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Peter Schwarzmann

Thermoforming

A Practical Guide

2nd Edition

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Thermoforming

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A Practical Guide

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*

Contents

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.

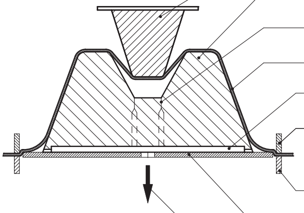


Figure 1.1 Concept of thermoforming

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.

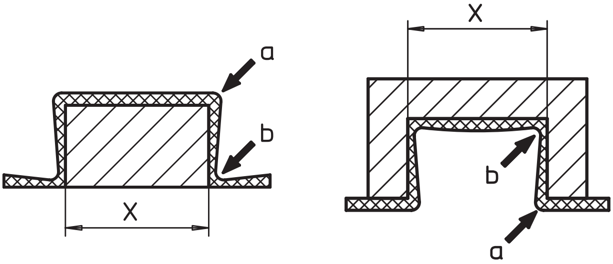
2.2 Positive and negative forming

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.



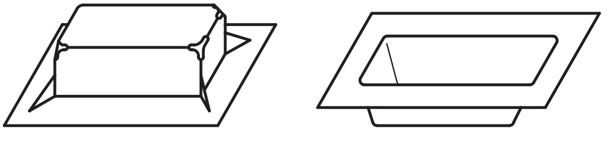
a) b)

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

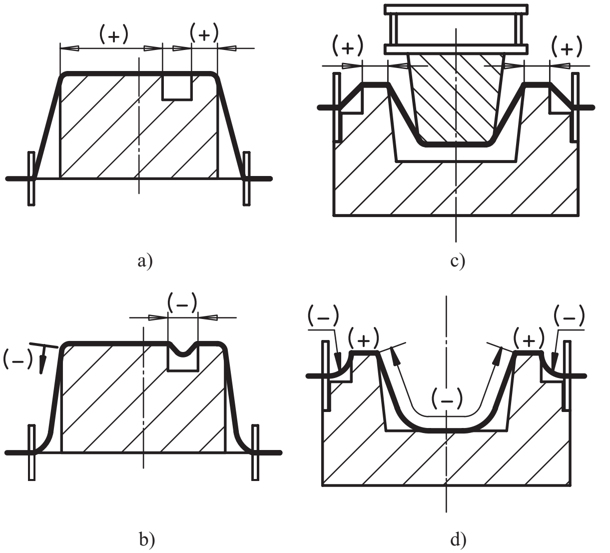


Figure 2.3 Schematic representation of resulting contour-molding pressure as sum of forming and return force of a material
a) and b) Positive mold
c) and d) Negative mold
(+) Surfaces on the tool where the return forces in the material and the contour-molding forces are exerted in the same direction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

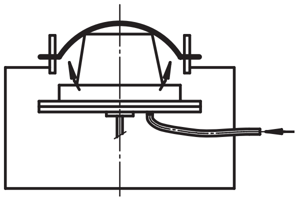


Figure 2.4 Preforming with preblow (this is not possible in all thermoforming machines)

Presuction

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

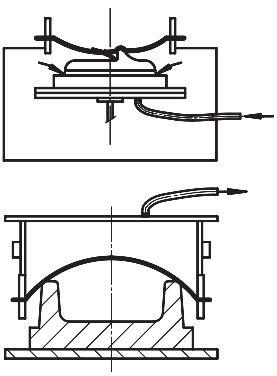


Figure 2.5 Preforming with presuction (this is not possible in all thermoforming machines)
Above: Presuction in a blow box
Below: Presuction in a vacuum/pressure box

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 deactivated, after which the pressure is immediately equalised with atmospheric pressure. This is the precondition for a reproducible demolding process sequence. During demolding of parts from large-volume or large-surface molds, air (demolding air) must be injected into the intermediate space that forms during demolding travel to prevent a vacuum from forming in the space between formed part and tool while the tool is in motion, allowing the finished part to be demolded. The quantity of demolding air must be adapted to the demolding speed.

2.6 Chill marks and blemishes

Chill marks are unintentional, partial, bead-like thick areas on formed parts. In contrast with unsatisfactory wall-thickness distribution, a chill mark appears as aesthetically disturbing and incorrect when the formed part is viewed. Chill marks are always undesirable.

