LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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COMPARISON OF THERMOFORMING MACHINERY BETWEEN EUROPE AND CHINA AND RELATED MATERIALS

Examiner(s): Professor Juha Varis
D. Sc. (Tech.) Ville Leminen

ABSTRACT

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Comparison of thermoforming machinery between Europe and China and related materials

Master's thesis

2017

81 pages, 59 figures, 14 table

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Keywords: bio-based plastics, PLA, composite materials, thermoforming, thermforming machinery, mechanical tests

Plastics products exist extensively, and thermoforming is one of the most popular manufacturing methods of plastics in packaging industry. Acknowledging common thermoforming machinery in Europe and China is valuable in describing thermoformed industrial process. This thesis focuses on presenting and comparing thermoforming machinery in Europe and China about production capacity, final product quality and components by the way of literature review. Moreover, fossil-based thermoformed plastics lead to environmental issues and waste disposal problems. Replacing it by some environment-friendly plastics is unavoidable and meritorious. Therefore, the other objective is evaluating materials which is the best among bio-based plastics, PLA and composite materials received from different places with experimental tests approach.

Through a great deal of literature review, Chinese thermoforming machinery is behind European, which mainly represents in three aspects, core components, material requirements and production capacity. Tensile tests, bending stiffness and air permeability are conducted in this thesis to describe some properties of materials, and these materials are PLA, composite materials and bio-based plastics which are similar with LDPE. The result reveals that PLA owns high mechanical performance compared to other conventional thermoplastics with the same thickness, and PLA-250 is the most effective material among these materials.

ACKNOWLEDGEMENTS

This work was accomplished at Lappeenranta University of Technology, Finland, between 2016 to 2017. I am really appreciated to have the chance to express my thankful to whom help me and gave me guidance during this process. Firstly, I want to thank professor Juha Varis, thanks for his advice and comments. I am very grateful to Dr. Ville Leminen and Dr. Panu Tanninen, this project could not be completed without their suggestions and comments. Sami-Seppo Ovaska who assisted me in conducting some experiments several times. His attitude was so patient and he gave me some ideas about tests process.

I would like to thank my teachers in China, who are professor Zhang Lei and professor Jiang Guichang. They always encouraged me and game me a hand. My friends, Yao Qianru and Zhao Fei, thanks for the valuable and precious discussion we had in our apartment.

Søren Emborg, who was from Infiana company in Germany. I really appreciate for his selfless assistance of providing some materials. When I had some questions, he always supported me and answered confusion as much as he can.

The biggest gratitude is deserved to my parents for their concern, encouragement and support about my living and study in Finland. I also wish to thank my friends in China who accompanied me on spending this happiest time via social software.

Zhen Li

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Lappeenranta 11.4.2017

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Area of the sheet [m^2]
m	Mass of the sheet [g]
w	Grammage [g/m^2]

ABS	Acrylonitrile butadiene styrene
APET	Amorphous polyethylene terephthalate
CD	Cross direction
EVOH	Ethylene vinyl alcohol
GHG	Greenhouse gas emissions
GSP	Global sustainable program
HDPE	High density polyethylene
IR	Infrared
LCA	Life cycle assessment
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
MAP	Modified atmosphere package
MD	Machine direction
OEM	Original equipment manufacturer
PA	Polyamide
PA12	Polydodecalactam
PBS	Poly butylenes succinate
PC	Polycarbonates
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Poly hydroxyalkanoates
PLA	Poly lactic acid
PLC	Programmable logic controller
PP	Polypropylene
PS	Poly styrene
PVC	Polyvinyl chloride

PVDC	Polyvinyl dichloride
ROP	Ring-opening polymerization
TEA	Tensile energy absorption
Tg	Glass transition temperature

1 INTRODUCTION

Plastics are kind of pervasive materials in the modern world and they are especially effective due to low cost and satisfactory functions. Plastics are ubiquitous, from packaging automotive and transport, to engineering, to agriculture, and to houseware. (PlasticsEurope 2017.) From figure 1, packaging accounts for a large amount in plastics market.

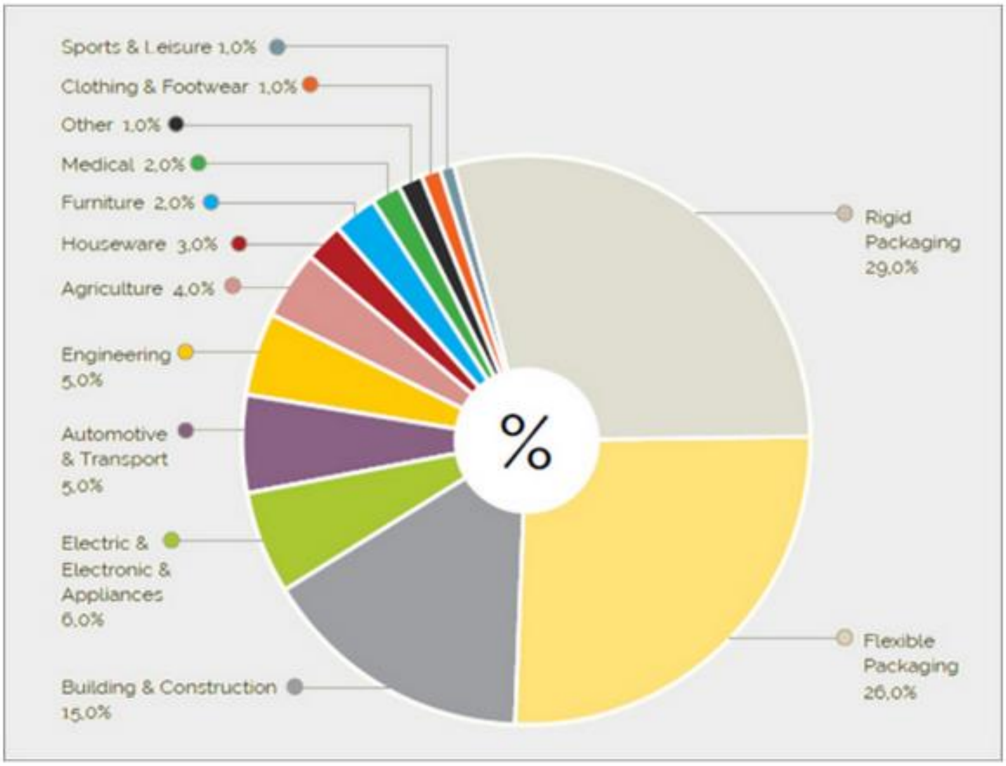

Figure 1. Plastics applications (Plastixportal 2015).

1.1 Background

Nowadays, plastic packaging is almost single-used and only 14% can be recycled. Even though, the reused plastics are just used for lower value applications. Each year, the ocean accepts at least 8 million tons of plastics because of leaking, which means there is a truck of garbage dumping into the ocean per minute. According to number of researches estimate, there are more than 150 million tons of plastics in the ocean. If no actions were taken, there would be 1 ton plastics for every 3 tons fishes by 2025, and the ocean would contain more plastics than fish. The conventional plastics are petroleum based products, which are manufactured with non-renewable resources and some waste is almost non-degradable (Liu et al. 2011, p. 90). 90% plastics are produced directly from petroleum. With the consumption enhancing, carbon influence would be more significant. In 2015, the oil consumption for all the plastics is similar with aviation section, which is 6%. If business as usual, the plastics consume oil would be increased to 20% and it might burden 15% of "the global annual carbon budget" by 2050. Figure 2 is the comparison of Plastics volume, oil consumption and carbon budget in 2014 and 2050. In addition, Plastics always comprise complex chemical substances, and it is reasonable to consider that whether these substances would affect human health and lead to environment impact. (World Economic Forum 2016, p 26.)

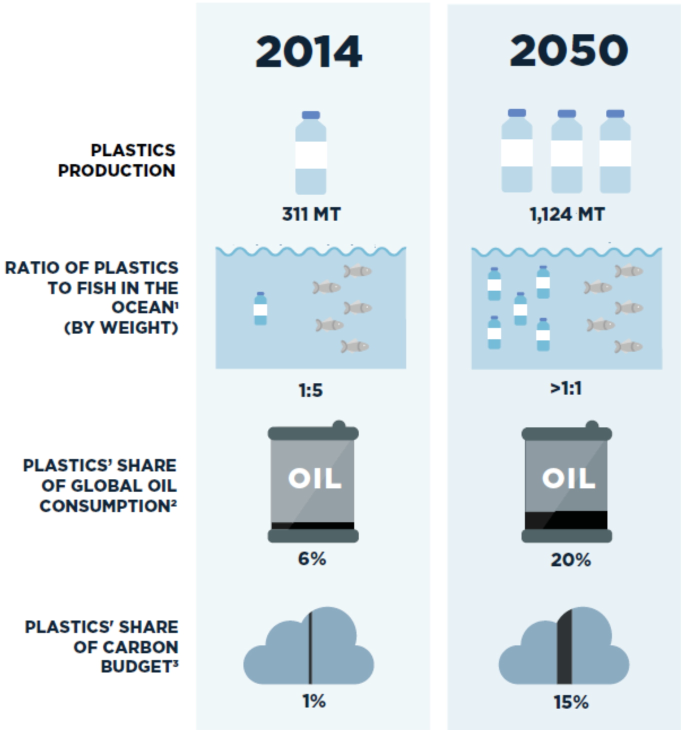

Figure 2. Comparison of Plastics volume, oil consumption and carbon budget in 2014 and 2050 (World Economic Forum 2016, p. 28).

Based on some reasons, bio-based plastics emerged at the right moment. Many countries have realized clearly the valuable meaning of bio-based plastics' profitable functions in biomass resources, energy conservation and emission reduction, and environment protection aspects. And some beneficial measures have been taken.

America regards the bio-based material study as a crucial content in Biomass Multi-Year Program Plan and launches Bio-based and Renewable Industries for Development and Growth in Europe (BRIDGE), aims at accelerating the marketization process of bio-based products (Liu 2014, p. 14). EU Commission has already carried out various EU strategies to support sustainable and effective bio-based plastics. The most important is Europe 2020. (European bioplastics 2017). In China, bio-based materials industry experiences a rapid development, and it has been a popular investment area. The gross output is more than 5800 thousand tons and bio-based plastics is about 800 thousand tons. Bio-based materials has been brought into “Made in China 2025” strategy and it is focused to be one of the most important project in process (Weng 2016, p. 714).

Regarding the final products, thermoforming machine takes part in an important role, such as heating and cooling systems, which determines the properties of final products directly. European and Chinese machinery are the two of the biggest markets in the world. Comparing these is of great guiding significance.

1.2 Research problem

Plastics products exist extensively, and thermoforming is one of the most popular manufacturing methods of plastics in packaging industry. Acknowledging common thermoforming machinery in Europe and China is valuable in describing thermoformed products. Furthermore, conventional thermoformed plastics brings about environmental issues and waste disposal problems. So it is excellent to replace it by some environment-friendly plastics, which is bio-based plastics. But the quality of thermoformed products made of conventional plastics and bio-plastics are not certain.

1.3 Research questions

Based on background of thermoforming materials and thermoforming machinery, the research questions are obvious. What kinds of machinery are used in Europe and China? And what is the difference between thermoformed products quality made of bio-based materials and conventional materials? This report would focus on these questions.

1.4 Objectives of the thesis

The first objective of the thesis is introducing the thermoforming machinery in Europe and China and then, comparing the production capacity, final product quality, cost and other characters. The other objective is testing some materials which are suitable for thermoforming, and measuring some mechanical properties, such as bending stiffness, tensile tests and air permeability. This data is valuable for evaluating thermoforming products quality.

1.5 Research methods

In order to compare the machinery in Europe and China, reading literatures is the way to achieve the results. Some machines are described through some pictures, data and tables. Considering the thermoforming materials, some experiments are conducted to measure some mechanical properties, which are employed in this work to make the objective come true. These experiments are performed in the Laboratory of Packaging Technology, Mechanical Engineering at Lappeenranta University of Technology.

1.6 Outline

The outline of this thesis is as followed:

- Chapter 2 is an introduction to different thermoforming methods, conventional materials and what kinds of products could be manufactured by thermoforming.
- Chapter 3 is an introduction to bioplastics, including bio-based PE (polyethylene) and PLA (poly lactic acid), their production and applications.
- Chapter 4 is a comparison of thermoforming machinery in Europe and China.
- Chapter 5 presents the main materials used in the tests and testing projects.
- Chapter 6 illustrates the results and analysis of the testing projects.
- Chapter 7 exhibits conclusions of the work.

2 THERMOFORMING

Thermoforming is a process in which a thermoplastic sheet is heated above the glass transition temperature after cutting into a certain size and shape, which means plastic under high elastic state. Then applying pressure force to bend and stretch, when it reaches a certain pattern, plastic product is made namely after cooling finalizes the design. (Dai & Zhou 2005, p. 42.)

The heating temperature of sheet is a crucial point during the thermoforming process. If the heating is not enough, forming is difficult to achieve, which may lead to breakage or it is not unable to reach each position. If the heating temperature is too high, the flowing velocity is extremely fast and the wall thickness would be too thin. Cooling always take place in the mold. (Cai & Zhao 2009, p. 57.) The temperature of mold is often controlled by recycled water in channels (Joseph 2013, p. 28). The cooling water temperature could also be maintained by some systems, such as infrared sensor according to Lappe (2013, p. 34) which increases production throughput. The product could not be removed until it is cooled to deflection temperature.

2.1 Thermoforming methods

Thermoforming is a post forming technology based on various kinds of thermoplastic sheets, which comprises of vacuum forming, pressure forming and plug assisted thermoforming. All these forming technologies need force or vacuum to drive thermoplastic sheet against the contour of mold to achieve the final shape. (Shen et al. 2000, p. 37.) The used force types depend on the material type, thickness and parameter, the mold material and design, product characteristics, final product size and the annual production volume (Manufacturing ET. 2017).

2.1.1 Vacuum molding

The thermoplastic sheet or plate is placed on the mold and it is heated to softening temperature. Then the air between the sheet and mold would is drawn through vacuum pump. In this way, the sheet can be against the cavity. When cooled, the sheet will achieve the shape of mold and it is separated with compressed air. (Wang et al. 2008, p. 222.)

Vacuum molding includes male die forming, which mold shape is convex; female die forming, which is concave. Different thermoforming methods will develop various wall thickness. The basic theory is the heated plastic will be stretched, when it contacts the mold, the stretch would be stopped. (Cai & Zhao 2009, p. 57.) Figure 3 describes the process of vacuum molding. The more stretch of material, the much thinner of wall thickness. Thinning always take place with relatively deep female mold, and the thinnest section of the product is the edge and corner of mold due to the most stretch. (Plaram 2017.) The ununiform thickness can be seen in figure 4. Marks, from the mold, also can be developed on the outside of the product. Vacuum molding is suitable for the forming of simple and shallow products.

