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Peter Schwarzmann

Thermoforming

A Practical Guide

2nd Edition

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2nd edition

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Preface to the 2nd English Edition

The success of the 3rd expanded German edition has resulted in ILLIG Maschinenbau professionally translating the book into English. This 2nd English edition of the work shows the extensive technological innovations in thermoforming processes and new applications that have arisen since the first edition was published. A highlight is the decoration of moldings in Chapter 19 “Decoration and thermoforming”, which describes the innovative process of in-mold labelling (also IML-T in-mold labelling in thermoforming) and other design possibilities of molded parts. The revised English edition is intended to create and support even more thermoforming experts worldwide. The author, Mr Peter Schwarzmann, has checked and approved the English content. Thank you for your intensive support.

Heilbronn, September 2018 *ILLIG Maschinenbau GmbH & Co. KG*

Preface to the 3rd German Edition

The supplementary material added to the translations into English, French, Chinese, Russian and Spanish has combined with advances in thermoforming technology and the demand for more information regarding tool technology to inspire the substantial revisions and new material incorporated in this 3rd edition. The author, Mr Peter Schwarzmann, has consistently kept sight of this work’s original objective while expanding its scope.

Heilbronn, June 2015 *ILLIG Maschinenbau GmbH & Co. KG*

Preface to the 2nd German Edition

The success of the 1st edition, which has also been translated into the English, French, Chinese and Russian languages, has combined with extensive technological innovations in thermoforming processes and new applications to inspire this 2nd edition with its comprehensive revisions and new material. The original objective of this work

Heilbronn, October 2008 *ILLIG Maschinenbau GmbH & Co. KG*

Preface to the 1st German Edition

The manufacturing processes employed in industrial thermoforming are currently finding extensive use in an array of applications that could hardly been conceived of just a few decades ago. Thermoforming has expanded beyond its traditional sectors, such as vacuum forming of panels for displays, refrigerators and automotive components, into pressure forming to produce packaging materials, ultimately conquering a considerable market share. Continuous improvements in thermoplastic materials have combined with ultra-modern machinery and tools to create increased production counts featuring greater precision in the formed parts. Originally situated in the realm of manually executed crafts, thermoforming has evolved into an established production process relying on consistent application of scientific insights from material sciences, supported by technology for measurement and closed-loop control. Reproducible process parameters allow application of procedures for industrial use in high-performance assemblies. In addition to numerous articles published in magazines, for several decades ILLIG Maschinenbau GmbH & Co. KG has also been disseminating the basics of thermoforming in training courses. What has been missing is a comprehensive compilation of the basic processes and procedures for the student as well as the engineer or technician who is currently active in the field, in a work capable of simultaneously serving as an introduction to the discipline for both groups by furnishing basic knowledge as well as more extensive expertise concerning individual questions. The objective of “Thermoforming: A Practical Guide” is to close this gap by fulfilling the stated objectives. It provides comprehensive descriptions extending beyond thermoplastic materials to embrace all of the steps in the thermoforming process along with an array of machine types and the basics for building molds and tools, explained with examples from actual practice. The genesis of this book is closely connected with the 50-year history of ILLIG itself. Accordingly, numerous insights, suggestions and experiences have entered this book, and I extend my particular gratitude to the author, Mr Peter Schwarzmann, for providing a detailed portrayal of this subject matter. I would like to thank Mr Günter Kiefer, who has served as the head of the Development and Engineering Department at ILLIG for many years, and Prof Dr Günther Harsch for their critical proofreading of the manuscript, and for their numerous suggestions for improvements and additions. The publisher and the author hope that “Thermoforming: A Practical Guide” will serve as a source of convenient access to the essentials of thermoforming and furnish useful assistance in resolving problems when they arise.

Heilbronn, January 1997 *Adolf Illig*

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1

Introduction

Thermoforming is understood as the process of reshaping thermoplastic materials at high temperatures in order to create formed parts.

The illustration in Figure 1.1 shows the concept of a thermoforming process relying on vacuum forming.

The stages in this process are:

- Heating the semi-finished material to its forming temperature within the elasto-plastic range
- Endowing it with a shape defined by the thermoforming tool
- Cooling under forced retention, which continues until a temperature at which the formed part achieves geometrical stability is reached
- Demolding the geometrically stabilised formed part

The finished part's wall thickness is defined by the ratio of elongation in the generated surface to the initial surface area. The wall-thickness distribution in the formed part is primarily determined by the mold and the forming procedure.

