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Advanced Thermoforming: Methods, Machines and Materials, Applications and Automation
Sven Engelmann

Advanced Thermoforming
Methods, Machines and Materials, Applications and Automation

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For my lovely wife Ulrike
and my wonderful children
Leo, Peter, and Luzy.

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Preface

This book focuses on practical applications. It deals with technical parts, but also with packaging (the topics range from bathtubs to syringe blisters). Beside the applications, the respective machine and tooling technologies, automation, and, of course, semifinished products and materials are described. Also a large part of the book is dedicated describing innovations in materials, so that the book can serve as a useful reference work on raw materials and semifinished products. Also discussed are multilayer structures, which are finding increasing use for fuel tanks as well as cheese packaging. Reliable applications of machine, tooling, and materials are demonstrated. The basic principles of extrusion, which are important for thermoforming are named for clarity's sake without going into depth.

The basic principles of thermoforming and thermoplastics are covered briefly, as there are already several standard works dealing with these subjects. The present book is intended to complement, not replace the existing literature on thermoforming, and to open up new perspectives on the applications considered within. The author is grateful to all those writers who have advanced, described, and explained thermoforming and made it popular.

The aim of the book is to communicate points worth knowing about thermoforming and to arouse interest. The author hopes this book will show the reader the diversity and sophistication of the thermoforming industry and ways of implementing cost-effective production.

Sven Engelmann

Chapter 1

Introduction

Reference books can be difficult to read and understand. Often technical connections and contexts are described by using a lot of mathematics—and often right from the beginning—so that a large part of the target group is overcharged or quickly loses interest. However, reading books on technology and engineering can be fun. Books dealing with technology should impart knowledge at an adequate pace. We live in a world that is dependent on a multitude of technologies. Yet it can be observed that fewer and fewer young people are interested in technical professions. What are the reasons for this development? It is true that the rush of today's technology can initially have a discouraging effect. A lot of technology has become so complex and abstract that it is no longer possible to understand the connections through mere reflection or observation. As the modifications to technologies and processes come even faster, is it possible to keep up with these developments? The answer is yes!

There will always be technological development because economic issues and ecology are driving forces. Technological advancements, however, depend on the degree to which enthusiasm for technology can be aroused in persons with a certain talent and a disposition toward engineering. To some extent this book is based on a series of lectures called the "Basics of Thermoforming." Among these lectures the discussions range over many topics, even to the "mere" production of a yogurt cup.

There are many people who are not directly involved in the development of technologies but who exert nonetheless an influence on technological developments. These decision makers, however, do depend on basic knowledge of the technological linkages and contexts.

This book is intended as a reference book for the relatively small industrial sector of thermoforming applications. This book focuses on thermoformed products and applications. All of us once had the experience of asking ourselves, when contemplating a formed part, how was this part produced? This book is subdivided into the description of technical formed parts and of packaging.

Some parts may not even look like thermoformed parts to the casual observer. This book will discuss the enormous possibilities of thermoforming at a level that

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presents an overview of the diversity of this plastics-processing method for nonprofessionals. At the same time the book includes useful detailed knowledge for the professional practitioner.

This book takes the thermoformed part and traces it back to the process chain. Machine and tooling technologies and the possible automation steps are explained in full detail, as are the materials used. For the description of the materials, the effects of the extrusion process are also considered and the characteristics of the raw materials are explained. Where the process chains are similar for some of the described applications, only the distinctive features are identified. The book also describes methods for the optimization of the thermoforming process.

If you look closely at your surroundings, you will find countless objects in your daily use that were produced using the thermoforming process. Bath and shower tubs are thermoformed parts and among the first thermoforming products you will see on entering your bathroom in the morning. If you decide to use a new toothbrush, you have to tear open its packaging made of thermoformed material. Opening your fridge, you will see thermoformed yogurt cups, and even your fridge itself has a thermoformed interior housing (liner). Even though thermoforming is being more and more used for automobile interiors and exteriors, the automotive industry has not yet played a big role in plastics engineering. But the pressure for more efficiency, cost cutting, and longer durability of some products has managers changing their outlook on thermoforming.