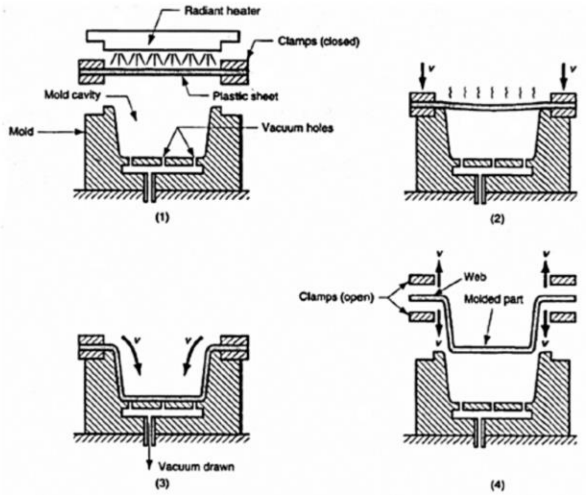

Figure 3. Vacuum molding process (Lappe 2013, p. 32).

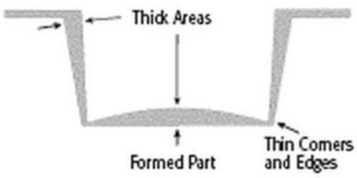

Figure 4. The ununiform thickness of vacuum molding (mod. Plaram 2017).

2.1.2 Pressure forming

In the vacuum forming, the pressure on the bottom side of plastic is near zero, while the pressure on the other side is an atmospheric pressure. Therefore, the maximum forming pressure is one atmosphere pressure (0.1Mpa). In terms of certain applications, this forming pressure is not enough for a good-quality stretching. It is possible to increase the air pressure on one side of plastic if the thermoforming equipment permits. Figure 5 shows how pressure forming works.

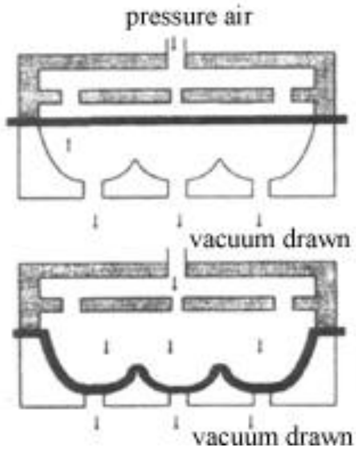

Figure 5. Pressure forming (mod. Cai & Zhao 2009, p. 58).

Pressure forming mold is much durable, made of better manufacturing material and higher price than vacuum forming. Furthermore, the equipment is more complex and expensive. Generally, female die is often used in this process. Pressure forming mainly used for material which is hard to form and some extremely precise components and parts. (Cai & Zhao 2009, p. 59.) In addition, trimming could be completed when forming.

2.1.3 Plug assisted thermoforming

Plug assisted thermoforming usually employs combined female die and plug and forces the plastic to the die cavity. There are two kinds of forming approaches, vacuum forming and pressure forming.

Figure 6 shows the process of plug assisted vacuum forming. A plug with similar shape with mold cavity (but smaller) penetrates the plastic sheet for pre-stretching the material. When the plug platen is about to the bottom of mold, a vacuum is drawn through the mold to attach the material towards the mold surface. Different shapes of plug will create different wall thicknesses of work piece. When the material contacts the plug areas, stretching will be prevented. So the thickness would be much thicker resulting from cooling effect. Therefore, plug design is a vital decisive factor in the final product dimension. (Empire west 2017).

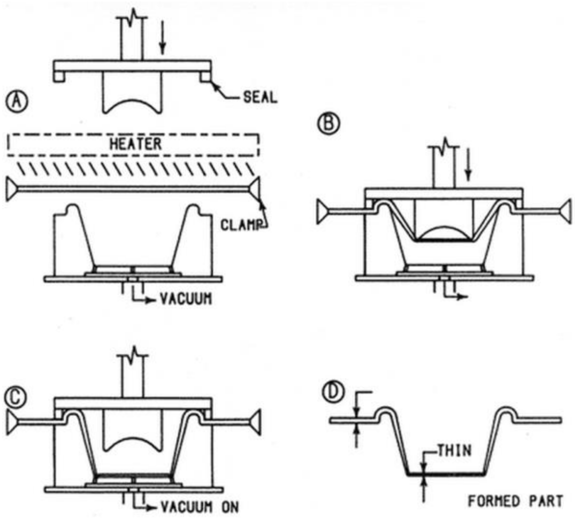

Figure 6. Plug assisted vacuum forming - female (Empire west 2017).

Figure 7 shows plug assisted pressure forming process. This process is similar to plug assisted vacuum forming. When the plug finishes stroke, and reaches the bottom of mold, air between the sheet and mold is output into the atmosphere while air pressure is entered from the upper side. Plug temperature should be taken into account as well.

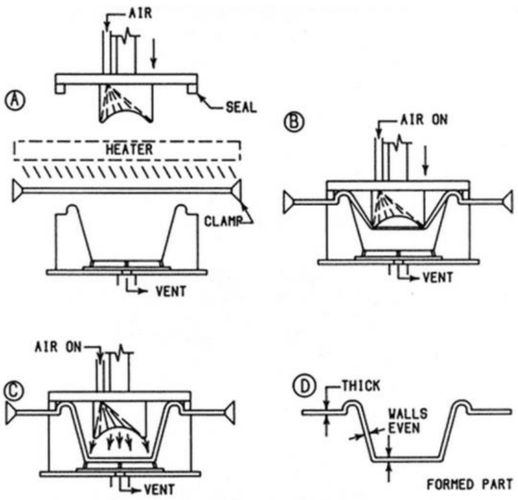

Figure 7. Plug assisted pressure forming (Empire west 2017).

2.2 The conventional thermoforming materials

All thermoplastic materials that are available in sheet or roll form can be thermoformed. Some of the most common materials used in thermoforming are polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE) and composite materials.

2.2.1 PE

Polyethylene is a wax-like thermoplastic whose density is less than water and softens at about 80 to 130℃. It has very good chemical resistance property and it is a remarkable electrical insulator and tough, but tensile strength is secondary. (Ashter 2014, p. 40.)

High Density Polyethylene (HDPE), Linear Low Density Polyethylene (LLDPE), Low Density Polyethylene (LDPE), these are various types of polyethylene. They all have different properties to a certain extent but do have a few shared mechanical characteristics. The shortcoming is the dimensional stability of final products about size and shape. The typical applications always are tanks, ruck bed liners, tote bins, pallets, feed bins. It is obvious that the precise dimensional tolerances and appearance are not strict for these applications. However, these shortcomings can be improved by adding chemical additive.

Polyethylene is very sensitive to cooling stresses and it has high mold shrinkage which means the part will be shrinked after removed from the mold. Usually it is about 2.2% to 3%. Thus plastic tends to shrink and break the vacuum seal when cooling on the mold. Before PE is suggested to put into production, three factors should be think over - cost of a temperature controlling tool, “get the finished tool sandblasted”, and “a moat put around the edge of the tool flange”. (Boser 2013, p. 71.)

According to a literature that the glass transition temperature (Tg) range is 213℃ - 220℃. And some studies found that 220℃ was the highest possible Tg value. For majority of commercial polymer grades, molecular structure contributes to the crystalline melting point which varies from 108℃ to 132℃. (Ashter 2014, p. 41.)

2.2.2 PP

Polypropylene is one of synthetic resins with rapid increased production and widespread application in the world, whose characteristics are small relative density, wide raw material resources, easy recycle, superior mechanical properties, high-temperature resistance, light weight, corrosion resistance, low price, great chemical stability and without odor. Due to the soften point is close to the melting point of crystalline phase, PP sheet is hard to thermoforming. However, with the improvement of thermoforming technology, especially the application of accurate temperature control system and modification with PP, the problem has been settled fundamentally. (Li & Li 2008, p. 7.)

In spite of the shrinkage of polypropylene is less than polyethylene, it relies on processing factors such as cooling time, melt temperature and mold temperature. General speaking, any condition of reduced crystal structure growth has a tendency to decrease shrinkage. High melt temperature results in a highly-disordered melt, so shrinkage values is particularly lower at high melt temperatures. (Ashter 2014, p. 44.) Injection molding is the more widely used forming method than thermoforming. Some vacuum forming moldings are food containers, acid tanks and tool cases inside with living hinges. (Boser 2013, p. 72.)

2.2.3 PET

Polyethylene terephthalate is milky white and semi-transparent or colorless and transparent, whose relative density is 1.38, refractive index is 1.655 and light transmittance is 90%. PET has moderate barrier property and oxygen transmissibility coefficient is 50~90 $cm^3 \cdot mm/m^2 \cdot d \cdot Mpa$, CO_2 transmissibility coefficient is 180 $cm^3 \cdot mm/m^2 \cdot d \cdot Mpa$, Water absorption is 0.6% that means hygroscopic is quite high. Compared with other thermoplastic materials, tensile strength of PET is high, which is nine times than HDPE and three times than polycarbonates (PC) and polyamid (PA). It can be comparable to the aluminum foil. PET sheet is valuable to make various of complex shapes of thermoformed products due to good barrier properties, dimension stability, high transparent, satisfied impact strength, nonpoisonous and tasteless and easy to thermoformed. (Wang et al. 2008, p. 222.) These properties make it different in some fields such as beverage bottles, electronics and electrical parts. It enables to be crystallized and oriented, which will improve the strength of material and then the product properties would be built up.

2.2.4 Composite material

Material composited with different thermoplastics can also be used for thermoforming, such as PS (polystyrene)/PVDC (polyvinyl dichloride)/PE, PS/EVOH (ethylene vinyl alcohol)/PE or PP/EVOH/PP for sterile plastic cup (Li 2000, p. 49), PA/PE or PA/EVOH/PE for thermoformed tray for meat. In addition, PC/PE has a high temperature resistance. PE/PP coated paperboard is safe in microwave food processing field.

These materials often made of anti-static agents, fire retardants, ultraviolet inhibitors and other additives to obtain packaging requirements. Also, multiple-layer thermoplastic sheets can provide more efficient barriers to oxygen and moisture than single layer sheets. Other special properties are also acquired by multiple layers composition.

2.3 Applications of thermoforming products in packaging industry

The features of thermoforming products are thin wall thickness, a large surface area from the tiny packaging box to a large-scale tray, skiff and entertainment car shell. There are numerous types of products such as cups, plates or other daily utensils, medical wares, radio and TV shell, billboards, toys. Except these, there are also auto parts, building components, chemical equipment and so on. Thermoforming products are widely used in packaging engineering, involving in pharmaceutical packaging, chemical packaging, food packaging and so on.

Tray

Generally, pallet package refers to a kind of container with a large area and shallow depth, whose features are suitable for thermoforming (figure 8). As a result, plastic trays are mostly produced in thermoforming method, such as vacuum thermoforming. At present, some thermoformed trays which are made of PP, PS, PE, PVC (polyvinyl chloride) and PET are applied to food packages, such as meat, aquatic product, fruits and pastry. In addition, some trays are specialized used in cryopreservation and microwave heating. (Wang et al. 2008, p. 224.)

Figure 8. Plastic tray (Plastics and Storage Australia 2017).

Plastic cup

The height of plastic cup is much higher than width, which is a sort of deep cavity container. Because the proportion of height and width is close to 1 or more than 1, so it is hard to use the common vacuum forming. Otherwise, the waste rate would be increased and some defects might take place, the uneven thickness and lack of rigidity. In that case, plug-assist vacuum forming is a perfect solution to solve these problems. Plastic cups are usually used in jelly package, yoghurt, ice cream and instant noodle bowl. (Wang et al. 2008, p. 224.) Figure 9 shows the jelly cup package. The most common thermoformed cups materials are HDPE, acrylonitrile butadiene styrene (ABS), PVC, polycarbonate and PP with high impact strength. Each material choice relies on the end user's demand and cost. (Ashter 2014, p. 198.)

Figure 9. Jelly plastic cup package (Tarami 2017).

Blister package

Blister package is sealing the product into the plastic sheet. It includes blister and cover material. Blister package is illustrated in figure 10. The choices of cover materials are PE, PP, PVC films or composite plastic sheet (Al/PE or paper/PE) and glass paper. Sometimes logo or labels are embossed on the cover materials and the printing ink should be bear high temperature (200℃).

Figure 10. Blister package (Shetterstock 2017).

Paper plastic, aluminum, aluminum plastic composition of capsules, tablets, candy or pills block materials from medicine industry, health care products, chemical industry and food industry are all blister packages. In addition, some small toys, hardware, tools and daily necessities, blister package may be adopted. Pharmaceutical blister packages are the most common application in the medical industry. And the chemical stability of the contents is very sensitive to moisture, therefore it is crucial that transmission rate of water should be as low as possible. (Ashter 2014, p. 197.)

3 BIO-BASED PLASTICS

In recent years, with the increasing prices of international raw petroleum and resources shortages, the pressure of petrol supply is higher (Uyama 2013, p. 47). At the same time, white pollution is a serious challenge based on fossil-based conversional plastics. The waste deposit is an urgent mater as well. In this case, low carbon development based on low pollution, low emission and low energy consumption is going to be world tendency with the fact that global climate change has a huge influence on human survival and development (Liu et al. 2011, p. 90). Owing to resource-saving and green, bio-based material is becoming a leading research area to science and technology innovation and economic development in the modern world (Tolinski 2012, p. 181).

3.1 Bio-based materials

Bio-based materials are new materials or chemicals employ renewable material as raw materials such as legume, bamboo, grain, wood powder, and straw. This kind of materials comprise bio-based fiber, plastics produced by biomass thermoplastic processing, bio-based polymer, basic bio-based chemicals, and bio-based rubber. (Weng 2016, p. 711.)

Bio-based materials have a wide range of applications. Main fields are as followed.

- *Medical biodegradable polymer materials.*

  In addition to medical functions, medical material should also safe, non-toxic and good biocompatibility. Biodegradation materials would be hydrolysis or enzymatic hydrolysis into micro molecule after playing an efficient role, and it could be absorption or excretion by human metabolism.

- *Biodegradable material in packaging.*

  Human production and life activities demand for the packaging material consumption greatly. As a result, most plastics are left in nature without degradable, and various countries are realizing an extremely environmental and social problems after industrialization, which is “white pollution”. Nowadays, Coca Cola company utilizes bio-PET to produce bottles, which are environmental friendly and recyclabile (figure 11).

- *Agricultural bio-based materials.*

The primary application is agricultural shed film. Figure 12 shows the film is used in sweet corn. Bio360 is a kind of biodegradable agricultural film, which could be transferred into water, biomass and CO_2 under the function of humidity, temperature and microorganisms in the ground without leaving toxic reside. (Duboisag 2017.)

- *Technology products materials.*

For instance, the automobile industry is going to be green. The typical example is Ford fuel tubes (figure 13). Nylon 11 is entirely derived from castor bean oil, which is now used in fuel tubes. It is benificial to reduce consumption of petroleum by about 4532000 kg/yr and CO_2 emissions by 4985200 kg/yr when compared to PA12 (polydodecalactam). Now, 95% of Ford vehicles are using this product. Ford is leader in technology and first original equipment manufacturer (OEM) to launch in production.

