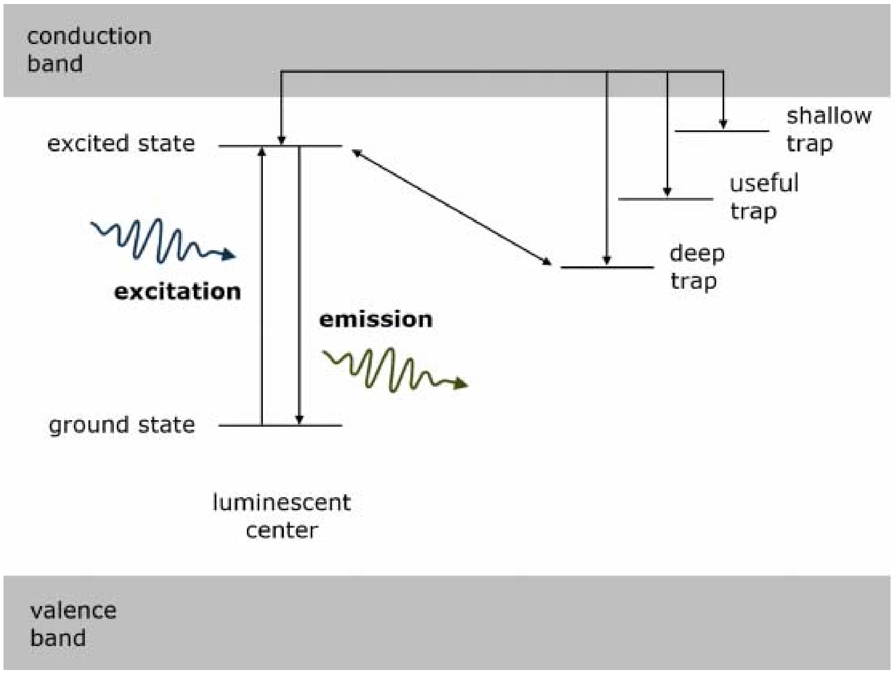

Figure 2.1: Excitation and relaxation of luminescent centre[5].

There are two categories of EL namely Injection EL and High-field EL. Injection EL generates light through direct injection and subsequent recombination of electron-hole pairs at a p-n junction. For example, the minority carriers are injected into a forward biased p-n junction and recombine with the majority carriers across the band gap of crystal. This mechanism is applied in light emitting diode (LED) and laser.

On the other hand, High-field EL requires charge carriers accelerated by electric field to excite the luminescence centre and generates light emission through the atomic transitions localised at the luminescence centre. The high energy electrons raise the centre to excited quantum state and the excited centre will then relax to ground state through radiative relaxation process. For High-field EL, there are powder phosphor EL that is used in EL lamps and thin-film EL that is applied in EL display panels. [6]

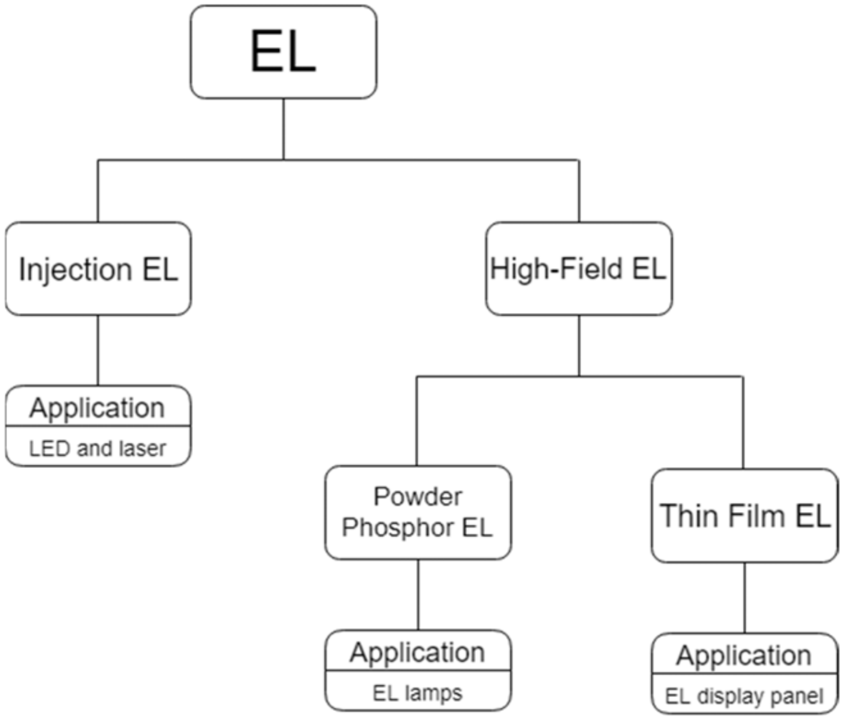

Figure 2.2 : Types of EL and the applications of each types of EL[6].