Thermoforming has a vast area of applications. From bathtub to toothbrush blister, from a cookie tray to a car roof, it does not matter which product you look at; most often it is a high tech application.

This book should help give an overview and insight in this advanced technology. There are different processes you can use depending on the application you need. The machine technology is getting more refined, enabling users to get with higher productivity, better quality, less material cost, and so forth. With the use of new machine drive concepts and digital machine control systems, modern machines need less energy.

The mold technology has dramatically developed in the past few years. Flexible molds require less change over times. This book shows the possibilities available with the new standard technology.

The literature so far has covered little regarding the handling of the semifinished products and formed parts, as well as further handling in inline processes. Automation is well on its way and will not stop for technical parts or in the packaging industry. This book will show the possibilities of automated processes. The forming, filling, and sealing processes will be reviewed in particular, as these processes are not exhaustively treated in other works of literature.

Many innovations, such as thermoformed automobile body parts or fully automated packaging assembly lines, include end packaging. These innovations need to be discussed in a written work and so are addressed in this book.

A discussion of thermoforming should also include the various developments from the resin producers and semifinished product producers. A large part of the book will cover such materials, so that the book will serve as a useful reference.

The discussions of multilayer laminates have applications ranging from fuel tanks to the packaging of cheese.

The simulation of formed parts will be covered in another chapter in this book. The thermoforming simulation is even less discussed than, for example, simulation for injection molding. This and many other procedures of the entire field of thermoforming are described in this book.

The book therefore takes a comprehensive view of thermoforming and shares the expert knowledge of experienced thermoformers. With regard to the available literature, the application of thermoforming differs significantly from that of injection molding, and it is all the more important to assemble the available knowledge on thermoforming, as it is in this book. While much information contained in this book can be researched, the thermoforming applications assembled here will help the user to better understand the end results.

Of course, companies that specialize in thermoforming processes are dependent on their workers' know-how. In many circumstances knowledge of the tricks of thermoforming can lead to significant competitive disadvantages. Indeed I have benefited from people who supported the ideal of this book by divulging their knowledge. Experienced thermoformers, for example, Dr. Manfred Reichert, Horst R. Dänzer, and above all Rudi Salmang, have greatly contributed to the writing of this book. For several decades they have collected experiences in the field of thermoforming and the related processing steps. They were all willing to share their knowledge. For these persons it is certainly true that tradition does not mean the keeping of the ashes, but the passing on of the fire.

The compilation of the book was also supported by a number of companies that, despite the hard times during the economic crisis in 2009 to 2010, made a point of describing interesting applications and providing information. First of all Kiefel GmbH, Freilassing, Germany, must be mentioned. Here the support was chiefly provided by Erwin Wabnig and Reinhold Plot, who in the European Thermoforming Division are deeply involved with the Society of Plastic Engineers. Both men significantly contributed to the development of this book by drawing attention to interesting research at their company and providing relevant information. Likewise Geiss AG, Seßlach, Germany, contributed to the making of this book by providing information. Manfred Geiss, in particular, must be mentioned, who, as is well known, always presents up-to-date technologies in his speeches. Thanks must additionally be extended to the tooling manufacturer Bosch Sprang BV, Netherlands, especially to Berry Smeulders, who gave information about interesting examples arising from engineering practices.

A large part of the book deals with the description of raw materials. It is very gratifying that so many companies and persons who were interviewed were so willing to share their knowledge; they significantly raised my understanding of thermoforming materials. My particular interest in writing this book is to sensitize the user to the connection between knowledge of the materials and successful thermoforming production. So far this is an area where not all phenomena have been recognized. The more knowledge we have about materials and their processing characteristics, the more economic efficiency we can impart to production.

Special thanks goes to Paul de Mink of Borealis, Austria, who shared his knowledge about extrusion and thermoforming of PP. Rudi Salmang also contributed his profound knowledge on extrusion and thermoforming of PS. Furthermore, he shared his vast experience in helping to proofread the final typescript of this book. Additional thanks go to Willy Onclin, PhD, of Eastman Chemical BV, the Netherlands, and Frank Kleinert of Klöchner Pentaplast GmbH & Co. KG, Germany, for their counsel regarding the development of the articles dealing with PET material.