Figure 11. Coca Cola bottle (Reynolds 2015).

Figure 12. Bio-degradable agriculture film (Duboisag 2017).

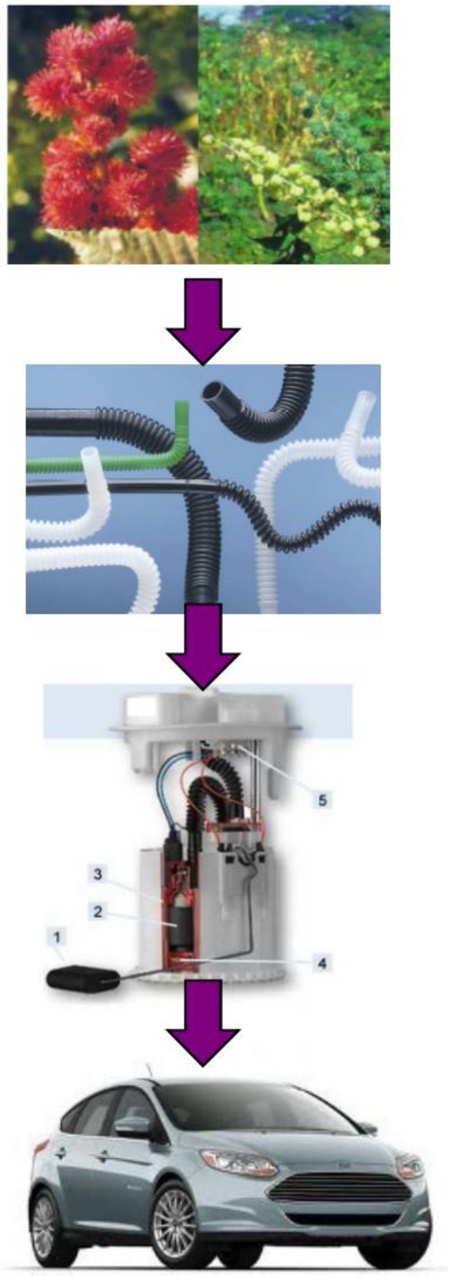

Figure 13. Bio-based nylon 11 usage in Ford fuel tubes (Ellen 2013, p. 25).

3.2 Bio-based plastics

Plastics can be divided into three categories based on different synthetic raw material. Bioplastics synthetic or composite with biomass; fossil-based plastics is made of petrol, coal or natural gas; inorganic plastic is based on limestone, salt, $CaCO_3$ and talc powder. (Wang 2011, p. 95). According to degradability, there are two types of bio-based plastics. One is biodegradable, such as PLA, PHA (polyhydroxyalkanoate), PBS (poly butylenes succinate) and starch blends. The other is nondegradable, the typical products are partial bio-based PE, PET and PA. The difference with conventional plastics is the raw material source which is biomass. The figure 14 vividly describes the plastic groups.

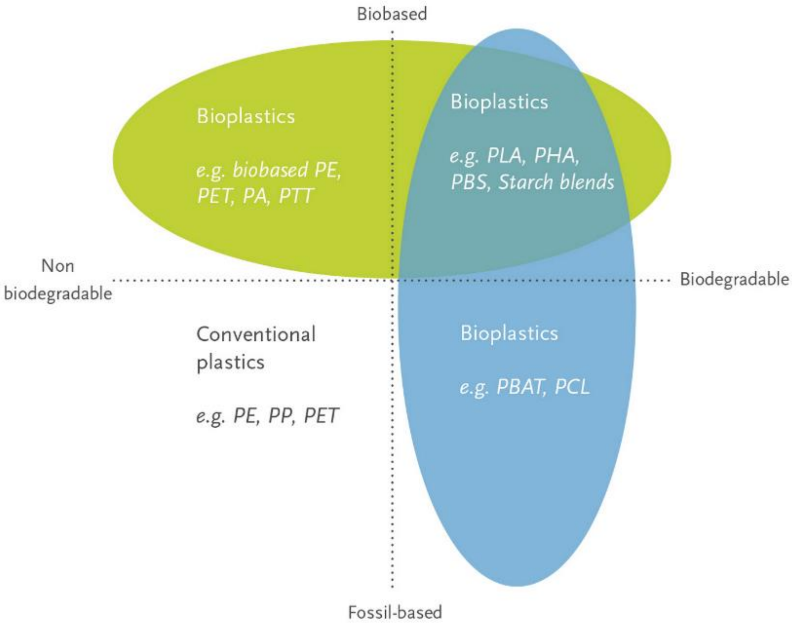

Figure 14. Plastics groups (European bioplastics 2016a).

The reason why bioplastics are non-degradable is that the biodegradable capacity of polymer is determined by their structure and raw materials have no impact on it. Renewable resources make a different in various kinds of polymers, which enable them to obtain special properties and distinguish the levers of degradable. Thanks to microorganisms, bioplastics could be break down or decomposed into some substance which used for feeding microorganisms. Therefore, chemical structure plays a confirmed role during which the process except the environmental conditions. (Voevodina & Kržan 2013, p. 7.)

Compared with petroleum based plastics, bio-based plastics represent competitive advantages, according to Wang (2011, p. 95):

- *Low carbon emission.*

  Biomass absorbs CO_2 in the process of growth and it is therefore carbon neutral. The emission is only 20% of petroleum, which enables it to be low carbon plastics. Applying this kind of plastics make it possible to decrease the CO_2 emission and it contributes to reduce warming rate of earth.

- *Recycle.*

Biomass grows naturally year after year, it is unlimited and inexhaustible. It is abundant resources.

- *Degradation.*

Some bio-based plastics can produce good biodegradability. When it is abandoned, white pollution would not take place.

As Zheng (2015, p. 268) said, the production of bio-based material had been more than 30,000,000 t, and bio-based plastic accounts for a large proportion. As some research conducted by European Bioplastics (2016a), nova-Institute, the global production capacities of bioplastics can be showed in figure 15. As it predicts, there will be 6.11 million tons bioplastics in 2021, which could be used in packaging (flexible and rigid), consumer goods, automotive and transport, building and construction, textiles, agriculture and horticulture, electrics and electronics industries. These applications could be described in figure 16. From this figure, it is easy to find that packaging would still be a promising market for bio-based plastics. According to Ceresana consulting corporation, some forecast report revealed that the benefit of bio-based plastics market all over the world would grow to 5800 million dollars, which means 2 times higher (Liu 2014. p. 14).

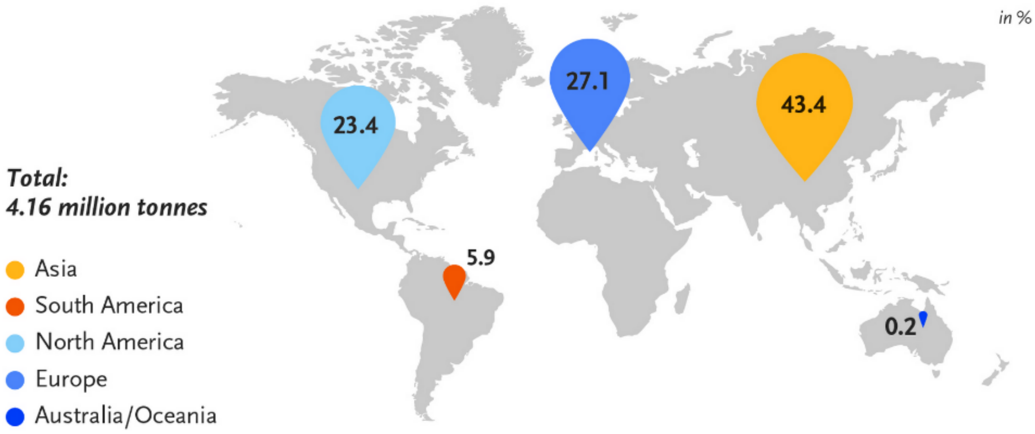

Figure15. Global production capacities of bioplastics in 2016 (European Bioplastics 2016b).

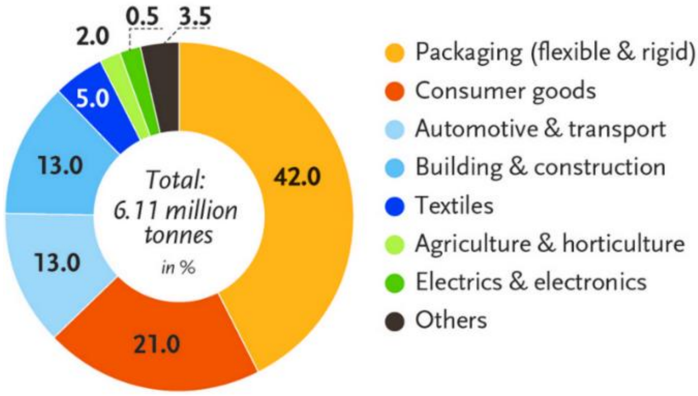

Figure 16. Applications of bioplastic in 2021 (European Bioplastics 2016c).

3.3 Bio-based PE

Bio-based PE has been produced at commercial scale in Brazil From 2010 and the bioethanol is derived from sugar cane. Nevertheless, the raw materials could also be sugar beet, sugarcane brass or starch crops such as wheat, maize or other grains.

Sugarcane-based PE producing process (figure 17) starts with"cleaning, slicing, shredding and milling" the sugarcane stalks. After these, there are always two products left. One is sugarcane juice - the main product with a 12–13% average sucrose content; The by-product is sugarcane bagasse, which is often served as dominating fuel source in the sugar mills. That is because burning bagasse provides sufficient heat to support running a representative sugar mill. Regarding the remaining heat and/or electricity, which could be sold to the grid or industrial users. (Li, Haufe & Patel 2009, p. 113.) Sucrose, also glucose, is fermented to ethanol under oxygen free condition based on the following reaction:

$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 \quad (1)$$

For removing water, ethanol is distilled and to generate an azeotropic mixture of hydrous ethanol (95.5 vol.%). During this process, another byproduct is yielded - vinasse, which is basically served as a fertilizer. In next equation, ethylene is finally coming into being through dehydrating ethanol at high temperatures with a solid catalyst (Li, Haufe & Patel 2009, p. 114):

$$CH_3CH_2OH \rightarrow CH_2{=}CH_2 + H_2O \quad (2)$$

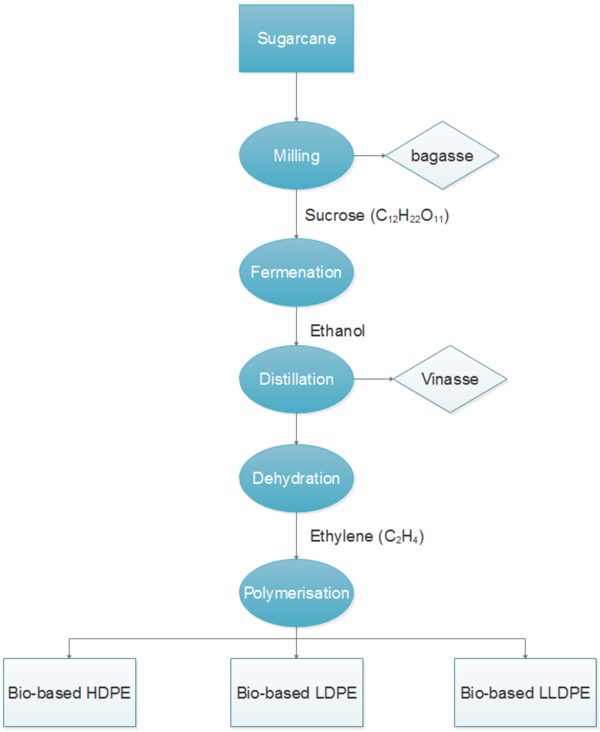

Figure 17. The flowchart of bio-based PE production (mod. Li et al. 2009, p. 114).

International standardization organization suggests use the Life Cycle Assessment (LCA) to evaluate the possible environmental influence related to a product. Collecting the relative inputs and outputs and assessing their impact on environment to illustrate the main part of the study. LCA is mainly used to compare selective processes or products or ensure the production steps resulting in the most serious environmental influence. (Weber et al. 2002, p. 115.) According to Braskem company, LCA is used to compare the environmental influence of bio-based PE and fossil-based PE. Figure 18 shows that producing every ton sugarcane-based PE absorbs 2.15 ton CO_2, while the conventional PE emits 1.83 ton.

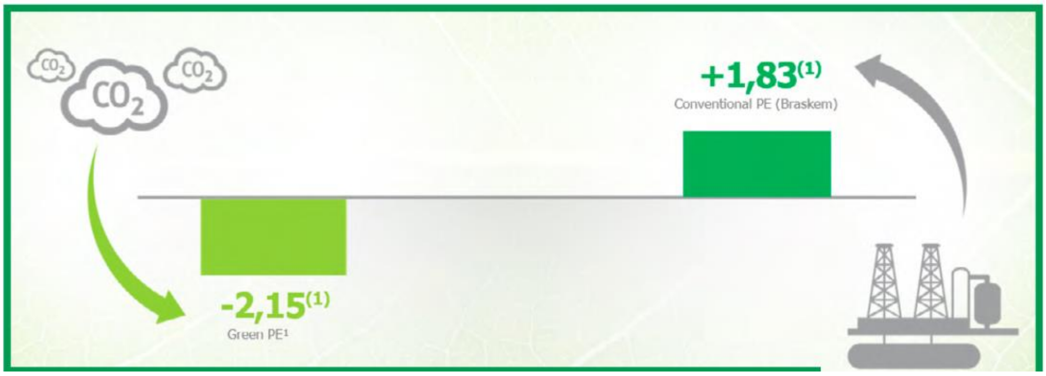

Figure 18. Carbon footprint comparison (mod. Avery Dennison 2017).

3.4 PLA

PLA is an aliphatic polyester produced with good mechanical properties and workability. Thanks to the establish of PLA production plant (Nature Works company) in 2002, enables it became the third commercialized bio-based polymer and it is a mass production at present. The basic component substance for PLA production is lactic acid. However, lactic acid manufactured by fermentation is optically active, and L (+) and D (–) lactic acid with opposite optically actives. They are could be obtained by using specific lactobacillus. L lactic acid is the most common usage to produce PLA. Hence, the abbreviation PLLA is often used. (Johansson et al. 2012, p. 2521.)

3.4.1 Lactic acid from a carbon substrate

Lactic acid is made of anaerobic fermentation of microorganisms such as bacteria or some fungi based on carbon sources, either pure (sucrose and glucose) or impure (starch). There are various raw materials suitable for lactic acid fermentation and the primary example is D-glucose. Adding a mount of compounds that can be easily decomposed into hexoses, such as sulfite liquors, rice, sugar beet juice, molasses, whey, sugars, and potato starches. (Li et al. 2009, p. 57.)