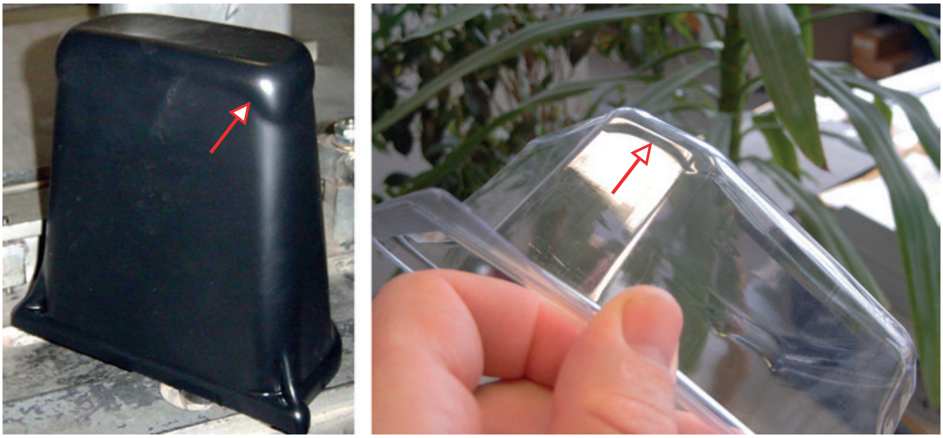


Figure 2.6 Chill marks

Chill marks occur in response to unfavourable parameters during preforming, such as:

- During initial contact between the heated material and the forming segment
- During contact with a plug-assist tool
- In some cases even as a result of the air stream from air that is too strongly concentrated during preblowing, in individual cases even as a result of a too strongly bundled air-discharge stream during forming of negative parts.

2.6.1 Chill marks on positively formed parts

The typical position for a chill mark on relatively flat positively formed parts is on the upper edge of the tool, see Figure 2.7.

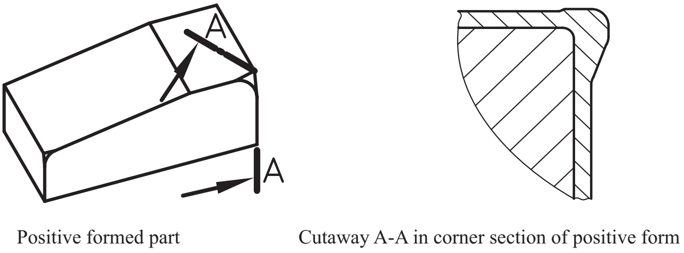


Figure 2.7 Typical position of a chill mark on a positively formed part

During substantial elongation, the chill mark is pulled into the sidewall during preforming.

Example of chill marks on positively formed parts

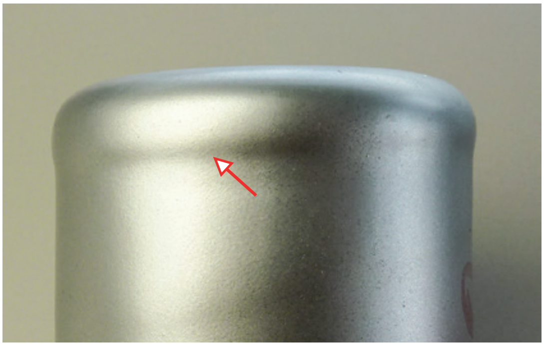


Figure 2.8
Lid in ABS, positively formed, with chill mark

Figure 2.9
Detail of display in impact-resistant polystyrene, positively formed, with chill mark

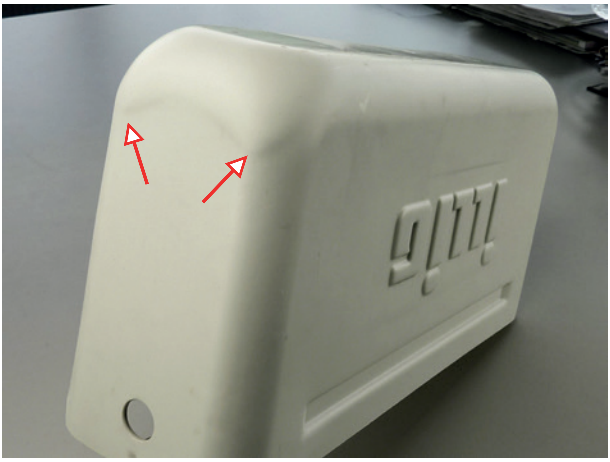


Figure 2.10 Formed part in impact-resistant polystyrene, positively formed, with chill mark