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The stimulus for the development of this book also came from Hannes Jacob, Klaus Wlasak, and Marcus Schuck of Jacob Plastics GmbH. Special thanks go to Thorsten Eymael and Nina Schick of SE Kunststoffverarbeitung GmbH & Co. KG for their help as well. To Gerlind zum Hingst, Sabine Jettke, Bärbel Beyhl, and Karin Scherer, I want to express my gratitude for their support with the organization of this book and help with the translation. Also many thanks to Hartmut Thimig and Tobias Vogt.

All other persons who contributed to the development of this book are referred to in the relevant chapters. Last, but not least, I would particularly like to thank Gerhard Schubert, one of the most innovative machine designers, for his support.

In this book a semifinished product that can be wound is referred to as "film." Any semifinished product that, due to its material thickness, cannot be wound, is referred to as "sheet." While this book is an attempt to explain the world of thermoforming, it lays no claim to completeness or universal validity and assumes no liability.

Several persons and companies which deal with thermoforming are deliberately cited. The experiences of the author show that this provides support for someone who is seeking advice.

Naturally, the number of applications described in the book is not all-encompassing, because this book can only provide an overview about the various possibilities. Also, in this regards, only one reference per topic is mentioned in order not to create a competing impression.

Chapter 2

Basics of Thermoforming and Thermoplastics

Several very good books on the basics of thermoforming and thermoplastics have already been published. Some institutes and machine manufacturers are offering training courses for the acquisition of basic knowledge about thermoforming as well as of basic knowledge about thermoplastics. For this reason the present book does not describe in detail the basics of thermoforming. The plastics discussed in this book are illustrated by means of an example of use.

Thermoforming normally consists of heating a thermoplastic semifinished product until the forming temperature is reached, and subsequently the desired form is obtained by means of pressure difference and mechanic stretching. Mostly, this is carried out with only one mold half. Thus it can already be discerned that, compared with other plastic processing methods, thermoforming presents economic advantages relating to the forming tool.

Thermoforming is a forming method that, by means of several process steps, facilitates the production of an inherently stable plastic part. Basically the raw material is transformed by heating into a viscous-flexible phase and a relatively low load. The formed part cools in the tooling and is subsequently demolded. Due to the cooling down the orientations of the molecule chains keep their stretched positions. Re-heating results in a recovery to the original sheet state.

The process steps generally take the following order:

- *Heating of the semifinished product.* The semifinished plastic product is heated until the forming temperature is attained. This can be effected with heating elements, contact heating units, or convective heat. These heat sources can also be combined.
- *Forming.* This is mostly effected by means of a thermoforming tool.
- *Cooling.* Cooling is effected under a mold constraint until a temperature is attained for which the formed part is inherently stable.
- *Demolding.* Demolding of the inherently stable formed part.

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Over many decades different thermoforming methods have been developed based on the above-mentioned principle. Semifinished plastic products and thermoforming machines are, of course, subject to certain standards. The semifinished products can be processed either as film or as sheet, and they can be manufactured in an upstream process step in a machine placed directly in front of the thermoforming machine. Generally, films are commercialized as wound reels. If the semifinished product cannot be wound on reels due to its thickness, it is cut and handled as sheets. Most plastics that have a thickness of more than 2.5 mm are processed as sheets.

PC, PMMA, PA, POM, and ABS as well as fiber-reinforced composites and self-reinforced materials are semifinished products for technical applications. For the automobile industry, often thermoplastic elastomers and thermoplastic polyolefins are used.

PET, PS, PP, PVC, and PE are semifinished products for packaging applications. They are provided with corresponding additives for the modification of their characteristics. Modifying agents are necessary to obtain food compatibility and resistance, such as to improve their permeation characteristics.

For the manufacturing of technical parts as well as in the packaging sector, foamed semifinished products are increasingly utilized as they reduce weight and offer insulation advantages.