The first step is the derivation of sugars or starch. This is typically acquired in a tapioca mill, a corn mill, or a sugar mill such as cane or beet. In the term of a tapioca or a corn factory, the starch is transfered into sugar via acid hydrolysis or enzymatic. And then microorganisms ferment it into sugar. At last, under the condition of anaerobic, lactic acid is achieved by the lactate dehydrogenase reaction:

$$\text{Glucose} + 2\ \text{ADP} + 2\ \text{Pi} \rightarrow 2\ \text{Lactic acid} + 2\ \text{ATP} \tag{3}$$

In equation 3, Pi is inorganic phosphate. According to this production method, the conversion efficiency is significant (more than 95%). The fermentation is a continuous or batch process. Since most microorganisms are not able to stand against extreme acidic conditions and the fermentation is usually stopped. So, the addition of lime is a good choice to keep proceeding. Lactic acid is produced by acidification. The acidification step involves an important substance - free acid, which is generated by treating soluble calcium lactate with sulfuric acid, at the same time gypsum ($CaSO_4 \cdot 2H_2O$) (about 1 t/t lactic acid), which is a byproduct could also be reachable. (Li et al. 2009, p. 58.) The acquired free acid is then purified in order to reach the requirement of chemical synthesis.

3.4.2 PLA from lactic acid

The route (figure 19) adopts a continuous manufacturing process employing ring-opening polymerization (ROP) of lactide to transform into high molecular weight by Nature Works and PURAC. First is the production of low molecular weight with less than 5000 Dalton by lactic acid condensation. And then, raising the polycondensation temperature and reducing the pressure to depolymerize the prepolymer, which will generate lactide stereoisomers mixture. During this process, an organometallic catalyst (such as tin octoate) is always playing crucial roles - selectivity of the intramolecular cyclisation reaction and enhancing rate. Vacuum distillation is necessary to purity the molten lactide mixture. At the end of step, PLA polymer with more than 100,000 Dalton is achieved by ROP in the melt. And the remaining monomers would be recycled to be used again. (Li et al. 2009, p. 59.)

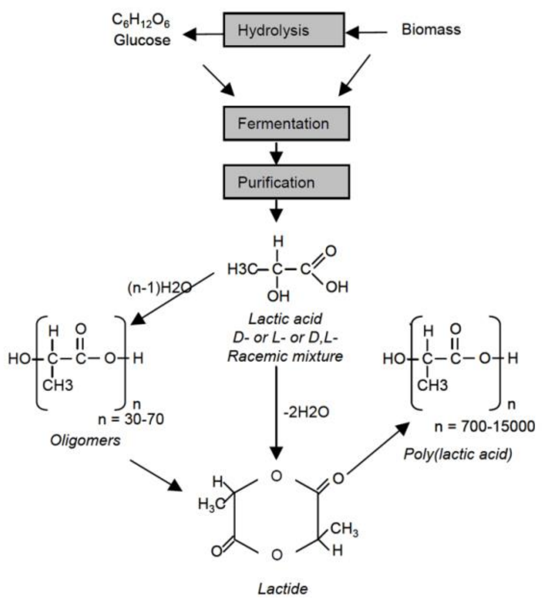

Figure 19. Production of PLA from biomass (mod. Li et al. 2009, p.60).

3.4.3 The properties of PLA

The density of PLA is 1.24 g/cm^3. it means it is higher than many other conventional polymers such as PP (0.92 g/cm^3) and LDPE (0.90 g/cm^3), but it is lower than PET with 1.34 g/cm^3. PLA considerably has high gloss and it is transparent as well. However, the optical properties of PLA are influenced by manufacture process and additives. The mechanical performance of PLA is much better than standard thermoplastics. The elasticity, impact strength, stiffness and hardness of PLA are similar to that of PET.

PLA can resist flavor and odor perfectly and it is also effective to oil and grease resistance; thus it would be a good choice for viscous oily liquids packaging. While it is not suitable for packaging some liquids beverages, because it is not good at preventing from O_2, CO_2 and water vapor. (Li et al. 2009, p. 64).

However, there are some considerations which should be taken into account. PLA is fairly brittle at room temperature and it is easy to cracking and breaking during shipping process. So some storage condition and handling are of great importance. In addition, the sheet and the products should not be stored at more than 40℃ and relative humidity above 50%. Otherwise, there would be a risk of deformation. (William 2010, p. 30). Based on this feature, several methods have been taken to improve this situation. Now the new modified PLA has been generated (table 1) and the optical purity is over 99.5% and the melt point is up to 179℃.

Table 1. Enhanced properties of polylactides (mod. Chen & Wang 2015, p. 960).

Entry	D-lactic acid content	Tm (℃)	Heat resistance (℃)	Application
1st Generation	≤4%	140	58	Tray, cup
2st Generation	≤2.5%	155	60	Tableware
3st Generation	≤0.7%	175	120	Automobile, electrical
4st Generation	Stereocomplex PDLA	220	200	Fiber, engineering plastics

4 COMPARISON OF THERMOFORMING MACHINERY IN EUROPE AND CHINA

The quality of thermoformed products usually depends on thermoforming machines. Industrialization advancement contributes to the rapid development of polymer process machinery industry in Europe in the 1930's. No matter the automation lever, steadiability or reliable parameter, all these capacities achieved a satisfactory status. However, Chinese machinery industry begins in the 1950's, and the relative technologies are developed based on widely applied of polymer especially in 1970's. Therefore, there is a wide gap between Chinese and European machinery. (Illig 2007, p. 1.)

4.1 Thermoforming machinery

There are some parts in almost every thermoforming machinery, which are gripper, heating section, forming system, molds, cooling and mold release. As introduced in chapter 2, there are different thermoforming methods – vacuum forming, pressure forming and plug assist forming. The biggest diversity lays on the forming system, which means what kind of force is applied to forming.

Gripper

Gripper is used to clamp materials when forming and cooling, strip mold, and transportation. The gripper comprises two plates: lower plate and upper plate. The upper plate is controlled by compressed air, which could force the materials against the lower plate. The lower plate is usually fixed.

Heating section

Heating section occupies a central position, which has a directive influence on production rate, energy consumption and product quality, and these aspects are correlative. Reducing the heating time is able to reduce energy, but sheet with too low temperature leads to poor-qualitied product. While too high temperature would bring about thermal degradation, it also damages the product quality. As Shen, Chen, Liu and Li said (2000, p. 39), the heating time is account for 50% - 80% of the whole production cycle, and the energy consumption occupies 80% of the overall consumption.

The main resources are gas and electric. Gas is relative cheap, but electric can be controlled easily. There are three heating methods. One is gas convection. It suits large and thicker sheet, and the cycle time is extremely long. A big fan is needed to convert hot air to sheet surface. (Ashter 2014, p. 88.) The second one is contacting heat. The heated metal contacts with sheet, and heat is transferred. This method is proper to even heat thin thermoplastic films. (Ashter 2014, p. 85.) The third one is radiation heating, which is the most common used. It is the easiest way to control and effective. Sheets can be heated by absorbing infrared radiation energy from heater.

Forming system

The widely applied forming forces are vacuum and compressed air. The maximum differential pressure of vacuum forming is less than 90kPa, which is proper to thin sheet. If this is not enough to forming, compressed air would make a difference. Generally, the pressure is 550-710 kPa, and the rated displacement is 0.05-0.3 m^3/min. (Drobny 2007, p. 126.)

Mold

There are three different types of mold, female mold, male mold and matched mold. Female mold could be used to form external surface or bulge of products, which is concave mold in the cavity. Male is bulge in the cavity and leads to internal surface or concave of products. Matched mold is concluding an upper mold and a lower mold, and it is possible to develop the complicate products. These molds are described in figure 20. It should be noticed that appropriate draft angles contribute to easy remove. Table 2 shows the general draft angles of mold. Special circumstances could require less draft. Deep cavity allows a bigger draft.

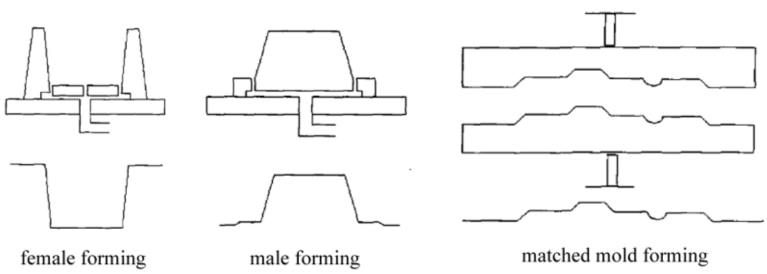

Figure 20. Three types molds (mod. Drobny 2007, p. 127).

Table 2. General draft angles (mod. Universal Plastics 2014, p. 14).

mold	Minimum degrees
Male mold	3-4
Female mold	1.5-2

Cooling

With the purposes of improving production efficiency and acquiring good quality, products need to be cooled before mold release. In theory, both of internal and external surfaces should be cooled and it would be better if the mold contains cooling coil. Air cooling, with the help of water spray, is much more suitable for plastic mold because of poor heat conductivity. If natural cooling is possible, impact resistance would be enhanced. In spite of water cooling is high efficiency, the internal stress is increased. (Zhang 2002, p. 22.)

Mold release

Mold release is aimed at removing the products from the mold. No matter female mold or male mold, products are usually cooled and shrink against the mold. Vacuum extraction holes or blowing in reverse direction is effective way to get out of mold. (Zhang, Luo & Zheng 2013, p. 213)

In a word, the thermoforming technological process is illustrated in figure 21. It also describes the common used methods at each process. 1-film coil; 2-preheating; 3-thermoforming; 4-filling; 5-coding; 6-film coil; 7-sealing; 8-cross cutting; 9-straight cutting; 10-products. Figure 22 is the setup time of important work stages.

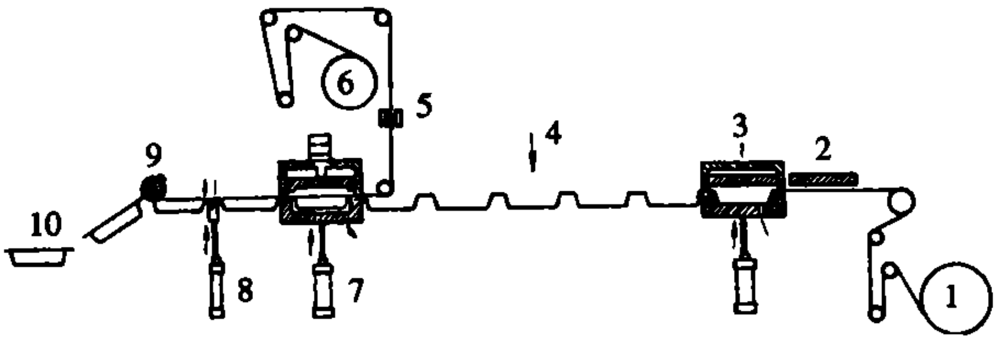

Figure 21. Thermoforming technological process (Zhang 2002, p. 17).

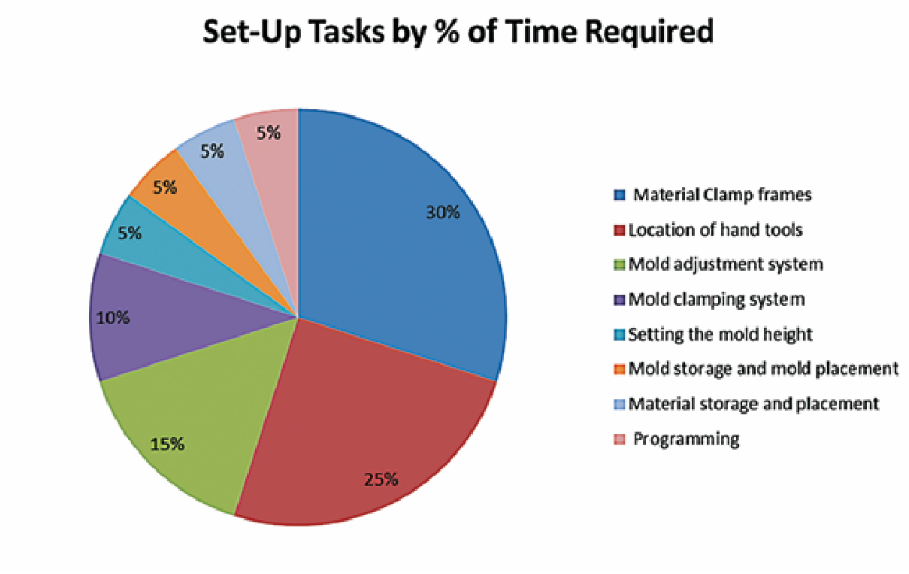

Figure 22. The setup time of important work stages (Joannou & Zamprelli 2013, p. 12).

4.2 Thermoforming machinery in China

There are two kinds of thermoforming machinery in China. One is only producing containers. Manual thermoforming machine is very suited to small business in villages and towns or individual. This kind of machine could product containers. Although it is low effective, it is universal and fast to change production varieties. Automatic thermoforming machine enables to produce containers continuously and automatically. It is high efficiency energy-saving and it is adaptable to mass production.

LK-71S made in Guangdong

Figure 23 is LK-71S semi-automated vacuum thermoforming machine of LOOKER company in Guangdong province, which is suited to kitchen and automobile appliances (figure 24). There is visual digital temperature controller and the heating element is ceramic with two furnaces. Lower mold is controlled by big cylinder to run smoothly. Cooling section is water to low temperature rapidly. The forming force is vacuum pump with 60L, 80L or 100L. The common materials are thick plastic material (PVC, PET, PE, PS, ABS and Acryl). The machine’s parameters are showed in table 3. The price is $15000. (LOOKER 2017.)

Figure 23. LK-71S semi-automated vacuum thermoforming machine (LOOKER 2017).

Figure 24. Kitchen and automobile appliances (LOOKER 2017).

Table 3. Parameters of LK-71S (mod. LOOKER 2017).

Model	LK-71S
Power supply	AC380 50/60 Hz
Max. forming length	610 mm
Max. forming width	610 mm
Max. forming weight	150 mm
Material thickness	1-5 mm
Output	100-200 molds/H
Machine size	2700 x 1400 x 2000
Net weight	2500 kg

CH-61A/61B made in Guangdong

Figure 25 is CH-61A/61B automated vacuum forming machine made in Guangdong province. This machine can be used in toys, food, medicine, hardware, lunch boxes and sanitary materials, which are 3-D products. The heating system adopts dense far infrared (IR) ceramic heating brick and it could reach the required temperature within five minutes. Solid-state temperature controller is assembled with the machine as well, it could ensure the constant temperature by adjusting voltage. The cooling fans are integrated with the device that enables to take care of wind volume. The molds could be made of aluminum, electrolytic copper, gypsum or bakelite. In addition, changing mold quickly is available. The machine details are illustrated in figure 26. Many thermoplastics are suitable, such as PVC, PET, PP, PC, ABS, HDPE, LDPE sheet and so on. Clips are able to place the material at exact position. The detailed parameters of this machine are showed in table 4. The price is ranging from $4000 to $8000. (SHENGHAO 2017.)

Figure 25. CH-61A/61B automated vacuum forming machine (SHENGHAO 2017).