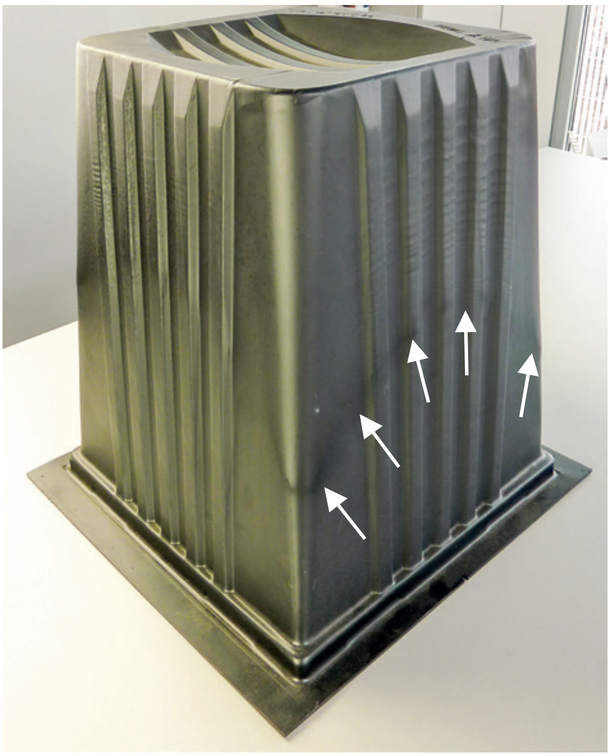


Figure 2.11 Formed part in impact-resistant polystyrene, positively formed, high stretch with chill mark pulled downward

Figure 2.12 Refrigerator interior tray in impact-resistant polystyrene, positively formed. Detail of chill mark, see Figure 2.13 and Figure 2.14

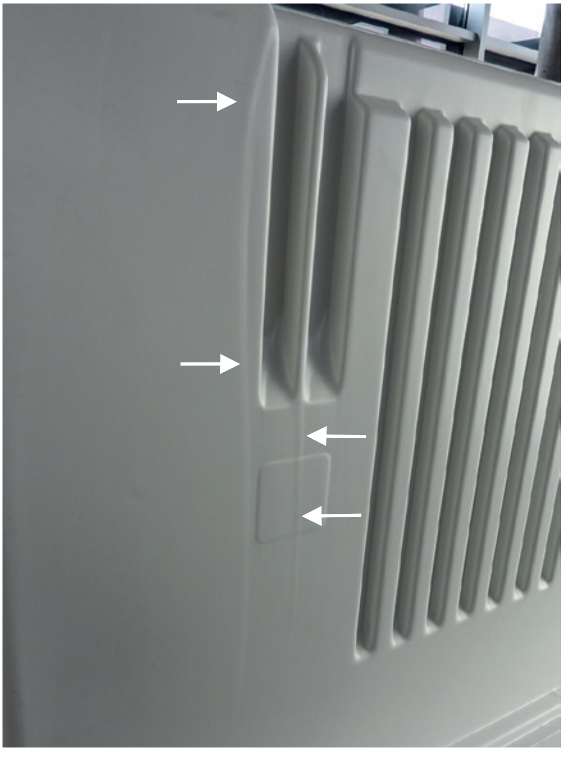


Figure 2.13 Detail of Figure 2.12, chill marks stemming from plastic cooling while sliding over the relatively cool edges of the mold

Figure 2.14 Chill mark on refrigerator inside tray from Figure 2.12 (viewed from the side).

The pattern of the chill mark in Figure 2.14 reflects the first contact of the plastic with the upper edge of the tool.

2.6.2 Chill marks on negatively formed parts

In contrast with the chill marks on positively formed parts, the chill marks caused by contact with the negative forming segment never slide down into the sidewall.

Chill marks in the sidewall of a negatively formed part always stem from the plug-assist tool.

Example of chill marks on negatively formed parts

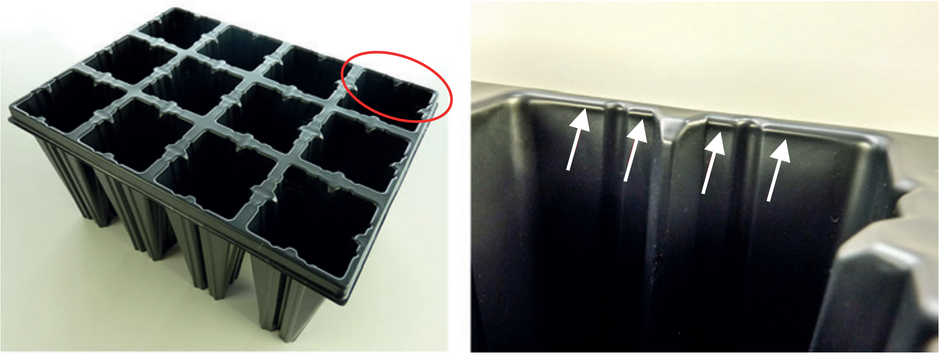


Figure 2.15 Negatively formed part in polystyrene with chill marks in edge sector