Many semifinished products consist of several different layers in order to provide the final product with the best possible characteristics. In the food-packaging sector the following characteristics are especially demanded:

- High oxygen, gas, water vapor, and aroma barrier
- High product neutrality
- Light protection and UV barrier
- Excellent thermoforming and sealing characteristics
- Good mechanic properties
- Good printability
- Peelability

However, multilayered semifinished products are also available for technical products, for example, in lacquer coats for car bodies. Recycled material may even be incorporated into the intermediate layer of semifinished product.

2.1 THERMOFORMING METHODS

Because thermoforming is normally effected in one mold half, only a one-sided definition is possible. The advantage is that only one mold half must be designed, dimensioned, and manufactured.

The forming technologies are differentiated into the following subgroups:

- Positive
- Negative
- Compressed air

- Vacuum
- Plug assisted
- Lamination

To some extent these methods can also be combined.

2.2 POSITIVE FORMING

In the positive forming method the heated semifinished product is drawn over the forming mold. The definition is on the inside of the finished part. During the forming process the inside has contact with the forming mold and takes over its shape.

In a first step, the thermoplastic semifinished product is brought to its forming temperature. In order to receive a uniform wall thickness distribution, the material is pre-streched by means of pre-blowing. After this, the mold closes, and vacuum is applied to bring the material to its final shape. Demolding takes place after the plastic has cooled.

The positive forming method is often used in sheet machine applications.

2.3 NEGATIVE FORMING

A common application of negative forming is in the production of cups. After the heated film has been positioned in the forming station, the mold closes. As the plug assist pulls down, the trapped air in the cavity is released by means of venting holes. Then the forming air is applied and the part receives its final shape. Demolding takes place after the plastic has cooled down.

2.4 ADVANTAGES AND DISADVANTAGES OF THERMOFORMING

Thermoforming is mostly in concurrence with injection molding. The advantages and disadvantages listed below principally refer to a comparison with injection molding.

The manufacturing of technical articles by forming has the following advantages:

- Heavy parts can be produced (up to 125 kg)
- Large parts can be manufactured (up to 4 m^2)
- Flexible wall thickness (0.05–16 mm)
- Cost-effectiveness for small batches (tooling costs)
- Low costs for modifications and for color change
- Homogeneous multilayer applications are possible

The manufacturing of packaging parts by forming has the following advantages:

- Shorter cycle times
- High output
- Processing of printed semifinished product is possible
- Processing of multilayered semifinished product is possible

The disadvantages of thermoforming are the following:

- Less scope for design (undercuts)
- No uniform distribution of wall thickness
- Temperature control is difficult
- For a given semifinished product, the manufacturer has no influence over the formulation of the film, if dealing with purchased film

2.5 THERMOFORMING MACHINES

In order to fulfill the requirements of the different thermoforming methods, different types of thermoforming machines are available.

2.5.1 Sheet-Processing Machines

Sheet-processing machines are used in the following circumstances:

- For small- and medium-sized batches
- For rapid color changes
- For large-scale products

Typical formed parts are the interiors of refrigerators and automobile interiors and body parts.

2.5.2 Roll-Fed Machines

- Roll-fed machines process semifinished thermoplastic products that are delivered on rolls.
- For the production of high quantities, it is possible to place an extruder upstream of the thermoforming line.
- Depending on application and machine, it is possible to produce medium to high quantities.

Typical formed parts are yogurt cups, drinking cups, and cookie trays.

2.5.3 Skin and Blister Machines

In the skin method a heated film is formed over the product to be packaged. Unlike the blister method, no forming tool is necessary. Some examples of the use of the skin method are the packaging of pocket lighters, padlocks, and batteries.

2.5.4 Forming, Filling, and Sealing Machines

Forming, filling, and sealing machines have the following components:

- A forming station
- A filling station
- A sealing station
- A punching station

These machines consist of complete packaging lines into which the thermoforming process is integrated. The formed part is immediately filled and subsequently sealed with a lid film and then punched out. Some examples of multipack use are for yogurt, cheese, cold-cuts, single-portion packs, toothbrushes, and batteries.