Figure 26. The CH-61A/61B machine details (SHENGHAO 2017).

Table 4. The parameters of CH-61A/61B (mod. SHENGHAO 2017).

Model	CH-61A	CH-61B
Total power	13 kw	12.5 kw
Forming length	650 mm	650 mm
Forming width	560 mm	560 mm
Forming high	150 mm	150 mm
Power	380V three-phase four-wire	380V three-phase four-wire
Mechanical dimension	L2470xW1000xH1950 mm	L1600xW720xH1400 mm
Weight	800 kg	600 kg
Production rate	200-300 times/H	200-300 times/H
Vacuum	8 L/s	4 L/s

SPC made in Shangdong

Figure 27 is SPC automatic pressure thermoforming machine that comes from Shandong province. The forming force is compressed air and servo motor or gear motor is used for sheet feeding. Similar with CH-61A/61B and LK-71S, the heating method is also IR ceramic with top and bottom sides. The most important feature is pressing forming, forming, cutting and cooling could be completed in one mold. This machine has the ability to produce cups, trays, boxes and bowl-shaped products (figure 28). The suitable materials are PP, HIPS, PET, GPPS, HIPS and PVC. The parameters are described in table 5. The price is $34000-42000. (TONGYI 2017.)

Figure 27. SPC automatic pressure thermoforming machine (TONGYI 2017).

Figure 28. The products that could be produced with SPC pressure thermoforming machine (TONGYI 2017).

Table 5. The parameters of SPC pressure thermoforming machine (mod. TONGYI 2017).

Model	SPC-660B	SPC-660C	SPC-660D
Guide pillar	Two pillars	Four pillars	Four pillars
Max. Guide plate area	300x1050 mm	360x1200 mm	360x1200 mm
Max. Forming area	640x230 mm	660x300 mm	660x300 mm
Running speed	15-32 cycles/min (according to sheet thickness, material used and product shape)		
Sheet width for feeding	500-660 mm in rolls		
Sheet thickness	0.2-2 mm		
Max. Forming depth	140 mm		
Master motor power	7.5 kw	11 kw	11 kw
Max. sheet reel diameter	Diameter (D.) 800 mm		
Water consumption	(15-20 °C) 0.5-1 m^3/h (recycled)		
Air consumption	2.5-3 m^3/min, 0.6-0.8 MPa		
Sheet feeding method	2.2 kg gear motor	2.2 kg gear motor	3 kg servomotor
Plug stretching method	D.125 mm air cylinder	D.125 mm air cylinder	4.4 kg servomotor
Dimension	3.6x1.35x2.3 m	3.75x1.55x2.3 m	3.75x1.55x2.5 m
Weight	3600 kg	3800 kg	4000 kg

The other is Multifunctional automatic thermoforming packaging machine. Thermoforming, filling, sealing, trimming, transportation and scrap handling are all automatic and integrated in one machine.

DZL-320Y made in Zhejiang

Figure 29 is automatic DZL-320Y food vacuum packaging machine, which is made in Zhejiang province. This machine is applied to pack fast food, pasta or ready meal (figure 30) with modified atmosphere packaging technology, which enables to prolong shelf life of products. The frame structure is plywood with 304 stainless steel. In this machine, tray forming, filling, sealing, gas flushing and die cutting are all completed together (figure 31). Different working sections could be worked at the same time, which makes the production process faster and reduces defect probability. In order to ensure staff safety, some sensors are installed inside the door, under the film and other transport areas to make the machine shutoff when dangerous situation occurs. The detailed parameters of this machine are illustrated in table 6. The price is $52000-83000. (UTIEN PACK 2017).

Figure 29. Automatic DZL-320Y food vacuum packaging machine (UTIEN PACK 2017).

Figure 30. Fast food, pasta and ready meal applications (UTIEN PACK 2017).

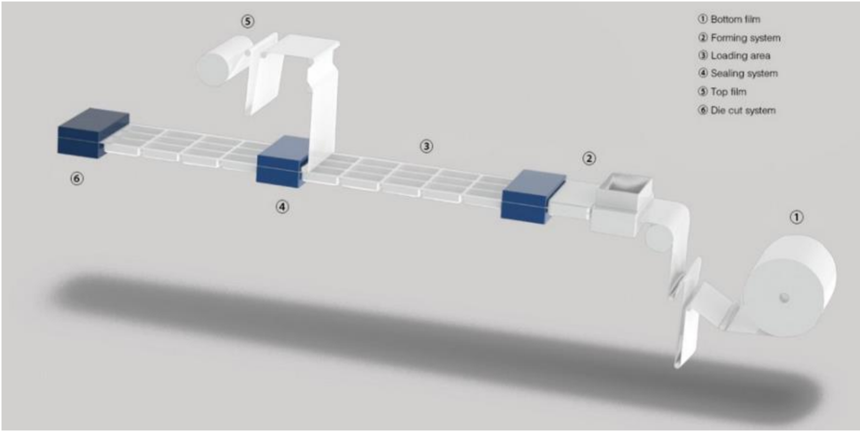

Figure 31. Working Schematic of DZL-320Y (UTIEN PACK 2017).

Table 6. The parameters of DZL-320Y (mod. UTIEN PACK 2017).

Machine parameters	
Dimensions	6000 mm x 1300 mm x 1870 mm
Weight	2000 kg
Working height	1000 mm
Operating panel height	1600 mm
Loading area length	1500 mm (flexible)
Working parameters	
Bottom film width	≤ 520 mm
Advance length	≤ 500 mm
Forming depth	≤ 150 mm
Top film	
Material	Sealable PE/PA multilayer co-extruded plastic film
Print	Pre-printed top film or transparent top film
Roll diameter	250 mm at most
Thickness	≤ 2 mm
Bottom film	
Material	Sealable PE/PA multilayer co-extruded plastic film
Print	Unprinted color bottom film or transparent film
Roll diameter	500 mm
Thickness	≥ 3 mm

Table 6 continues. The parameters of DZL-320Y (mod. UTIEN PACK 2017).

Components	
Vacuum pump	BUSCH (Germany)
Electrical components	Scheneider (French)
PLC (Programmable logic controller), Touch Screen and Servo Motor	DELTA (Taiwan)
Pneumatic components	SMC (Japan)

Small blister packing machine made in Guangdong

Figure 32 is small blister packing machine comes from Guangdong province. This machine is suited to capsule, sugar-coated tablet, milk tablet and leisure candy, one of the examples are showed in figure 33. It is specially designed for laboratory, mini-motor test workshop, mini-pharmaceutical factory, medicine institute and dosage tome in hospital. The forming force is compressed air and the mold cooling is utilization of recycled water or tap water. The detailed parameters of this machine are exhibited in table 7. The price is $5000-8000. (Mingyue 2017.)

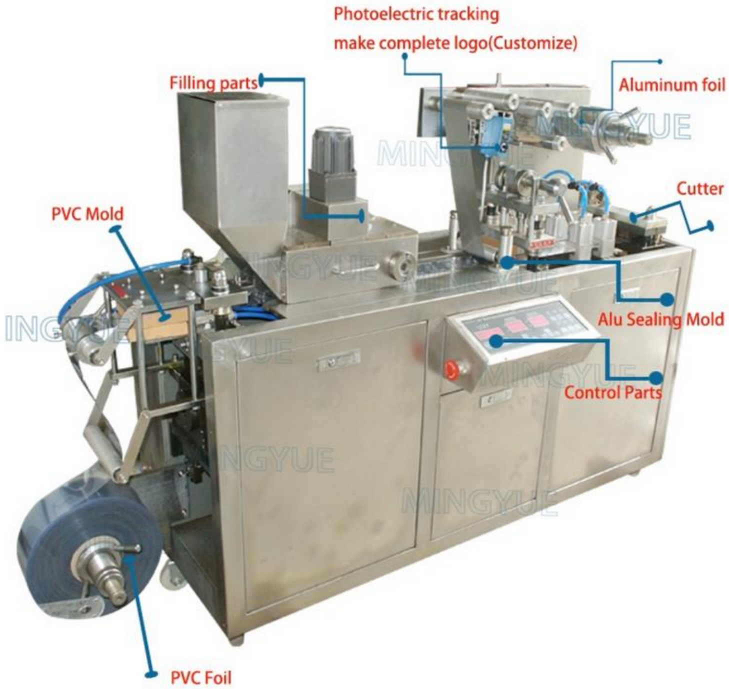

Figure 32. Small MY-80 blister packaging machine (Mingyue 2017.)

Figure 33. An example of blister packaging (Mingyue 2017).

Table 7. The parameters of MY-80 (mod. Mingyue 2017).

Cutting frequency	27 times/min
Stroke	40-110 mm
Max. forming area and depth	60x100x14 mm
Air compressor	≥0.03 m^3/min (provided by user) oil less air compressor is better
Air pressure	0.7 Mpa
Standard plate	80 x 57 (flexible)
Total power	380V/220V 50 Hz 2.8 kw
PVC hard pieces	(0.25-0.35) x 90 mm
Aluminum foil	(0.02 x 0.035) x 90 mm
Yield	99%
Max. capacity	18-30 pieces/min
Weight	380 kg
Machine package size	160x80x55 cm (WxLxH)

SH-300 rotary PVC blister machine in Shanghai

There is a blister machine that is similar with MY-80, named SH-300 rotary PVC blister machine made in Shanghai city, in figure 34. The rotaty place is the area that transferring the tray. The most important character is some electrical components are from OMRON and Pansonic in Japan, and Siemens in Germany. The applications are more widespread, from stationery to food to medical equipment to toys to cosmetics than MY-80. The price is $30,000-35,0000. (ShenHu 2017.)

Figure 34. SH-300 rotary PVC blister machine (ShenHu 2017).

4.3 Thermoforming machinery in Europe

In Europe, many companies are taking part in manufacturing thermoforming machines with similar working sections. Such as GEISS AG in Germany, MW Thermoforming Machines in Italy, ULMA in Spain, ILLIG Maschinenbau GmbH & Co. KG in Germany, Novapac in Germany, Multivac in Germany, VC999 in Switzerland, HAJEK in Austria and WEBOMATIC in Germany. Many companies have developed production sites in different countries.

GEISS AG in Germany

GEISS AG company produced T series and U series thermoforming machines. The T series represents massive drawing depth which is the German word “tief” with the meaning of high. U series stands for smaller sizes and the drawing depth is 300mm which is shorter than that of T series which is 750mm.

Figure 35 is the U8 vacuum thermoforming machine which could be assembled with loading and rolling platforms. There are two hearers are integrated in this machine. The top one is made of quartz elements and hearing size is 250x63mm with 485 watts output. The bottom heater is covered by glass ceramic plate and the heating size is same with the top one. Both heaters are driven by servo motors. Clamp system could be adjusted vertically and it is not necessary to set up material thickness. In addition, there are 4 fans with water mist injection system are used to cool the products. Furthermore, Siemens IFP 1500 is served to control all the processes. The most important is that any thermoplastics with any thicknesses are suitable to be employed in this machine. The detailed parameters are demonstrated in table 8.

Figure 35. U8 vacuum thermoforming machine (GEISS AG 2017).

Table 8. The parameters of U8 vacuum thermoforming machine (mod. GEISS AG 2017).

Types	600	800	1000
Max. sheet size	1000x600 mm	1000x800 mm	1500x1000 mm
Max. forming area	960x560 mm	960x760 mm	1460x960 mm
Max. stacking height	680 mm	680 mm	680 mm
Draw depth male or female	400 mm	400 mm	400 mm
Draw depth heated top and bottom	300 mm	300 mm	300 mm
Max. roll width	600 mm	800 mm	1000 mm
Max. roll diameter	1200 mm	1200 mm	1200 mm
Foil thickness of roll material	0.18-2 mm	0.18-2 mm	0.18-2 mm
Working height	1140 mm	1140 mm	1140 mm
Vacuum pump	100 m^3/h	100 m^3/h	100 m^3/h
Weight (basic machine)	37 kN	41 kN	54 kN

MULTIVAC in Germany

MULTIVAC is good at packaging solutions and package machines, which includes thermoforming machines and package lines. Both food and medical can be completed with MULTIVAC Clean Design™. There are also some unique machines for unique applications, for instance, R515 is designed for fresh meat package, and R685 is used for stacked sliced products. All the conventional thermoplastic films, fiber composite films, aluminum composite films or films made of renewable raw materials are all could be run on MULTIVAC thermoforming packaging machines. One of the features of this machine is the reduced energy consumption and water consumption. The lifting units for forming, sealing, cutting sections are remarkably energy consumers. But servo motors replaced pneumatic drives are energy-efficient and 80% energy could be reduced. Moreover, servo-motorized plug is helpful to decrease the compressed air consumption by reaching 25%. In addition, the MULTIVAC MVP vacuum pump is successful in lowing 40% energy consumption. There is a sensor in the cooling water channel to open or close the cooling water in case of cooling requirements, which cuts down the water consumption by 50%. Figure 36 is R535 thermoforming machine and the detailed parameters are described in table 9.

Figure 36. R535 thermoforming machine (MULTIVAC 2017).

Table 9. The parameters of R535 (mod. MULTIVAC 2017).

Pack types	Rectangular and round, Basic formats and Freely definable formats 
Film widths	220-830 mm (in 5mm steps)
Max. forming depth	230 mm
Cut-off lengths (without preheating)	< 1300 mm

Table 9 continues. The parameters of R535 (mod. MULTIVAC 2017).

Die changing system	Drawer system, automated
Forming systems	Standard/plug/posiform/upper web

HAJEK in Austria

HAJEK mainly manufactures vacuum packaging machine with different types. VS20, VS30 and VS40, which mean various required spaces. VS20 is a small one with 2-meter length. As a consequence, the loading area and weight are diverse. In addition, VS40 is suitable to pack a wide variety of products. Figure 37 is VS30 420 vacuum thermoforming machine for manual products infeed. Vacuum package, MAP (modified atmosphere package), closure package and skin package are all can be done in this machine. Also, transport chain 5/8 " with film clamping devices which is used for fixing materials during transport process and forming process. PLA with up to 99 programs storable and pneumatic control system are equipped in this machine. The frame is made of stainless steel, which enables it to work in humid environment. The specific parameters are exhibited in table 10.

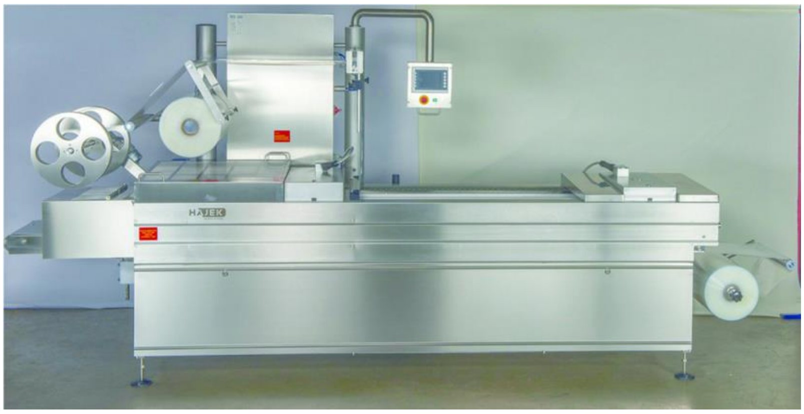

Figure 37. VS30 420 thermoforming machine (HAJEK 2017).