A standard EL is printed with multiple layers of different substrates. The upper layer usually consist of indium tin oxide(ITO) coated polyester film. The low resistance ITO coating and transparent polyester film is utilised to form a conductive and transparent layer on top of other layers.

The second layer is the phosphor layer which converts electrical energy to light. Phosphors are usually made from a suitable host material with an added activator. Some common types of phosphor layer are zinc sulphide doped with activator like copper(Cu) and aluminium(Al). Different activator in zinc sulphide(host material) will result in different emissions of colour.

The third layer is the dielectric layer which is highly resistant to the flow of electric current. The two main types of material applied are amorphous oxides or nitrites and ferroelectric materials like barium titanate ($BaTiO_3$).

The bottom layer is the rear conductor which consists of the printable silver electrode ink conductor. As opacity is no longer a concern in the rear conductor, silver is used as it has high electrical conductivity.

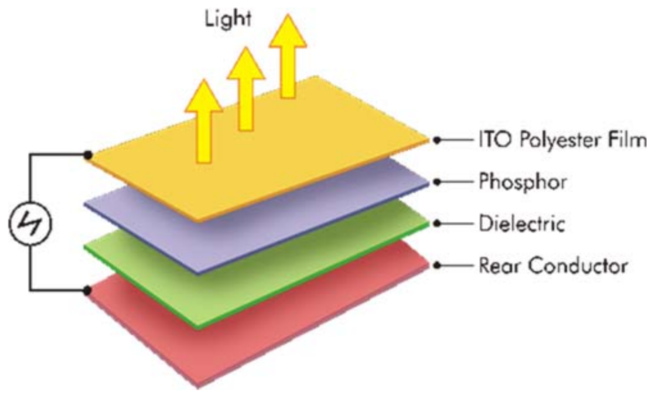

Figure 2.3 : Layers of substrates in EL[7].

2.2.3 Current trend of EL

Currently, EL is applied in various purposes such as lighting, safety, decorative and commercial purpose. For example, EL materials are used for production of light box, flexible display and car speedo meter dials in the market. EL materials has the advantage of low wattage consumption and operation without any external circuitry. Another main feature of EL is the flexibility and stretchability. This feature enable EL to be manufactured into flexible panel, narrow strings and other small objects.

Deformable electroluminescent(EL) device is flexible and stretchable. The mechanical conformability in these EL enable the application of EL in rigorous mechanical conditions such as stretching and folding. For example, stretchable EL is wrapped onto curve surfaces in soft interactive display system. These EL devices are made from rigid inorganic light emitting diode(ILED) and stretchable electrical interconnects on elastomer. The stretchable electrodes are fabricated by making thin metal into “wavy” structures and bonding them onto elastic substrates. This design of electrodes can relax the strain in the substrates when it is bent or stretched. The light emitting diodes are printed on the elastic substrates and connected to the electrical contacts in the stretchable electrode. As the ILED and the electrodes are connected, the stretchable EL devices can light up even on the curve surfaces.[8]

Figure 2.4 : The “wavy” structure of thin metal[8].

Due to the flexibility of the EL material, it can be printed on different substrates such as paper, textiles and plastic. Printing on non-transparent substrate requires special method. The material for the thick film electroluminescent structure have been modified to nanomaterials such as dielectric and luminophore nanopowders, carbon nanotubes and graphene platelets. This compositions allow the printing of EL on any elastic substrates and not limited to transparent substrates only. The printing EL on paper and textiles have been proven to be fully functional and the device can perform under simple bending test.[9]

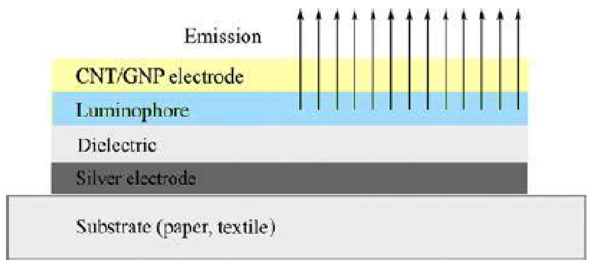

Figure 2.5 : Cross section of the printing structure on non-transparent substrate[9].