The contour definition – equating with the accuracy with which the mold's contours are reproduced – is primarily determined by the temperature-sensitive strength of the semi-finished product during the forming process and the effective contact pressure generated between the semi-finished product and the surface of the mold.

The formed part is usually cooled on one side through contact with the mold and on the other side through atmospheric or forced-air cooling.

This process is usually followed by various subsequent treatments, such as cutting, welding, adhesive bonding, hot sealing, painting, metallising and flocking.

The terms "vacuum forming" and "pressure forming" are also employed. This also refers to molding using vacuum and compressed air.

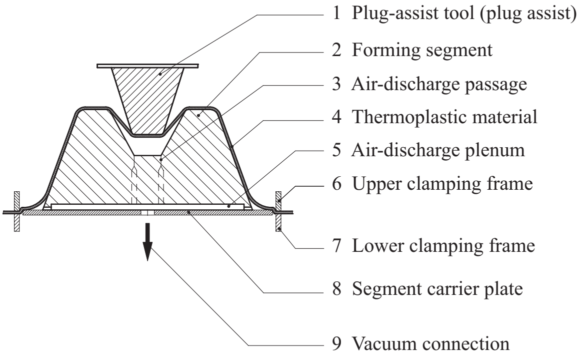


Figure 1.1 Concept of thermoforming

Advantages and disadvantages of thermoforming

A manufacturing process will only prove successful provided that it can produce parts of equal quality but at less expense, or in better quality at the same cost. There are also applications in which injection molding and blow molding compete with thermoforming. Thermoforming is usually without competition in the realm of packaging technology, except in those cases in which cardboard and paper are utilised as alternate packaging materials.

The essential benefits of thermoforming are:

- Formed parts with extremely thin walls, such as packaging units, can be manufactured using semi-finished materials with a high melting viscosity, although such parts require granulate with an extremely low melting viscosity for production with injection molding – provided that they can be manufactured at all.
- The smallest thermoformed parts assume sizes on the order of those used for medicinal tablets and button cell batteries. Large formed parts, such as garden ponds, reach sizes extending to between 3 and 6 metres in length. Formed parts in dimensions embracing multiple square metres can be produced without problems, while the process technology imposes no inherent limits on the size of the formed parts or the gauge of the semi-finished material.
- Semi-finished materials with gauges ranging from 0.05 to 15 mm are used, with foamed materials extending to 60 mm.
- Application of multilayer materials renders it possible to produce formed parts with combinations of properties regarding flexural and tearing strength, surface gloss, haptic compliance, anti-slip properties, suitability for sealing, UV resistance, barrier characteristics, embedment of granulate in a layer below the surface, inclusion of layers incorporating fibres, etc. When the individual layers fail to furnish adequate adhesion, then intermediate layers can be incorporated to facilitate bonding.

- Thermoforming is suitable for processing foamed materials, fibre-reinforced materials and thermoplastic materials with laminated textiles as well as preprinted semi-finished products.
- The stretching representing an intrinsic element in the process enhances the formed part's mechanical properties by promoting orientation.
- Owing to forming contact on just one side, thermoforming molds are more economical than (for instance) injection molding tools, which rely on bilateral form contact to define wall thickness.
- The modest tooling costs represent a benefit of using thermoforming for limited production runs. Thermoforming's salient assets in large production runs consist of the minimum wall thicknesses that can be achieved and the high production rates reached by the thermoforming machines.
- Thermoforming machines featuring modular design configurations allow adaptation to the required production rate.
- Waste materials such as the skeletal sheet webs and clamped edge strips are granulated, only to return to the processing cycle when recycled during manufacture of the semi-finished product.

The materials used in thermoforming assume the form of semi-finished products consisting of sheet material in rolls or formed into pre-cut sheets that are produced from granulate or powder in an initial shaping procedure. This entails supplementary expenditures relative to injection molding for the initial material.

In thermoforming, the semi-finished product is only in contact with one side of the thermoforming tool as an intrinsic characteristic of the process. It is for this reason that the formed part represents an accurate reproduction of the mold's contours on only one of its sides. The contour on the opposite side is produced by the resulting elongation.

Future perspectives

Within the plastics-processing sector, it is thermoforming that represents the realm promising the highest growth rates. This applies to formed parts destined for technical applications as well as packaging.

- In its guise as a process that relies on careful craftsmanship and extensive experience, thermoforming is currently in a state of transition as it evolves into a highly controlled process.
- Sensors combine with closed-loop control technology to allow automation of the thermoforming process.
- Recycling waste materials from production, granulation and admixture to form new materials has long been the state-of-the-art in technology.