Table 10. Parameters of VS30 420 (mod. HAJEK 2017).

Packaging material	Flexible films	Semi-rigid/ rigid materials
Film width	285 mm/320 mm/355/420 mm	
Film core	76 mm/3"	152 mm/6"
Draw-off length	up to 300 mm	up to 400 mm

Table 10 continues. Parameters of VS30 420 (mod. HAJEK 2017).

Max. Package size	263 mm/298 mm/333 mm/ 398x300 mm	263 mm/298 mm/333 mm/ 398x400 mm
Loading area	approx. 850 mm	larger length on request
Max. drawing depth	up to 150 mm	
Vacuum pump	100 m^3/hour	on request
Electrical connection	3x230/400 V, or 3x220 V, 50-60 Hz	country-specific
Control	SPS	
Compressed air	6 bar	
Cooling water needs	approx. 3 l/min	
Weight	approx. 650 kg, without die-set and options	

ILLIG in Germany

ILLIG manufactures various package technology, package machines and tools for thermoforming. The thermoforming machines are bottle former, pressure forming machine and form-fill-seal package line. Figure 38 is RDK 90 automatic pressure forming machine. Servo motor is served to drive motion sequence and steel rule dies are installed in the RDK 90 forming tool, which are contributed to achieve the high cycle speed of 55 cycles/minute. In addition, there are two alone cooling circuits on the upper and lower positions of the forming section and the inlet and outlet temperature, flow rate are exhibited on the screen.

Figure 38. RDK 90 automatic pressure forming machine (ILLIG 2017).

Numerous options could be combined with the forming machine, such as hole punch press, roll pre-heater, various stacking stations or separate steel rule punch press. Handling system is applied to connect for treating products in the next steps. The two-axis handling for stacking station is one of the features (figure 39). Though integrated the ILLIG NetService with a production line, service engineers can observe all components and working sections by internet from Heilbronn. In this way, part of errors could be detected and some corrections is possible to be made. Table 11 is the specific parameters of this machine.

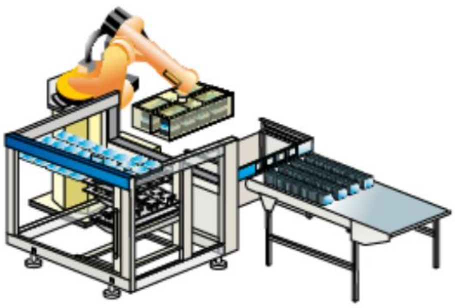

Figure 39. Stacking by 2 axils handling system (ILLIG 2017).

Table 11. Parameters of RDK 90 (mod. ILLIG 2017).

Forming area for forming/punching operation	max.	827 x 657	mm
Forming area for forming operation with actuated clamping frame	max.	840 x 670	mm
Tool width between material transport with actuated clamping frame	max./min.	870 / 500	mm
Tool width between material transport without/with actuated clamping frame	max./min.	870 / 500	mm
Tool length in operating direction	max./min.	700 / 350	mm
Material width with actuated clamping frame	max./min.	900 / 550	mm
Material width machine discharge side	max.	950	mm
Spreading dimension per side	max.	25	mm
Material thickness subject to material type	max.	2.5	mm
Material thickness	min.	0.2	mm
Accuracy of material transport (measured on intermediate bridge of skeletal)		±0.2	mm
Index length	max./min.	700 / 330	mm

Table 11 continues. Parameters of RDK 90 (mod. ILLIG 2017).

Height of formed part above material level	max.	160	mm
Height of formed part below material level	max.	160	mm
Height of total formed part	max.	160	mm
Table stroke on top	max.	180	mm
Table stroke on bottom	max.	180	mm
Stroke of clamping frame on top	max.	180	mm
Stroke of clamping frame on bottom	max.	180	mm
Servo-drive of pre-stretcher	max.	180	mm
Heater length upper heater		2800	mm
Heater length lower heater		2800	mm
Conveying capacity of vacuum pumps	max.	200	m^3/h
Forming pressure		6	bar
Number of cycles, only forming	max.	55	/min
Number of cycles, forming and punching	max.	55	/min

WEBOMIATIC in Germany

WEBOMIATIC company manufactures different types of thermoforming machines used for various materials, sizes, functions and production rates. Figure 40 is the ML-C 7600 that meets the high hygienic standards. One of the major features is the on-the-fly tool change choice. Two different formats are assembled in parallel and the option of on-the-fly is able to be selected by the sophisticated PLC to dominate. Complex tool and film changes are not necessary during production, so it is time-saving and more efficient. It is quite fast with process capacity of 20 cycles per minute compared to RS compact 3 thermoformer made from VC 999 company, which is 6-8 cycles (VC999 2017). The forming process could be vacuum, compressed air or plug assist forming. Various cutting systems, filling manually or automatically, codling or labelling systems are all can be installed in this machine. Strip punch is possible to be adopt to create special contours. Also, the top films are available to form a shape of lid. The parameters are illustrated in table 12.

Figure 40. ML-C 7600 thermoforming machine (WEBOMATIC 2017).

Table 12. The parameters of ML-C 7600 (mod. WEBOMATIC 2017).

Dimensions	22000x1250x1995 mm
Working height	890-950 mm
Repeat length	200-1000 mm
Draw depth	Max.190 mm
Drive	Mitsubishi servo-drive, highly dynamic, electronically controlled
Control	PLC Mitsubishi FX with optional remote diagnosis
Monitor/display	hi-res Mitsubishi 12" color touchscreen
Vacuum pump	100, 160, 250, 400, 630, 1000 m^3/h, roots pump optionally
Bottom film	thermoformable and sealable flexible and rigid film e.g. PA/PE, A-PET, PVC; 322-622 mm width
Top film	sealable flexible film, e.g. PA/PE.
Packing capacity	Up to 20 cycles/min

4.4 Conclusion of this chapter

Considering a late starting, Chinese thermoforming machine is behind European, which mainly respects in the following aspects.

- With regard to some machine with good running properties, the core components are from other countries, such as PLC, electrical components and vacuum pumps.
- For some companies mentioned in this article, the fastest production capacity is 55cycles/min, while it is exceptional higher than Chinese machine.

- The most important point is that some European machine is versatile to all the thermoplastics with any thickness, however, Chinese machine is limited about this feature.
- Because of high labor cost, robotic gripper is more effective in Europe. In addition, it would remarkably improve the production rate and decrease a risk of accident.
- Most of the European companies adopt servo-motors as power supply to drive the production process. It is an economic way, no matter in energy-saving or lead time-saving.

5 MATERIALS AND METHODS

Thermoforming is a method that enables the forming of soft and pliable plastics after heating into three-dimensional shape products through a biaxial force (Lappe 2013, p. 12). In a thermoforming process, it is considerable vital that a material could be soft when heated and it is also able to be reshaped under bending and stretching by pneumatic or mechanical ways (Ashter 2014, p. 39). The most important is it should maintain its shape after cooling. Each thermoforming material owe special physical properties and advantages. By virtue of suitable material can greatly improve the properties of final product or make it appropriate for different containers. Furthermore, composite thermoplastic with multiple layers is employed for thermoforming as well. These can provide efficient barriers resistance to moisture and oxygen and other gases in unique packaging applications.

In order to compare some thermoformed plastics properties, some mechanical properties are measured in this article, including air permeability, tensile index, strain at break, and bend stiffness. These data could be used to evaluate thermoformed plastics properties.

5.1 Materials

In this experiments, bio-based PE, PLA and composite of PE are used to test some representative properties. Some companies and producers are taking part in producing these materials.

5.1.1 Manufacturer of Bio-based PE

Braskem

Braskem in Brazil is the world's leading bio-based polymer manufacturer and the largest petrochemical corporation in the Americas. As reported, the annual production capacity of thermoplastic resins and other chemical products is 25 billion pounds. In 2015, the production volume of polyolefins (PE and PP) reached 4.2 million tons and the gross revenue is $ 16 million. (Braskem 2016, p. 43.)

Global Sustainable Program (GSP) was launched in 2000 aimed at publishing greenhouse gas emissions (GHG) data of companies and Braskem joined in GSP, reporting statistics in 2008. In 2015, Braskem took part in “Paris Pledge” to reduce GHG and sought constantly to innovation solutions toward decreasing the consumption of energy, GHG and water, as well as lowing generation of waste and liquid effluents. (Braskem 2016, p. 35). $ 31 million was invested in environmental improvement projects and the saving of $ 144.4 million was achieved in 2015. According to the annual report of Braskem, the reduction of waste won the greatest success in the history and the generation index of marketable products is 2.01 kg/t, which means $ 3.7 million were saved in 2015. (Braskem 2016, p. 66.) It is also an indicator of energy efficiency and a lower impact on environment.

From 2007, Braskem are developing a research that utilization renewable raw materials to production plastic products, manufacture quality are maintained and of beneficial to environment at the same time. After three years, Braskem invested US$ 290 million to innovate Green Polyethylene plant in Triunfo. Now it is one of the major features-Green Polyethylene is a 100% sustainable and degradable plastic with identical mechanical and processability properties compared to conventional fossil-based plastics. (Braskem 2016, p. 92.) Since September 2010, Braskem has been manufacturing HDPE, LLDPE (linear low-density polyethylene) from recycled source on an industrial scale. In 2015, the production capacity of LLDPE is 120,000 tons (Braskem 2016, p. 89). But Braskem only manufactures granules.

Scanfill

Scanfill in Sweden manufactures a film named SCANFILL BIO Foil GYX52C1, which could be applied for thermoforming packaging. This material is similar with HDPE. It consists of 52% mineral and 48% Polyethylene comes from non-oil based sources. The energy consumption and greenhouse gas emission can be seen in figure 41. It is obvious that it consumes less energy to produce and emissions less greenhouse gas compared to conventional PE. It is fully recyclable as well. In addition to the excellent environmental interest, the mineral provides stiffness and strength that makes thinner thicknesses available, which means light weight, as well as higher heat conductivity. This structure determines lower material volume and lower amount of polymer, increasing the production speed. Some customers said 50-100% higher than PE in production speed. (Scanfill 2017a.)

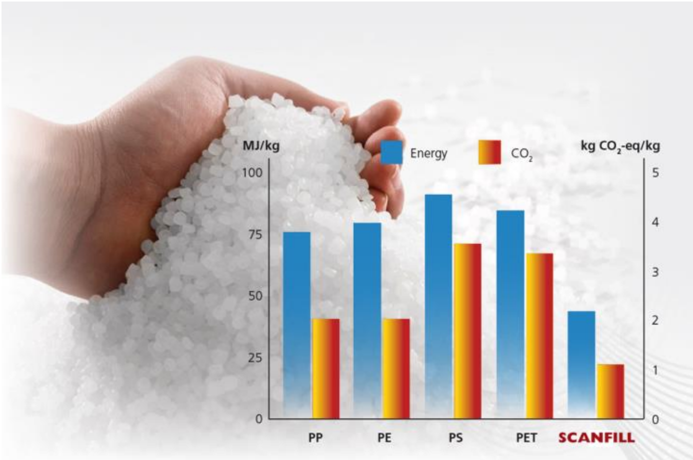

Figure 41. Energy consumption and Greenhouse gas emission (Scanfill 2017b).

Sweden uses about 185,000 tons plastic for packaging every year. If SCANFILL is applied to replace 1000 tons polystyrene, 2400 tons CO_2 emission could be saved. This is equivalent to the emission of a new common car drives 18 million kilometers. In addition, energy of 12.5 million kWh is gained as well. That is equivalent to the electricity consumption of 2500 medium sized household every year.

5.1.2 Manufacturer of PLA

Infiana

Infiana company was acquired by Huhtamaki in 1999, and it started to do business about paper and close-down bags in 2008. In 2009, it expanded businesses into bio film portfolio by PLA films. Prisma Pack, a hygienic films manufacturer in Brazil took over it in 2011, and it was renamed Infiana Group in 2015. In 2016, it has developing specialty film solutions and created 200 million euros of gross revenue.

Infiana offers thermoforming films for forming, filling and sealing applications (Infiana 2016a). These films are used for blister and trays packaging as well. Bio-based PE and PLA also available in this company. The manufacturing methods of Bio-based PE is similar to Braskem and it is also biodegradable. Furthermore, Infiana is good at processing technologies such as siliconization, laminating, printing, coating, varnishing and embossing. produce innovative films for specialized requirements or for mass market applications. (Infiana. 2016b.)

Nature Works

Nature Works is an innovator with Ingeo series products, and Ingeo portfolio is derived from renewable, abundant raw materials which is competitive with oil-based intermediates, fibers and plastics in performance and economics. In 2003, Nature Works built the largest lactic acid manufacturing facility in the world and a new fermentation laboratory was set up to research commercial-scale methane through lactic acid fermentation technology in 2016. It is aimed at skipping plants instead of microorganisms to directly transform carbon into lactic acid. (Nature Works 2017a.)

Currently, Ingeo is from corn which is intended to supply both feed and industrial end-uses at the same time. While only starch is used from corn for Ingeo and the plant-based proteins are transported to the animal feed industry. The figure 42 shows how one bushel (25.4kg) of corn applied numerous applications for both food and industrial.

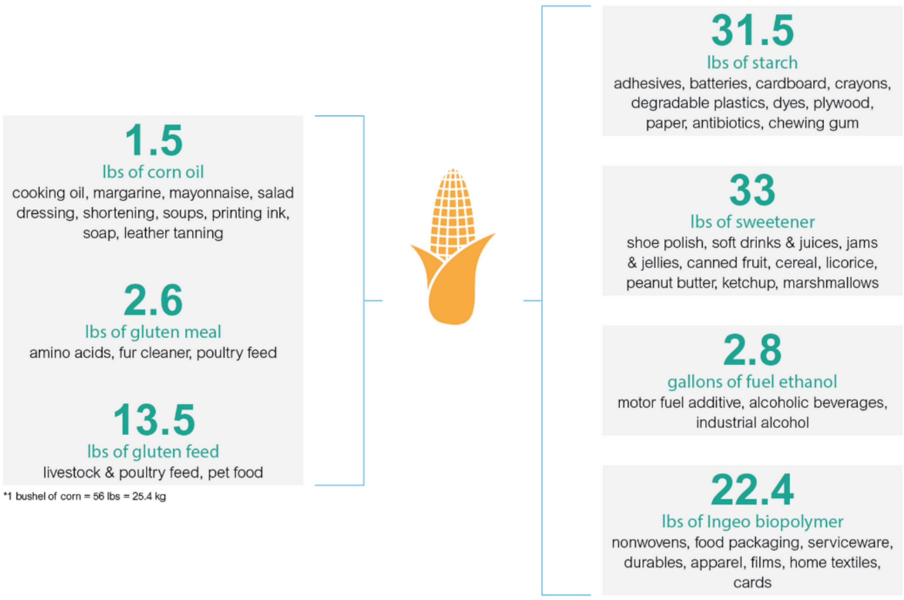

Figure 42. Applications in which one bushel of corn could be used (Nature Works 2013).