2.6 SEMIFINISHED THERMOPLASTIC PRODUCTS

Attention must be paid to two factors that influence the shape of the formed part and the process sequence for thermoforming:

- Free shrinkage
- Mold shrinkage

2.6.1 Free Shrinkage

If thermoplastics are heated beyond glass transition temperature, there is shrinkage caused by a relaxation of the molecules' orientation. The amount of shrinkage depends on the extent of relaxation of orientation forced during the heating processing.

Extruded semifinished products are subject to free shrinkage after heating. This fact must be taken into consideration for, to cite only one example, thermoforming machines with downstream production steps. The free shrinkage of the film creates tolerances that can lead to quality problems. For example, an offset may occur between a formed part and the punching position.

2.6.2 Mold Shrinkage

Thermoplastics are subject to a volume contraction during freezing in the cavity and so can cause the dimensions of the formed parts to be smaller than the respective tool dimensions by the shrinkage value.

Semicrystalline plastics have higher mold shrinkage values than amorphous plastics:

$$\text{total shrinkage} = \text{processing shrinkage} + \text{post shrinkage}$$

where

PS = 0.4 − 0.7%

PP = 1.5 − 1.8%

Mold shrinkage and free shrinkage are primarily influenced by the following:

- Shape of the formed part
- Evenness of the wall thickness of the formed part
- Temperature of the tooling
- Deep drawing ratio
- Forming temperature
- Filling additives in the semifinished product

In this book mainly the characteristics of PET, PP, PS, and PLA are described by way of examples of their use. Materials such as A-PET/PE and ABS/PMMA and other multilayer structures as well as flexible films are also discussed.

Blends and certain engineering polymers are covered to a lesser extent. Additives are utilized in order to give plastic parts certain defined characteristics. The semifinished products that are used for thermoforming are blended with additives during manufacturing, for example, during the extrusion process.

The typical additives are as follows

- ***Antiblocking agent.*** The antiblocking agent facilitates the unwinding of film from the reel and is useful for the reliable stacking and destacking of the formed parts. An antiblocking agent can be added during extrusion of the semifinished product. However, it is also possible to apply an anti-blocking agent to the surface of the semifinished product.
- ***Antifogging agent.*** The antifogging agent prevents the accumulation of condensate on the inside of packaging (e.g., salad cups), which impairs the transparency.
- ***Static inhibitors.*** The packaging of electronic components necessitates the use of an electroconductive material in order to avoid overvoltages und damage to these electronic parts.
- ***Talcum powder and chalk.*** Talcum powder and chalk are reinforcing and filling materials. The principle task of these additives is to make the application as cost-effective as possible.
- ***Nucleating agent.*** Nucleating agents affect the crystallization behavior of semicrystalline materials. Nucleating agents are used to improve the transparency and the processability of PP.

- ***Foaming agents.*** Foaming agents are used for the production of foam materials. There is a distinction between physical and chemical foaming agents. (1) Foaming gas is conducted into the extruder when using the physical process. (2) The chemical process requires substances that are mixed into the polymer melt. These substances cause the foaming phenomena.
- ***Crystallization accelerator (C-PET).*** Crystallization accelerators are used in the production of C-PET to effect temperature resistance.
- ***Crystallization inhibitor (PET-G).*** Crystallization inhibitors prevent crystallization and thus the opacity of PET-G, improving sealing behavior and enabling broader processing temperature range to be obtained.
- ***Glass fiber, carbon fiber, or aramid fiber.*** Glass fibers, carbon fibers, or aramid fibers are used to increase the mechanic properties of thermoform parts. These reinforcements can significantly improve the stability and load limits compared with unreinforced plastics.
- ***Plasticizer.*** Plasticizers are used to adjust the transition temperature of plastics. In particular, they are used if a plastic is too brittle in the range of the service temperature.
- ***Aging inhibitors and light stabilizers.*** These are additives that delay or prevent brittleness, a type of damage caused by exposure to light and deterioration of the material over time.
- ***Colorants.*** Colorants facilitate the use of color in the design of the material.