- Natural “bio” synthetics are becoming progressively more economical. The thermoforming process is predestined to apply these materials for thin-wall packaging with ever-increasing emphasis.
- Application of multilayer materials allows production of parts featuring a wide spectrum of potential applications.
- Meanwhile, in high-wage countries, the trend is continuing toward increased automation, integration of subsequent processes and higher productivity.

2 Basic principles and terminology in thermoforming

2.1 Process sequence

The thermoforming process consists of the following individual steps:

1. **Heating** the material to forming temperature
2. **Preforming** the heated material with prestretching
3. **Contour molding** the formed part
4. **Cooling** the formed part
5. **Demolding** the formed part

Heating

See Chapter 4 “Heating technology in thermoforming”.

Preforming

Various options for preforming are in existence, i. e.:

- Prestretching with preblow, i. e., bubble formation with compressed air
- Prestretching with presuction, i. e., bubble formation with vacuum
- Mechanical prestretching using a plug assist, also called plug-assist tool or upper plug
- Mechanical prestretching using the form itself
- Combination of the above-cited prestretching options

Contour molding

Examples of contour molding:

- Contour molding with vacuum (vacuum-forming machines)
- Contour molding with compressed air (pressure-forming machines or vacuum-forming machines with locked molds)

- Contour molding with compressed air and vacuum (pressure-forming machines with supplementary vacuum connection or vacuum-forming machines with locked molds)
- Contour molding with stamping. Stamping allows bilateral definition of the tool's contours. Applied for foamed materials, more rarely for stamping and calibrating edges.

Cooling

Cooling options for the formed part, based on machine type:

- Cooling through contact with the forming tool (usually unilateral)
- Cooling with air in various versions:
  - Air is ingested from the environment with suction (standard)
  - A building-installed system delivers cool air to the fans
  - Water spray mist is blown into the air current; as this spray mist evaporates in the air stream, it cools the air. At air velocities of approximately 10 m/s and a distance between fan and formed part of roughly 1.5 m, the air cools by about 10 °C. (Notice: When the airspeeds are too high, the formed parts become wet because adequate time for evaporation of the water spray mist is not available.)
- Free cooling in the air if procedure is without mold.

Demolding

Demolding proceeds once the thermoplastic material has cooled below its pliability temperature, i. e., it is stiff enough.

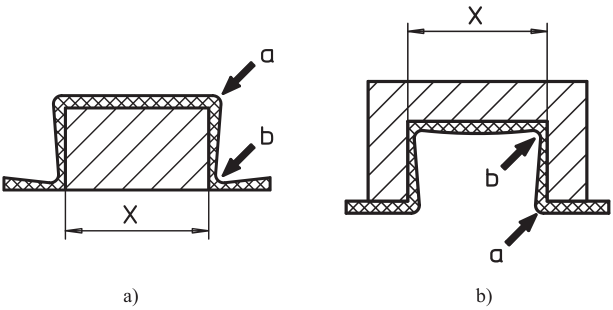
2.2 Positive and negative forming

Positive forming (Figure 2.1, a):

- Molding reflecting the outer contour of the form (simplified definition)
- The return forces in the material and the contour-molding forces are effective in the same direction.

Negative forming (Figure 2.1, b):

- Molding reflecting the inner contour of the form (simplified definition)
- The return forces in the material and the forming forces are mutually opposed.



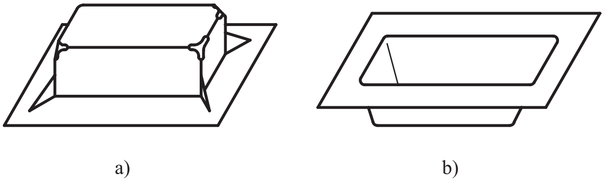
a) b)

Figure 2.1 Positive and negative forming
a) Positive forming (schematic)
b) Negative forming (schematic)
X = molded dimension from mold

Table 2.1 Comparison between positively and negatively formed part

Property	Positively formed part	Negatively formed part
Accuracy of molded image in the formed part	On the inside	On the outside
Dimensions (in drawing)	On the inside	On the outside
Thick edge sector	Edge thinned by stretching	Edge remains practically unstretched; wall thickness equals initial thickness
Thickest location*	On base	On edge
Thinnest location*	On edge (transition to sidewall)	On base (transition to sidewall)
Risk of wrinkle formation	At corners contiguous to edge	No wrinkle formation

* If molded without preforming, with relatively low stretching ratio



a) b)

Figure 2.2 a) Positively formed part with wrinkles toward the edge and chill marks at the corners marking the transitions between base and sidewalls
b) Negatively formed part without wrinkles and consistent edge thickness around entire periphery

2.3 Vacuum and pressure forming

Depending upon the forming pressure available for the thermoforming process, the standard reference is to vacuum or pressure forming.