The 4 series is designed to produce oriented films, graphic arts and card stock. For example, 4043D is general purpose film, 4032D is high heat film, 4060D is heat seal layer for film, and. (Nature Works 2017b.) Nature Works also have done some studies about blends of PLA. It provides a starting point for some end-users of PLA who intend to modify rheological or physical properties of polymers by blending with other polymers. For instance, PLA blends with PE, ABS and PVA. (Nature Works 2007, p. 1.)

Based on circular economy principles, Nature Works has working with Ellen MacArthur Foundation since 2015. This foundation encourages to support new materials innovation in global plastics, design more efficient packaging and "introduce new models for making better use of packaging". (Nature Works 2017c.)

ExTech

Nature Works only manufactures PLA granules, but ExTech can make films or trays with Ingeo™ PLA (figure 43). This polymer provides excellent flavor and aroma barrier, superior print and lamination, high gloss and stiffness. It is also could be used as food contact materials.

Figure 43. Thermoformed trays made of Ingeo™ PLA (ExTech Plastics 2017).

5.1.3 Materials used in this test

There are eleven types of materials used in the experiments. Bio-PE 98 is from Mondi company of prefoampack series in North America. Bio-film 170, 350, 620, 150, 300 and PLA 250, 50 are from Infiana in Germany, which are similar with LDPE. This kind of material is named by thickness according to the specifications the company provided. But the practical thickness would be measured in this article. APET (Amorphous Polyethylene Terephthalate)/PE, PET/EVOH/PE, APET/EVOH and APET/PE/EVOH/PE were supplied by Finnvacum Oy Ab. These materials' basic information is exhibited in table 13. Figure 44 describes some special materials appearance.

Table 13. The basic information of materials.

Material	color	Source
Bio-PE 98	White translucent	Mondi
Bio- film 170	Transparent	Infiana
Bio- film 350	Transparent	Infiana
Bio- film 620	White	Infiana
Bio- film 150	Yellow translucent	Infiana
Bio- film 300	White	Infiana
PLA 250	Transparent	Infiana
PLA 50	Transparent	Infiana
APET/PE	Black	Finnvacum
APET/EVOH/PE	Transparent	Finnvacum
APET/EVOH	Black	Finnvacum
APET/PE/EVOH/PE	Transparent	Finnvacum

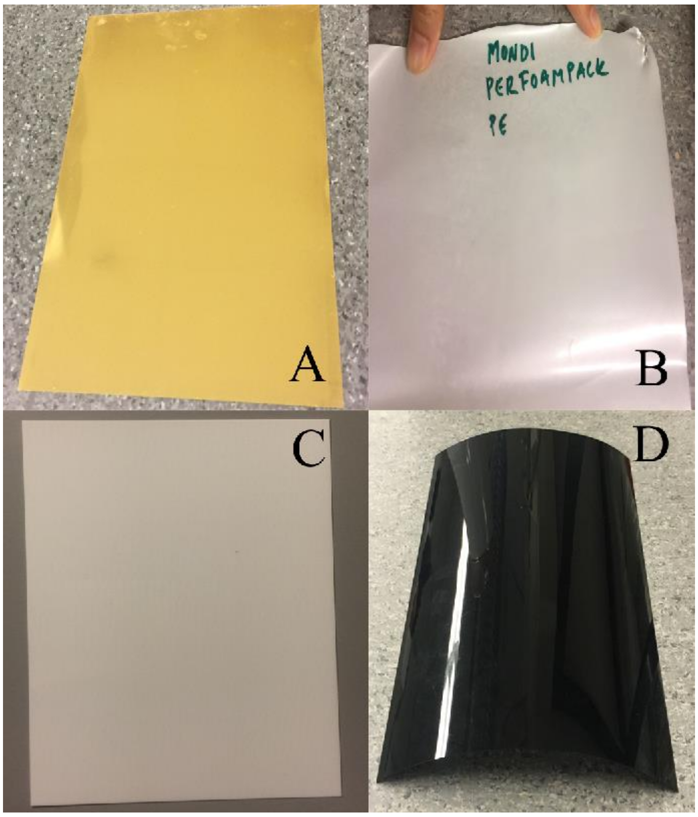

Figure 44. Some special appearance of materials. A is Bio- film 150, B is Bio-PE 98, C is Bio- film 300, D is APET/EVOH.

5.2 Testing projects

Some properties could be applied to describe thermoforming quality, such as bending stiffness, air permeability and tensile tests. Before that, it is necessary to measure the practical thickness and grammage that utilization in these tests.

5.2.1 Grammage and thickness

Grammage is a basis physical specification. Its' value and uniform is related to almost all of the physical, mechanical, optical and printing properties. Grammage (w) is the weight of the one square meter of film (g/m^2), which could be calculated from the formula

$$w = m/A \tag{4}$$

In the equation 4 the w is grammage (g/m^2), m is mass of the sheet (g) and A is area of the sheet (m^2). (DS Smith 2017.) The opreation is completed according to standard ISO 536 (2012, p. 57).

Single sheet thickness is measured using a motor driven micrometer (Lorenzen & Wettre, see figure 45). There is a button on the right side of the tester. Putting it and the detector would be lifting, when the space is enough, the material could be placed on the platform, the value on the screen is available until it is stability. The thickness of the material is tested 6 points on the samples and is determined by averaging these data with an accuracy of 0.01mm (ISO 534 2011, p. 7).

Figure 45. Lorenzen & Wettre thickness tester.

5.2.2 Air permeability

Air permeability is usually related to resistance property. It is tested using Bendtsen tester (Figure 46) based on standard SCAN-P 60:87, Bendtsen air permeability. It is the volume flow of the air through 10 cm^2 area under the 1.47 kPa of pressure difference. The unite is ml/min.

When open the machine, switch the selector valve to the air permeability position, put the sample between the chaps of the measuring head and press the handle against sample to decide measuring range, 0-300 ml/min or 0-3000 ml/min. In this test, 0-300 ml/min is much suitable. And then choose the area that is applied in this test which is 10cm^2. When the value on the screen is stable, push the measure button. After ten measurements are finished, push the “print report” button. This report reveals number of the accepted measurements, average, standard difference, variation, and the highest and lowest measurement result.

Figure 46. Bendtsen tester.

5.2.3 Bending stiffness

It describes the bending moment when bending the material with 38mm width to the angle of 5 degree (ISO 5629 1983, p. 5). L&W bending tester is used in this experiment (figure 47). The green button is for testing; grey button is for printing and orange button is for clearing. Before the test, materials are trimmed into spices with 30mm width and at least 50mm length. During this test, ten sample trips are used and the average value and standard deviation are calculated. Figure 48 is the cutting tools to cut into the required size. The trimmed material is shown like figure 49. In this test, the unit is mNm.

Figure 47. L&W bending tester.

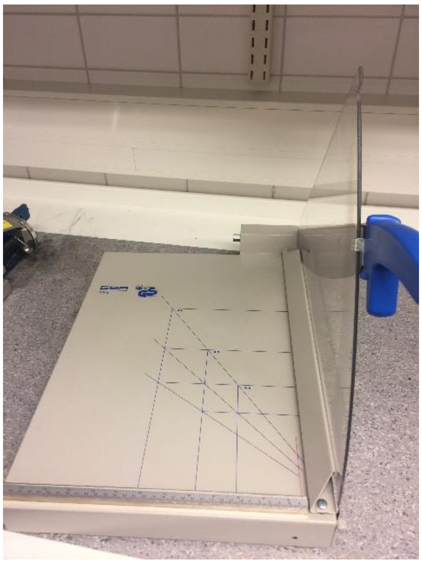

Figure 48. Cutting tools for 38mm width.

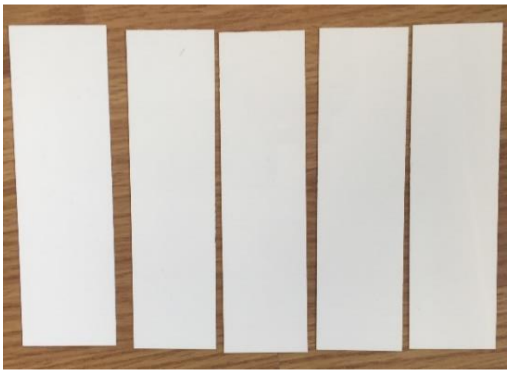

Figure 49. The trimmed material with 38mm width for bending test.

5.2.4 Tensile tests

Tensile strength can be tested with a horizontal tensile testing machine (figure 50). In this test, the unit is mN/m. In the tensile strength tester, speed is 100mm/min and the test piece with 15mm width is fastened to the point where rupture takes place (ISO 1924-2 2008, p. 6) and the trimming machine is described in figure 51. The trimmed material is showed like figure 52. Before testing, the test ID, thickness, grammage and how many specimens are used are put into the instrument though the manipulator. It could test the 5 MD (machine direction) sample stripes and 5 CD (cross direction) sample stripes or 10 CD sample strips sequentially in one program.

Figure 50. L&W tensile tester.

Figure 51. Cutting tools for 15mm.

Figure 52. The trimmed material with 15mm width for tensile test.

After every sample stripe is measured, the instrument calculates some properties automatedly, including the tensile strength, tensile index, breaking length, strain at break, tensile energy absorption (TEA), TEA index, E-modulus, tensile stiffness and the standard deviation of each property. After each testing program finished, the machine calculates and prints out the results intelligently. It should be pointed that tensile strength varies with different directions, which are CD and MD. In this research, tensile index and strain at break are more valuable numbers.

6 RESULTS AND ANALYSIS

A successful thermoformed product lays in a suitable selection of appropriate material for a specific application. There are numerous kinds of plastic materials, with particular properties, characteristics, weaknesses, and strengths. (Productive Plastic 2017.) The quality of final products should be evaluated by some properties, such as bending stiffness, tensile strength and air permeability. The main part of this chapter is some general information and strength properties about these materials acquired from three places.

6.1 Grammage and thickness

The measurements of grammage and thickness provide a foundation for mechanical tests. Tests methods and standards are described in chapter 5. The detailed results are exhibited in table 14.

Table 14. General information of materials.

Material	Thickness (μm)	Grammage (g/m^2)	color
Bio-PE 98	98	78.52	White translucent
Bio- film 170	159	217	Transparent
Bio- film 350	323	424.67	Transparent
Bio- film 620	568	786.4	White
Bio- film 150	145	190	Yellow translucent
Bio- film 300	284	369	White
PLA 250	245	314	Transparent
PLA 50	47	58	Transparent
APET/PE	409	560	Black
APET/EVOH/PE	272	362	Transparent
APET/EVOH	267	358.79	Black
APET/PE/EVOH/PE	443	608.97	Transparent

6.2 Air permeability

Air permeability is usually related to resistance property. When films are employed on the goods especially food, the gas concentration inside the package may change during storage, which would dramatically affect the chemical composition of the food, and result in food deterioration. Recognition and understanding of barrier property is one of the crucial criteria in designing the reasonable packaging structure. (Zhu 2016, p. 69.) The thickness of films is a crucial parameter since it directly influences the barrier properties and the shelf life of goods (Skurtys et al. 2017, p. 10).

The results are that these materials are totally barrier films except Bio-PE 98, Bio-film 170 and Bio-film 350. That means in terms of APET/PE, APET/EVOH/PE, APET/EVOH, APET/PE/EVOH/PE, Bio-film 620, Bio-film 150, Bio-film 300, PLA 250 and PLA 50, the air would not be permeated. The average air permeability value of Bio-film 98 is 4 ml/min, Bio-film 170 is about 2 ml/min and Bio-film 350 is 0.7 ml/min (figure 53). Based on this situation, it is therefore reasonable to infer that the barrier property would be increased with the raising of thickness. As Mondo Minerals B.V. (2017, p. 5) said, the barrier property greatly depends on the thickness of material. Thicker material increases the path length of the gasses and water vapor to pass through, which attributes to the reduced transmission rate and improved barrier property. Bio-film 150 is yellow translucent and Bio-film 300 is white, so maybe color makes them non-permeated and changes the path route.

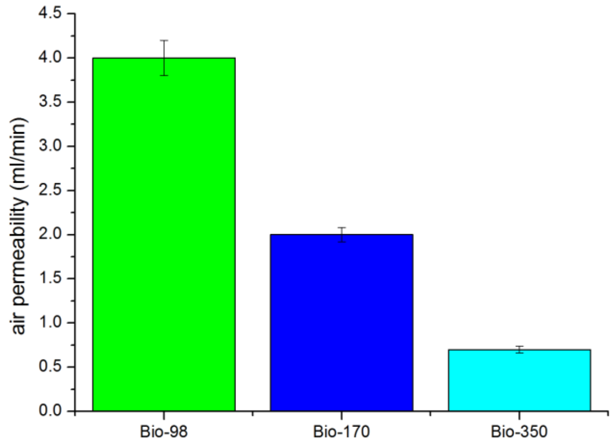

Figure 53. Air permeability of materials.

6.3 Bending stiffness

Bending stiffness is relative to the elastic properties of the material and it is a vital property for resisting deformation of thermoformed products. It gives a description of the ability on a strip to withstand a bending force, which is applied at the end of strip perpendicularly. Some printed receipts are exhibited in figure 54.

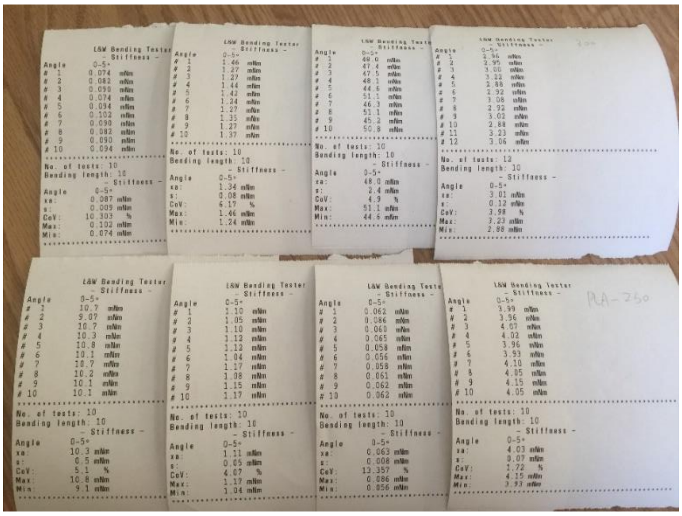

Figure 54. The bending test receipts of several materials.