On the other hand, the implementation of EL display on the plastic card was done through the new lamination method. In this method, the polycarbonate foils are deposited with transparent electrodes, dielectric and luminophore ink using spray coating technique. Then, the silver nanopowder ink is printed as the bottom electrode with an ink-jet printer. Lastly, the lamination process is done using uniform pressure in all process area. This method only require printing and laminating process without the need of additional processes.[10]

Electroluminescent material can even be utilised to make a flexible display named "Smart Foil Display" which can be used as traffic signaling system and message displaying system. Cyclist or skaters can insert this foil display into their bags to show their turning or braking signal in the less visible environment. The display can be controlled wirelessly through smartphone applications to display messages like names and email. This implementation of EL display system allow the production of devices with reasonable technical properties.[11]

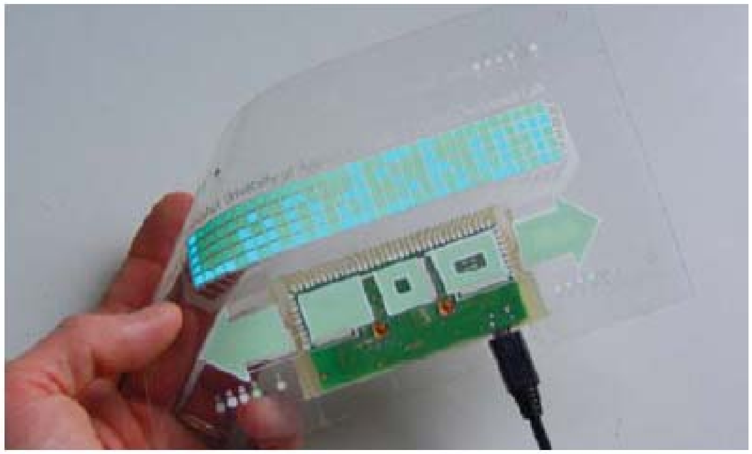

Figure 2.6 : EL display module with circuit board[11].

Currently, more and more researches focusing on the flexibility of EL materials are carried out to develop EL technologies including printing technique. For example, researches have been done for the application of EL as rear light of car. The application may reduce the complexity of the manufacturing process for rear light of car and thus save the cost. From these applications, EL technology will become mature and being applied in more field in the future.

2.3 Thermoforming

Thermoforming is an industrial process which form the thermoplastic sheet into the desired shape by utilising the suitable heat and pressure condition. This process is used widely in the manufacturing industries due to the low cost and the feasibility with almost all thermoplastic. For example, thermoforming are used in manufacturing packaging and disposable products that deals with plastic.

Thermoforming can be defined as the heating, shaping and cooling of thermoplastic. The thermoplastic is heated until pliable and stretchable before it is being shaped. Then, the thermoplastic is cooled and being postprocessed.[12] These processes have to be carried out at the suitable temperature and pressure for an suitable period depending on the types of materials.

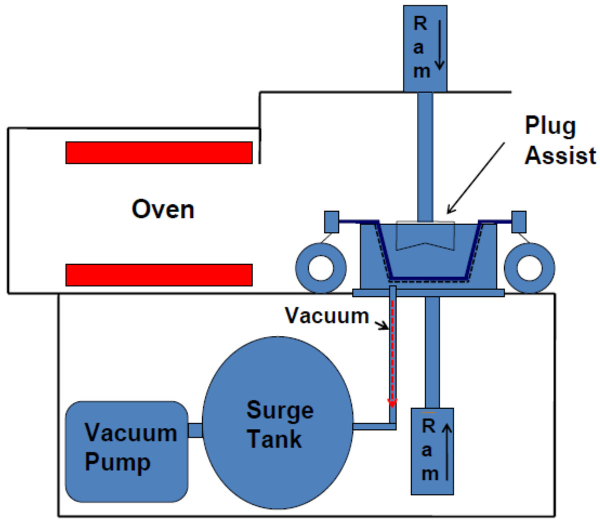

Figure 2.7 : Thermoforming machine[13].

The first procedure in the thermoforming process is the heating of thermoplastic sheet. The heating of thermoplastic must achieve the forming temperature of the thermoplastic which is the temperature which the molecules of thermoplastic can be relocated. At this temperature, the thermoplastic sheet is stretchable and it can be shaped by the forming process. However, plastic is a heat insulator and thus specific heating method is necessary to heat the sheet evenly. Therefore, the distance between heat source and thermoplastic sheet, the thickness of the sheet and the forming temperature of the sheet have to be determined to ensure even heating of the sheet.

Table 2.1 : Common thermoplastic materials and their forming temperature[13].