During vacuum forming, the vacuum pump supplies the vacuum applied to the heated material which has been heated, as well as preformed as required, to suck it onto the surface for the mold. This produces a forming pressure corresponding to the difference between atmospheric pressure and the vacuum generated by the vacuum pump, i. e., of a maximum of approximately 1 bar (100,000 Pa).

During pressure forming, compressed air pushes the heated material against the surface of the tool. This process relies on a sealed compressed-air chamber, into which the compressed air can flow as forming air.

With regard to the maximum forming pressure (also pressure of the forming air), various levels are available: up to 2.5 bar, 6 to 8 bar and special-duty machines with up to approximately 200 bar.

2.3.1 Differences between vacuum and pressure forming

Table 2.2 Comparison between vacuum and pressure forming

Property	Vacuum forming	Pressure forming	Comment
Forming temperature of the material	Higher	Lower	With the same contour definition, temperature differential roughly 20 °C
Sag	Higher	Lower	Determined by the material’s temperature-sensitive strength
Friction between material and plug-assist tool	Higher	Lower	Friction increases with higher material temperature
Friction between material and mold	Higher	Lower	Friction increases with higher material temperature
Required forming force	Lower	Higher	Determined by the material’s temperature-sensitive strength Attention to special cases: APET, CPET, lowest forming force at a specific temperature!
Contour definition	Lower	Higher	At same forming temperature
Wall thickness distribution	Worse	Better	Universal statement
Chill marks	Higher	Lower	Owing to friction/stiction
Thermal resistance of formed part	Lower	Higher	As the forming temperature increases, the residual stresses in the heated material decrease proportionately, with commensurate increases in thermal resistance
Cooling time	Higher	Lower	Owing to forming temperature
Cycle time	Longer	Shorter	Owing to cooling time

Table 2.2 Comparison between vacuum and pressure forming *(continued)*

Property	Vacuum forming	Pressure forming	Comment
Vent holes in mold	Larger individual cross-sections	Smaller individual cross-sections	Sample bores: ▪ For HIPS: 0.8/0.5 mm, ▪ for PP: 0.6/0.3 mm. Example of slots: ▪ For HIPS: 0.5/0.3 mm, ▪ for PP: 0.3/0.2 mm.
Tool costs	Lower	Higher	Differences: Pressure box for pressure forming, size and sum of vent bores and slots, overall stability of mold.
Tool weight	Lower	Higher	Owing to pressure box
Retention force of machine	Lower	Higher	If the mold has no locking mechanism
Energy consumption for contour molding	Lower	Higher	Universal statement for tools with “standard design”. Very substantial reductions in energy consumption for pressure forming are available through application of targeted solutions.
Manufacturing costs for small production runs	Lower	Higher	Generally applicable blanket statement
Manufacturing costs for large production runs	Higher	Lower	Generally applicable blanket statement

If the quality can be achieved with either vacuum or with pressure forming, and the machines for both are available, then a calculation of product manufacturing costs for the formed part will determine whether vacuum or compressed air should be used for forming.

2.3.2 Application for pressure forming

Packaging parts

- As a universal rule, articles that must be produced in large numbers, such as cups, lids, trays, packaging inserts, etc.
- For materials with which vacuum forming is accompanied by difficulties in the areas of transparency, wall-thickness distribution and contour definition:
  - PP in consideration of its low melt resistance (sag)
  - OPS owing to its low forming-temperature range
  - APET because its transparency and suitability for molding both decline as forming temperatures rise
- For preprinted sheet material owing to the low level of distortion in the printed image at low forming temperatures.

Parts for technical applications

- Parts in which an extremely high level of contour definition (extremely small radii) is demanded and the material cannot be formed with this level of precision using a vacuum, such as polycarbonate and cast acrylic glass.
- For particularly high demands for surface quality in formed parts.
- In general, if the forming force obtained with vacuum is not adequate.

Conclusion

Using pressure forming extends the borders of the realm of possibility.

Pressure forming always requires more complex tools, but always offers the advantage of shorter cycle times.