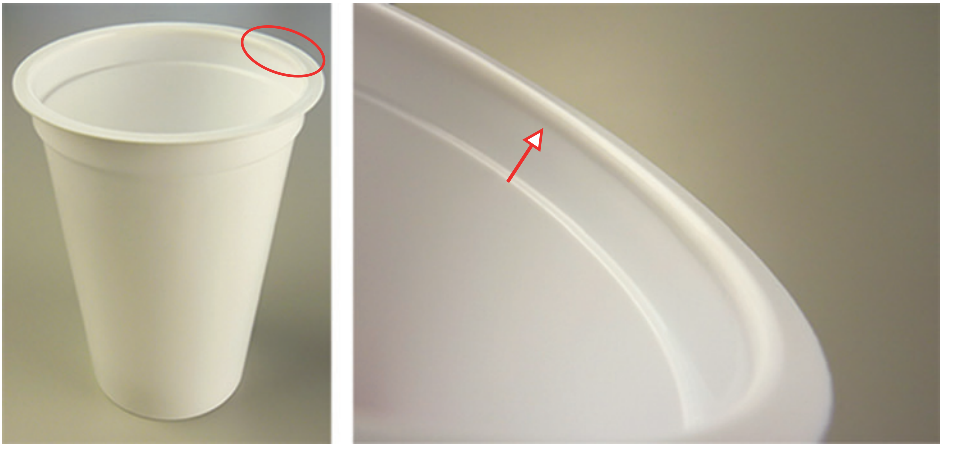


Figure 2.16 Sealed cup in PP, negatively formed, with chill mark in edge sector

Figure 2.17 Negatively formed part in PEHD with chill mark caused by the plug-assist tool

2.6.3 Causes of chill marks

A chill mark occurs during preforming as a result of unintentional and excessive cooling of the material during stretching in preforming.

Cooling relies on contact:

- With the forming segment
- With the plug-assist tool
- In unusual cases, even with a strongly concentrated air stream that impacts against the heated material during preforming.

Rapid cooling during formation of chill marks is subject to the standard rules of cooling through thermal conductivity during contact between the heated material and the tool. The most important of the related parameters subject to influence are:

- The temperature difference between the forming segment and the thermoplastic material at the contact location and/or between the plug-assist tool and the thermoplastic material at the contact location and
- during the contact time.

In a similar situation, important factors when cooling is contributed by a concentrated air stream include:

- Temperature of air
- Air speed

2.6.4 Options for reducing chill marks

Reduce temperature difference

Reducing the temperature difference between the forming segment and the thermoplastic material at the contact location, or between the plug-assist tool and thermoplastic material at the contact location. Options for reducing the cooling on restricted surface areas, meaning chill mark formation:

- Raise temperature of the forming segment
- Raise temperature of the forming segment at the contact location

Reduce the contact time

Reduce the contact time by:

- More rapid table travel motion
- Delaying contact of material using air cushion (depending on process and machine)
- Increasing air-discharge cross-section in negative forming with plug-assist tool

Reducing contact surface and intensity

If possible, modify the shape of the contact surface to reduce the proportional contact surface while retaining the same outside contours for the contact surface. Thus, for example, a canted corner is better than a spherical surface.

Ensure a continuous stretching process

It is important to prevent the slip-stick effect through:

- Reduction in stiction (both surfaces that are too smooth and surfaces that are too rough increase stiction).
- Avoiding excessively sharp edges on positive molds. Sharp edges prevent the hot material from sliding beyond them during stretching.

Selection of a different forming process

One of the best solutions – for instance, when attempting to manufacture parts for technical applications without chill marks using positive forming – is presuction and rolling the material across the mold.

2.6.5 Results of chill mark formation

The negative effects of chill marks extend beyond the appearance of the formed part.

Chill marks represent hot zones, and as such they are hotter than the adjacent thin wall during demolding. This leads to:

- Extended cooling times
- Changes in mold shrinkage, and not least important
- Distortion of the molding
- The material accumulation present in the chill mark is not present in the remainder of the wall.
- Thus, in many cases, chill marks also reduce crushing resistance (e. g., top load), and more material will need to be added to compensate for this effect.