In order to compare these materials properties, all these data could be integrated into one bar chart (see figure 55). From the bar chart, it is clear that the smallest bending stiffness is PE-98 which is 0.063 mNm and then is PLA-50, 0.087 mNm. The biggest bending stiffness is Bio-620, 48 mNm. But in terms of PLA-50, the bending stiffness is higher than Bio-based PE 98, even though the thickness is thinner. The similar phenomena could be found in comparing Bio-300 and PLA-250, the bending stiffness are 3.01 mNm and 4.03 mNm. It is reasonable to verify that PLA is much more effective than bio-based film which is similar to LDPE. This phenomenon also verifies that the mechanical properties of PLA are better than common thermoplastics (Li et al. 2009. p.64). Color does not have distinct impact on bending stiffness in terms of transparent Bio-170 and yellow translucent Bio-150. Furthermore, with the increasing of thickness, such as PLA-50 (0.063 mNm) and PLA 250 (4.03 mNm), Bio-170 (1.34 mNm), Bio-350 (10.3 mNm) and Bio-620 (48 mNm), the bending stiffness is growing remarkably.

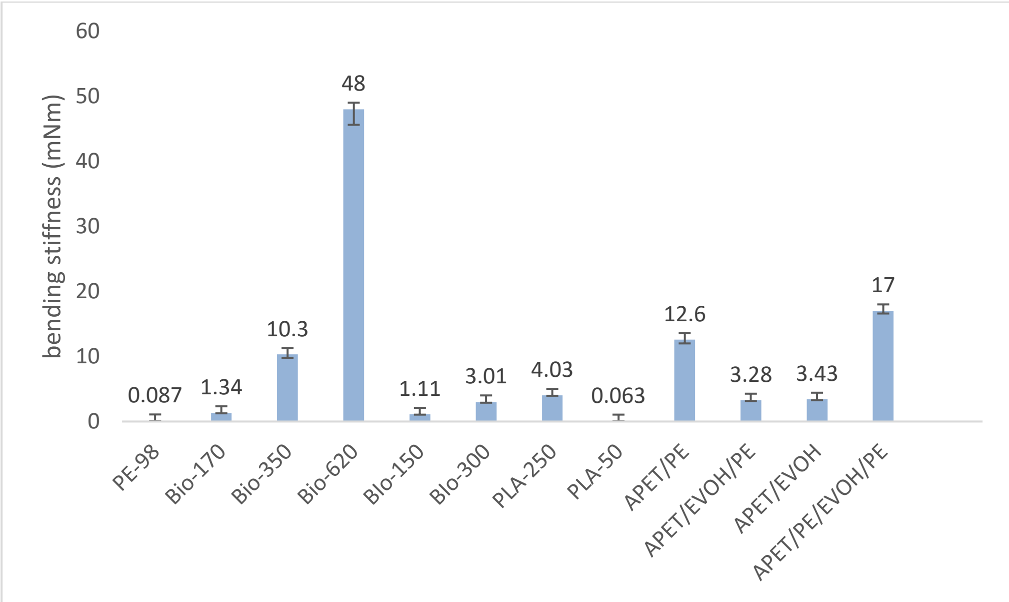

Figure 55. Bending stiffness of eight kinds of materials.

Considering APET/EVOH/PE and APET/EVOH, whose thickness is 272 µm and 267 µm, and the bending stiffness are similar as well, 3.28 mNm and 3.43 mNm respectively. As Qiao (2012, p. 29) said, PE with good seal performance, usually serves as heat-seal layer and contacts with packaged items directly. Therefore, PE layer does not have greatly impact on bending stiffness of composite materials probably. Based on this deduction, the bending stiffness of APET/PE/EVOH/PE (443 µm) is higher than APET/PE (409 µm) is mainly caused by thickness and EVOH layer.

6.4 Tensile test

According to Intertek (2017), tensile strength is the maximum force that the material could resist from breaking when a direction parallel load is applied. With the purpose of quality control purposes, tensile strength is served to evaluate breakability of many plastic films which experience a direct and simple tensile stress.

Ten pieces of specimen are used in this measurement. For Bio-PE 98 and PLA-50, strain at break in MD and CD both exceed 34%, and so it is with CD of APET/EVOH/PE and APET/EVOH, which is the instrument capacity, so their tensile strength could not be measured. In addition, there is not enough material for Bio-150 and Bio-300, so only CD tensile test with ten strip samples are measured. The printed receipts are exhibited in figure 56.

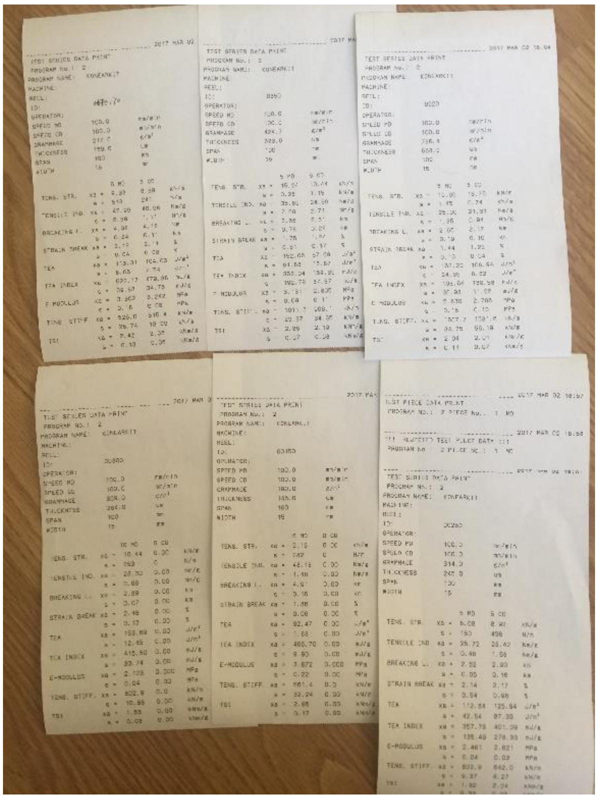

Figure 56. Recipes of several materials.

Tensile index is derived from measuring the tensile strength and divide it by grammage. Therefore, tensile index is more objective and it is an accurate indicator for different thickness materials. From figure 57, the tensile index of machine direction is higher than cross direction for bio-based materials, such as Bio-170, Bio-350 and Bio-620. And the highest tensile index is Bio-film 150 in cross direction, which is 48.18 Nm/g. The lowest tensile index is Bio-fil 620 (21.31 Nm/g). Regarding composite materials, tensile index in CD is a bit higher than MD, which is different from Bio materials. It is possible that there is molecular orientation when processing leads to the change of tensile strength. In contrast, APET/PE, APET/EVOH/PE, APET/EVOH and APET/PE/EVOH/PE with similar tensile index, which may be due to PE has no remarkable influence on tensile strength of composite materials. Considering bioplastics, the data is distinct different. It is possible affected by color.

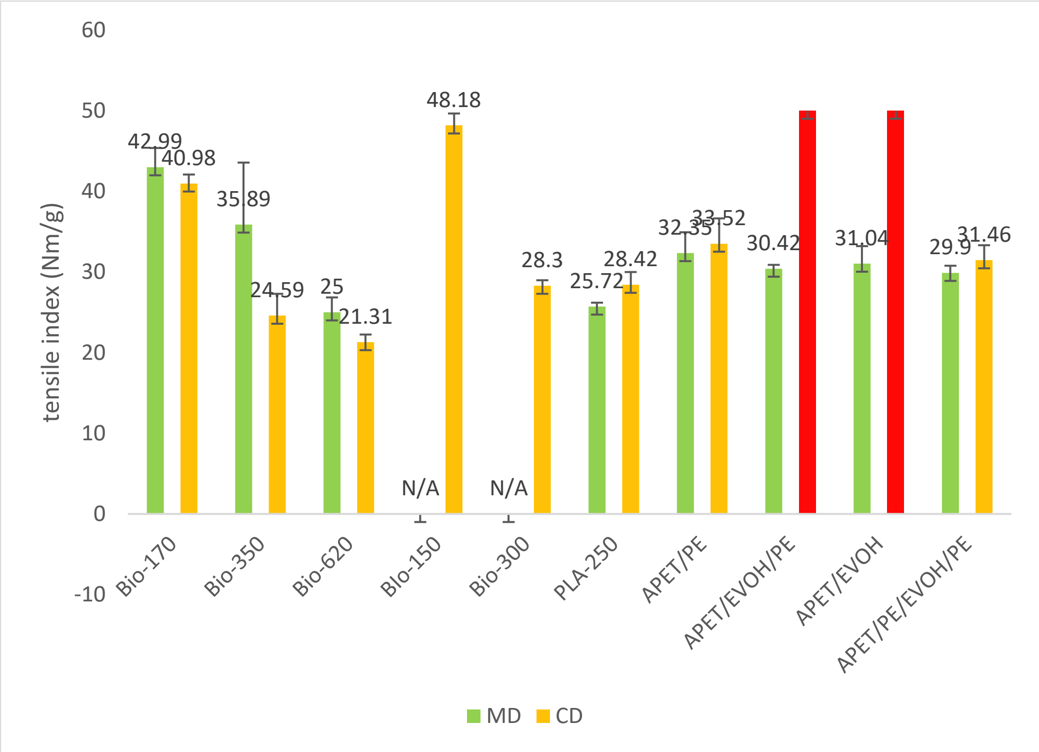

Figure 57. Tensile index.

Figure 58 is the strain at break of these materials. Strain at break is the ratio of elongation length and original length after the test specimen breakage. It stands for the capability of a material to withstand tensile stress and resist crack development. (Ensinger 2017.) Strain at break is related to the flexibility of molecular chain. This data can represent the interior structure of materials. From red column in figure 58, Bio 98 and PLA-50 are thin (98 µm and 47 µm), the tensile index outside the instrument capacity. It might be pointed out that the thinnest materials experience most elongation. From this figure, the strain at break of composite materials is much higher than that of bioplastics and compositing would improve the strength of base material.

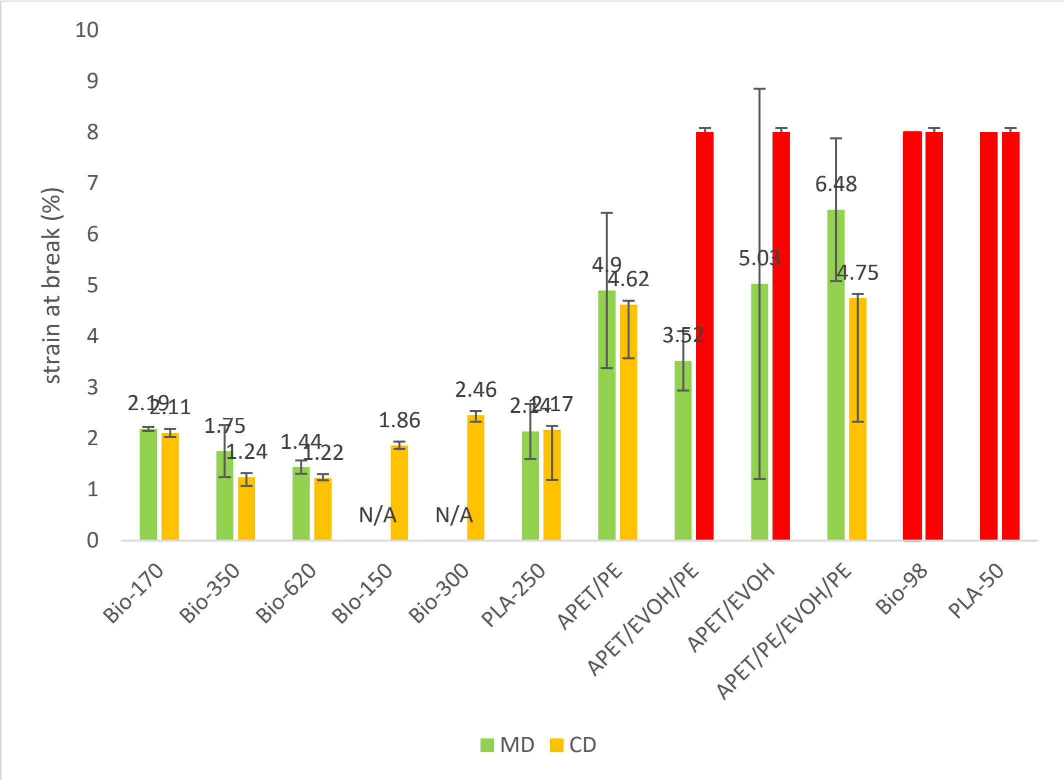

Figure 58. Strain at break.

The highest value is 6.48% that is APET/PE/EVOH/PE and the lowest value is 1.44% (Bio-film 620) in MD. With regard to bio materials, strain at break of MD is a bit higher than that of CD. However, composite materials see the obvious distinct in strain at break and there are no rules for MD and CD. For APET/PE and APET/PE/EVOH/PE, it is the same with bio materials. While it is totally opposite for APET/EVOH and APET/EVOH/PE.

The standard deviation of PLA-250 is much higher (0.98% in CD and 0.54% in MD) and so it is with APET/EVOH (3.82% in MD). Even though for the same materials, strain at break is fluctuation between various strip samples, because of interior defections, stress concentration, or interior deformation resulting from microcrack. Considering high polymer material, there are relaxation and orientation of molecular chain segments during tensile process, and the final micromorphology is achieved by a combined effect of these factors (Yang et al. 2008, p. 50). The final breakage material likes figure 59. It suggests that the breakage shape in MD is always flat and straight, while there is wave in the breakage lines in CD.

Figure 59. The example of APET/PE breakage.

6.5 Conclusion of this chapter

Comparing bioplastics with composite materials, composite is likely to improve barrier properties. The air permeability of Bio-350 is 0.7 ml/min, while APET/EVOH/PE is totally air resistant. PLA-250, whose thickness is similar with Bio-350, APET/EVOH/PE and APET/EVOH, but the bending stiffness is the highest among these materials, and it is also non-air permeability. In addition, the tensile index of PLA-250 is similar with APET/EVOH/PE and APET/EVOH. Therefore, PLA-250 is most effective material among these materials.

7 CONCLUSION

Plastic products exist extensively, and thermoforming is one of the most popular manufacturing methods of plastics in packaging industry. Acknowledging common thermoforming machinery in Europe and China is valuable in describing the the quality of thermoforming products and thermoforming industrial process. Therefore, one research questions in this thesis was aimed at presenting and comparing thermoforming machinery in Europe and China about production capacity, final product quality and components. Moreover, fossil-based thermoformed plastics result in environmental issues and waste disposal problems. Replacing it by some environment-friendly plastics is unavoidable and meritorious. The other research question was evaluating which material would acquire the best quality among several kinds of materials received from different places.

Given thermoforming machinery, many core components of state-of-art machinery in China are employed from other countries. Vacuum pump is from Germany, electrical components are from France and pneumatic components are from Japan. Furthermore, the material categories and requirements are limited compared with European machinery. Some European machine could accept any thermoplastics with any thicknesses. And Europe considers more about energy saving when designing machinery. Besides, there is a difference in production capacity.

In terms of bio-plastics, PLA and composite materials, some results have been found though mechanical tests. Compared to conventional thermoplastics with the same thickness, PLA has better mechanical performance. In a word, PLA-250 is the best material among these materials, and it is also degradable.

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