The energy consumption during pressure forming is generally higher than in vacuum forming. Minimum compressed-air consumption implemented with appropriate tool technology can allow increased pressure for the forming air, which makes it possible to reduce the material's forming temperature. The energy consumption must be calculated to determine whether increased tool expenditure for decreasing compressed-air consumption represents a worthwhile investment.

Vacuum forming is better for limited production runs because the tools are simpler – with the proviso that the formed parts display the demanded quality.

The manufacturing costs incurred in producing the formed parts in large production runs are usually more favourable than with vacuum forming. The production costs for the formed parts must be subjected to mutual comparisons as the basis for unambiguous conclusions.

2.4 Forming pressure, contour-molding pressure, and contour definition

The forming pressure in a machine with vacuum forming corresponds to the difference between the atmospheric pressure on one side of the material and the vacuum that the vacuum pump is generating on the other side of the material. At sea level, the barometric pressure is approximately 1 bar (100,000 pascals), and this figure decreases by roughly 0.1 bar with each altitude increase of 1000 m. Thus the reshaping, or forming pressure (at sea level) will be about 1 bar with an as-new vacuum pump. At 1 m^2 A forming force of roughly 10,000 daN is thus exerted against the forming surface during vacuum forming. This corresponds to the total weight of approximately ten compact cars.

The contour-molding pressure as applied reshaping pressure of the material against the walls of the mold results from the forming pressure and the return tension in the material during stretching.

Within the mold, the positions indicated with (+) in Figure 2.3 are:

> *Resulting contour-molding pressure* = *Forming pressure* + *return tension in the material*

Applicable to positions identified with (–) in Figure 2.3:

> *Resulting contour-molding pressure* = *Forming pressure* – *return tension in the material*

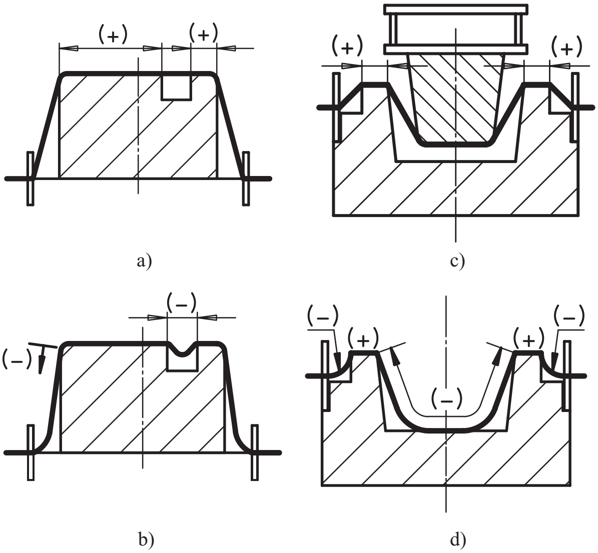


Figure 2.3 Schematic representation of resulting contour-molding pressure as sum of forming and return force of a material
a) and b) Positive mold
c) and d) Negative mold
(+) Surfaces on the tool where the return forces in the material and the contour-molding forces are exerted in the same direction
(–) Surfaces on the tool where the return forces in the material and the finish-forming forces are mutually opposed during forming

The contour definition achieved in a specific section of the part will primarily depend on the type of plastic, the forming temperature and the resulting contour-molding pressure.

2.5 Preblow, presuction, pressure equalisation, air injection

Preblow

Preblow (Figure 2.4) designates prestretching the semi-finished material by forming a bubble using positive pressure. The preblow pressure in most machines is a maximum of 0.03 bar.

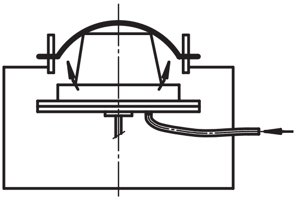


Figure 2.4 Preforming with preblow (this is not possible in all thermoforming machines)

Presuction

Presuction (Figure 2.5) designates preforming the semi-finished material by forming a bubble using a vacuum.

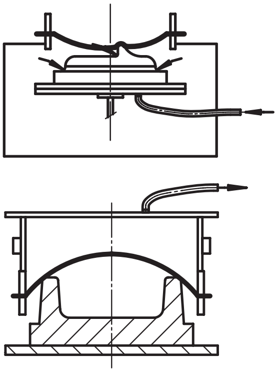


Figure 2.5 Preforming with presuction (this is not possible in all thermoforming machines)
Above: Presuction in a blow box
Below: Presuction in a vacuum/pressure box

Pressure equalisation

Once the cooling time has elapsed following the forming process, but before air-assisted demolding starts, the forming pressure (vacuum or compressed air) is