2.6.6 Use of typical wall-thickness distribution in chill marks with snaps on clamshell packages

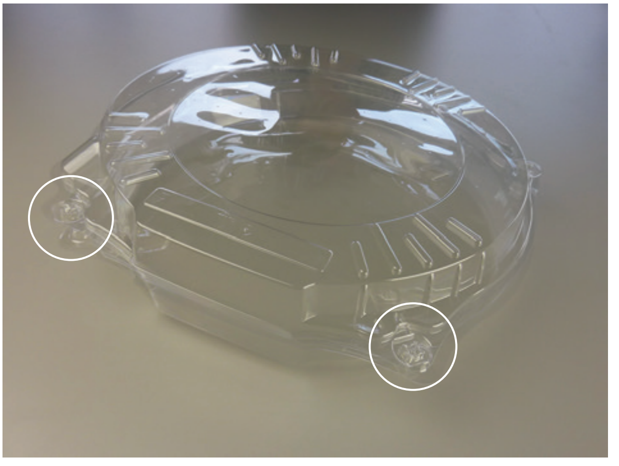


Figure 2.18 Clamshell package featuring two snap buttons

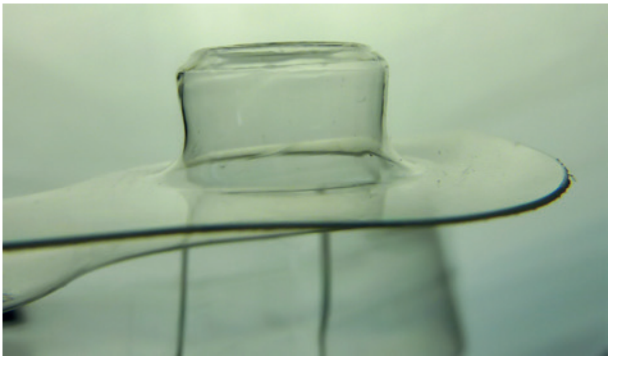


Figure 2.19 Push button positive section of clamshell package in Figure 2.18

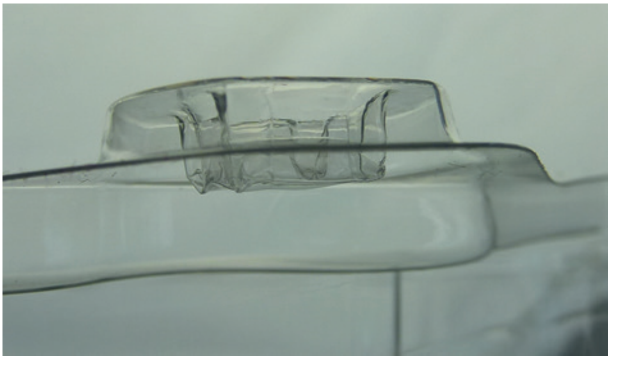


Figure 2.20 Push button negative section of clamshell package in Figure 2.18

2.6.7 Conclusions with regard to chill marks

The reasons for avoiding chill marks extend beyond aesthetic considerations.

Chill marks always have negative effects on:

- Wall-thickness distribution
- Cooling time
- Distortion in the formed part

Once the causes of the chill marks are known, in most cases they can be minimised, and sometimes completely eradicated.

Potential remedial factors include:

- the machine's equipment (the travel speed of the tables)
- the tool design
- the tool's temperature control, and
- the selected forming process

The effects of the processed semi-finished material should also be remembered. For instance, ABS displays a more pronounced tendency toward chill mark formation than impact-resistant polystyrene.

Push buttons for clamshell packs represent a special case in which the typical wall-thickness distribution patterns for positive and negative forming are used. The chill marks that are usually impossible to avoid in the real world do not play an optical role in this case. They are utilised as an advantage in order to obtain a good "snap" effect when closing the package. Under these circumstances, the important consideration is wall-thickness distribution, along with chill marks in this case.

2.6.8 Blemishes and markings

In contrast with chill marks, blemishes and markings form around the air-discharge bores when the forming segment's surface is too smooth, and the air-discharge bore is closed during demolding before the material achieves complete contact, at which air remains trapped between the formed part and the forming segment. Marks and blemishes around air-discharge bores are usually round.

The schematic representation in Figure 2.21 shows markings around the air-discharge bores that occur when the surface of the positive mold is too smooth. (Faults in positive segments when transparent parts such as blister packs are formed.)

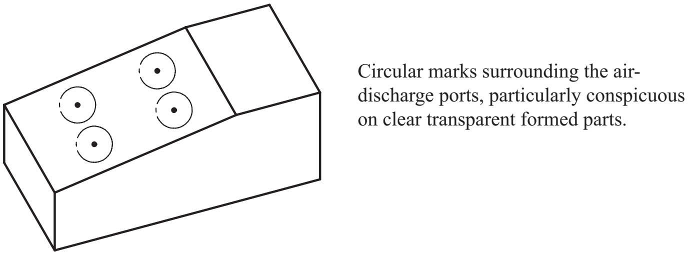


Figure 2.21 Markings surrounding air-discharge bores on a transparent formed part, schematic

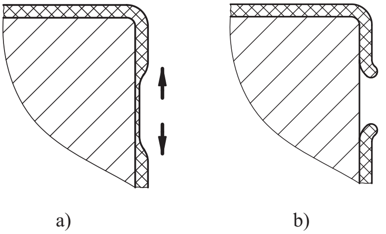


Figure 2.22
Separation and open tears
a) Separation on positive formed part
a) Open tear on positive formed part

2.7 Wrinkle formation during thermoforming

Wrinkle formation is understood as the undesired conjoining of border zones within a heated material during the forming process. Wrinkles can form in both negative and positive formed parts. Examples of wrinkles, see Figure 2.23.