Material	Forming temperature(F)
Acrylic	350
Polycarbonate	375
Polyethylene Terephthalate(PETE)	300
High Density Polyethylene(HDPE)	295
Low Density Polyethylene(LDPE)	285
Polypropylene(PP)	320

The second step in thermoforming process is the forming process. There are four main types of forming method namely mechanical forming, vacuum forming, pressure forming and the combination of all. Mechanical forming is done by two mold closing the sheet and the sheet will be shaped according to the shape of the two molds. Vacuum forming creates a vacuum region under the sheet and utilise the atmospheric pressure to press the sheet into the mold. Pressure forming is similar to vacuum forming, but it uses compressed air which have much higher pressure than atmospheric pressure. Last but not least, the combination of the three method is used to produce the best quality products with fine details. Plug-assisted thermoforming is an example which utilise both mechanical plug and air pressure into the shaping process of the sheet.

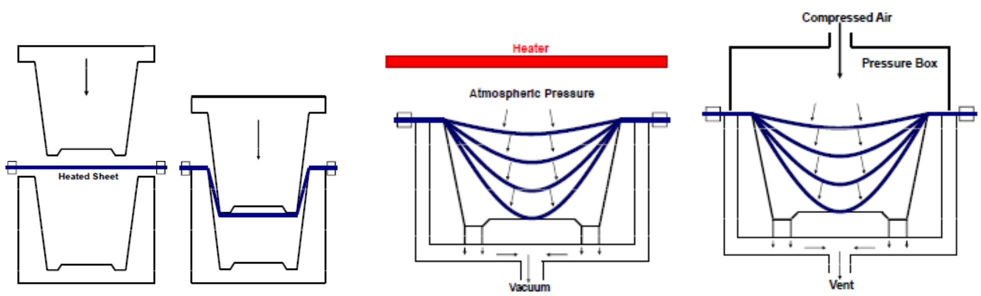

Figure 2.8 : Mechanical(left), vacuum(middle) and pressure forming(right)[13].

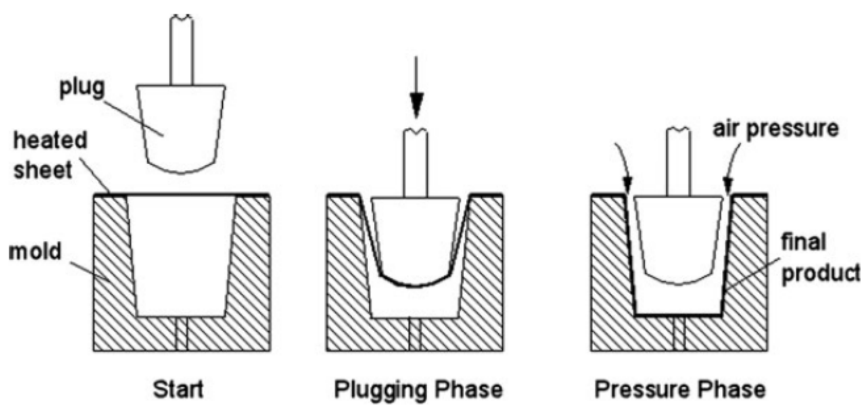

Figure 2.9 : Plug-assisted forming process[14].

The third procedure is the cooling process after the desired shape is formed. The cold mold surface absorbs heat from the hot shaped thermoplastic through conduction. Then, the mold surface is cooled by the water in the drilled passage in the mold. This sequence of heat removing steps may occupy different length of time depending on the temperature of the thermoforming and the thickness of the formed thermoplastic. After the cooling process is completed, the thermoplastic is removed from the mold surface. The thermoplastic is postprocessed and the final product is formed.[13]

Thermoforming process is an effective and productive method in forming thermoplastic into any desired shape. The feasibility with almost all thermoplastic enable it to be applied widely in the industry. This advantage enables the printed electronics on plastic substrate to be thermoformed into various shapes. Therefore, the application of thermoforming in the industry can be investigated in more detailed.

2.4 Parameters effect on thermoforming process

Ideal thermoforming product should have an even thickness among all the wall but there are many factors that will affect the thickness distribution. These factors can be divided into two main categories namely the material parameters and process parameters. Material parameters are the properties of the substrates, mold and plug design while process parameters are the air pressure and mold temperature.

In the plug-assisted thermoforming, the variation in plug design can affect the final product. The plug design can be different in sidewall taper, base radius and plug diameter. A slight increase in sidewall taper angle does not affect the base wall distribution but increases slightly in the sidewall while large increase causes an extremely thin base and a thick sidewall which is not desirable.

The increase in the base radius shows a trend of reducing base thickness and increasing sidewall thickness as more material is pushed to the sidewall when the roundness is present at the base of plug. Next, the decrease in the plug diameter reduces the thickness in the lower part of the plug. The thickness increases at the sidewall and lip part of the product. From these observations, a small changes in the three parameters mentioned above can produce a more even wall thickness distribution while large changes will cause over-thinning problems to the product. [14]