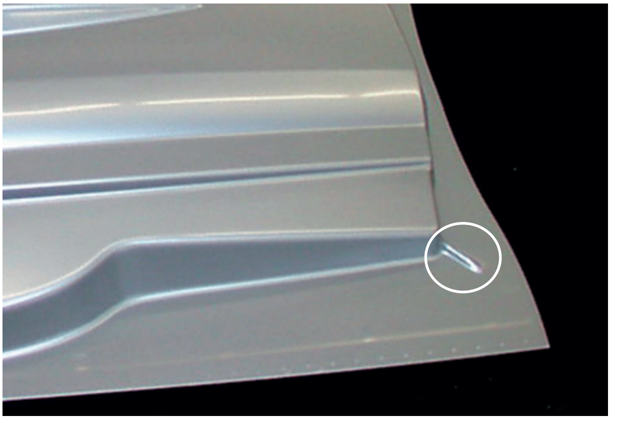
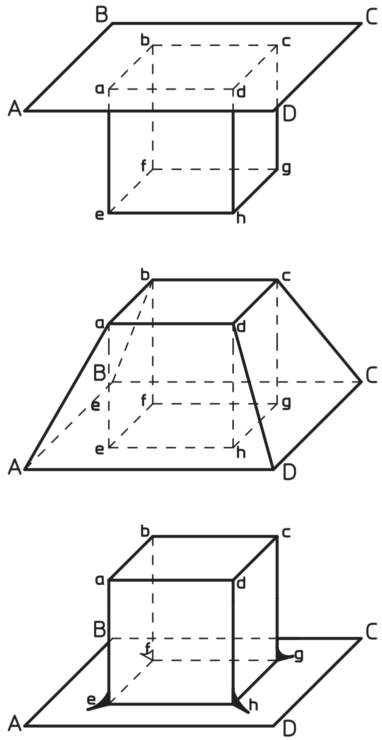


Figure 2.23 Wrinkle at corner of a positively formed part

2.7.1 Wrinkle formation sequence in positive forming

The wrinkle-formation sequence is illustrated in Figure 2.24.



ABCD = heated material (formed surface)
abcd = upper contact surface of mold with the material

Preforming as prestretching process with form completed, stretching not yet started

Finished molded formed part with wrinkles at the lower corners

Figure 2.24 Wrinkle-formation sequence in positive forming

Explanation of wrinkle formation in positive forming

Figure 2.25 provides a sketch explaining wrinkle formation.

1. Before the start of contour molding with vacuum or compressed air starts, the hot material is stretched like a tent between the positive form's upper level abcd and the clamped edge ABCD.

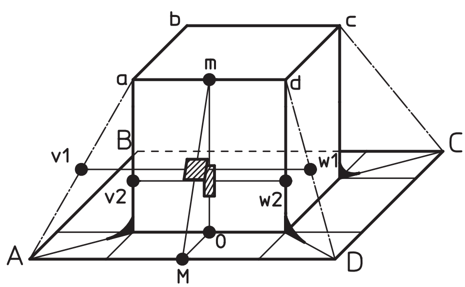


Figure 2.25 Schematic explanation of wrinkle formation on positive form

2. The centre line of the front tent wall AadD is stretched to MO + Om during contour molding. The element portrayed in the centre stretches upward.
3. The horizontal centre line v1w1 is compressed to the reduced length v2w2 during contour molding.

Conclusion:

- During contour molding, the plastic is elongated in one direction and compressed in the other. (Wrinkles are never produced by stretching, but only through compression.)
- No wrinkles occur as long as the heated plastic remains "compressible" during contour molding.
- This compressibility depends on the visco-elastic properties of the processed material, i.e., on the type of plastic, the plastic temperature, upset ratio and the compression speed.

Wrinkles are produced when the compressibility is exceeded.

The upset ratio is greatest at the lower corner zones of positive forming; thus, the risk of wrinkle formation with rectilinear positive forms is greatest at the corners in the lower zone.

Preventing wrinkle formation in positive forming

Options for preventing wrinkles:

a) Revising the machine's adjustment settings:
   - Reduce the compression speed by lowering the cross-section for air discharge for a brief period during air suction ("prevacuum").
   - Correct the material temperature to allow compression: Heat the material to a higher temperature if it has been cooling too quickly during stretching.
   - Heat the material less if it is formed too quickly during stretching.

b) Prevent wrinkles by reducing the intake zone at the corners. Blinds in the clamping frame reduce the intake zone and, thus, the upset ratio. The principle is illustrated in Figure 2.26. A becomes A1, B becomes B1, C becomes C1 and D becomes D1.

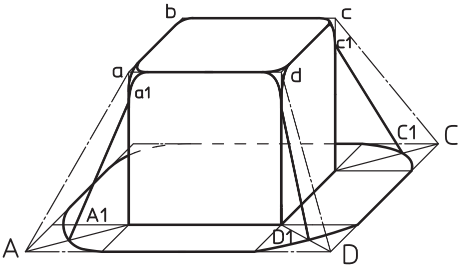


Figure 2.26 Preventing wrinkle formation in positive forming, schematic

c) Preventing wrinkles with the plug-assist tool:

The applicable tenet is: "Small wrinkles can be pressed out, while large wrinkles must be pulled out". For small wrinkles, it will be possible to fabricate a plug-assist tool that can be used to press the small wrinkle back into a flat position. If this were attempted with a large wrinkle, then the plug would fold the wrinkle together. The plug must be in its correct position before the wrinkle is created.

d) Prevention of wrinkles by modifying the forming contour in the waste zone:

- Raise height of mold to displace wrinkle into the waste zone (only possible if this zone is separated).
- Pull wrinkles apart: This can be implemented with two artificial rises (e.g., hemispheres), with one on the right and one on the left of the wrinkle. A depression below the wrinkle will provide similar results.

e) Preventing wrinkles by revising the positive form radii in the upper sector:

Increasing the radii in the upper sector of the positive form reduces the initial surfaces of the "tent" prior to contour molding (Figure 2.26). a becomes a1, b becomes b1, c becomes c1, d becomes d1. In this context, it should be noted that modifications to the mold are considered to represent design changes and the approval of the customer will be required.

f) Change in the mold to allow the wrinkle to assume the appearance of a deliberate reinforcement rib. Create more surface area in the lower sector, making it possible to "use up" the wrinkle's surface.

2.7.2 Wrinkle formation in negative forming

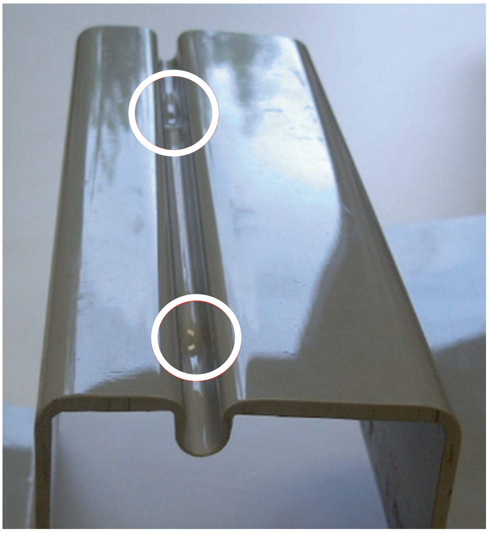


Figure 2.27
Wrinkle formation in a negatively formed groove

Explanation of wrinkle formation in negative forming

Preforming through preblow and/or stretching with the forming segment is not sufficient to form a groove. The groove is not created until contour molding with the following process:

Neither the thickness of the material, nor the contour-molding temperature, nor the distribution of internal stresses are perfectly uniform, and as a result, during the gradual elongation of the material into the groove, it reaches some locations at the base of the groove earlier, while the groove is further away from the base at other locations.

This means that the material forms undulations in the groove during stretching, at which its length is longer than the length of the groove itself.

However, this simultaneously means that the plastic undergoes compression at the locations when contact occurs later, before the material lies completely against base of the groove.

The compression always results in wrinkle formation when the material cannot thicken in response to compression forces.

Preventing wrinkle formation in negative forming

Stretching must be temporally uniform to prevent wrinkles during negative forming. This can only be implemented mechanically with the assistance of a plug-assist tool.

2.7.3 Wrinkle formation on surfaces

Surface wrinkles are created when the surface of a heated material is larger than the surface of the mold on which the material must be formed. This is the case when the material sag is high and the height of the forming segment is low.

Solutions for preventing surface wrinkles

- Install the flat forming segment at a greater height, creating a new forming surface, forming segment + elevation that is greater than the material's surface created by the sag.
- If the edge zone is a waste zone, then elevations for supplementary stretch can be placed in this area.

2.8 The tool set

All of the parts in an assembly required for manufacture of a new product are called the tool set. All of the parts except for the mold are designated as format parts.

Sheet processing machine with permanent format frame

In a sheet processing machine with fixed format frame, loading station and separate heating station, the tool set consists of:

- forming tool
- mold substructure
- plug-assist tool
- clamping frame for forming station
- clamping frame for heating station
- multi-pad vacuum lifter (suction plate) for the loading station

Sheet processing machine with adjustable clamping frame and adjustable substructure

In a sheet processing machine with an adjustable clamping frame, adjustable substructure, permanent format frame, loading station and separate heating station, the tool set consists of:

- forming tool
- plug-assist tool
- multi-pad vacuum lifter (suction plate) for the loading station

Automatic roll-fed machine with punching and stacking station

In an automatic roll-fed machine with punching and stacking station, the tool set consists of:

- forming tool
- mold substructure
- clamping frame
- plug-assist tool
- steel rule die with cutting board
- stacking components

2.9 Forming surface, intake surface, clamped edge

The forming surface is the name for the section of the material's heated surface available for thermoforming, regardless of whether it is stretched or not. The intake surface is the proportion of the forming surface that is stretched in the selected forming process. See Figure 2.28.

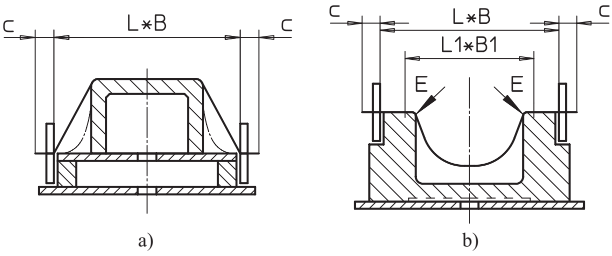


Figure 2.28 Forming surface, intake surface, clamped edge (c), schematic
a) Positive form: Intake surface = Forming surface = ($L \times B$)
b) Negative form: For preforming with preblow:
Intake surface = Forming surface = ($L \times B$)
Without preforming: Intake surface ($L_1 \times B_1$) < Forming surface ($L \times B$)
The contour of the corners E determines how much of the surface will become intake surface.

Not all thermoforming machines are equipped with clamping frames to clamp the material for the forming process.

In sheet-processing machines, the clamped edge retained by the clamping frame is not heated by the radiant heat emitters. In this process, please observe the following:

- If the clamped edge of a formed part is detached immediately after demolding, then it need not be heated, but should still be separated as quickly as possible after demolding.
- In contrast, if the clamped edge remains on the formed part (trimless forming), then the clamped edge must have the same temperature as the formed object during demolding. Since the clamped edge cannot be heated with the radiant heat emitter, it must be heated through contact with the heated clamping frame.

  Both the lower and the upper clamping frame should be heated.

  If the contact heating time for heating the clamped edge in the forming station is too short, then it will be impossible to reach an adequately high temperature for demolding in the core of the clamped edge. The solution is to raise the temperature of the clamping frames contact surface at the start of the heating time and then reduce it before the end of the contact time. Special clamping frames are required for this purpose.

2.10 Downholder, upholder

Downholders

If multiple forming tools are applied to a forming surface (Figure 2.29), then it will be beneficial to subdivide the entirety of the forming surface into individual forming surfaces using downholders, at which an individual bubble can be created for each single form during preforming with preblow. This guarantees better wall-thickness distribution.

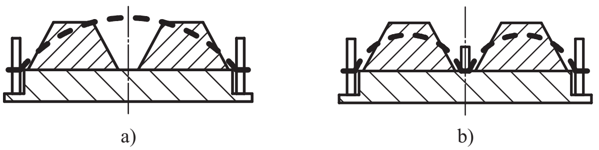


Figure 2.29 Double positive forming tool
a) Preblow without downholder
b) Preblow with downholder in upper clamping frame

Upholder

Upholders (Figure 2.30) ease demolding by retaining the entire periphery of the molding being demolded. The upholders provide support for semi-finished materials exhibiting severe sag, such as polypropylene, when heat is applied in the forming station (in sheet-processing machines).

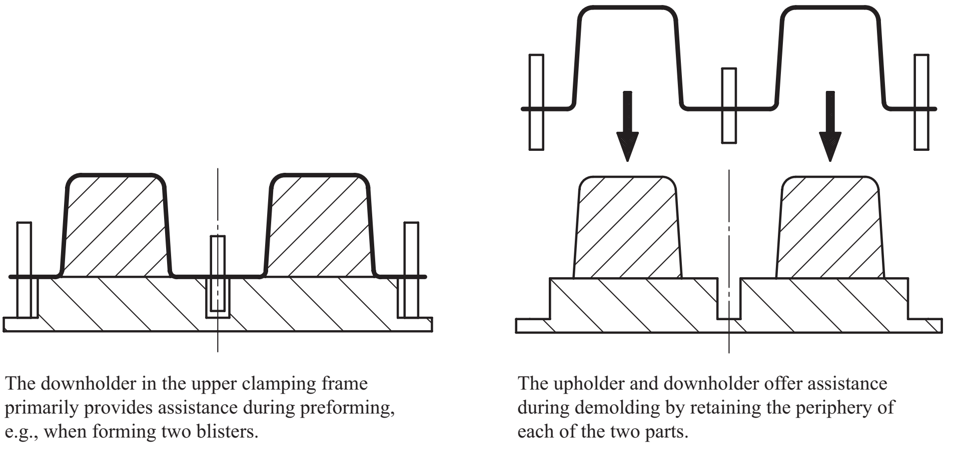
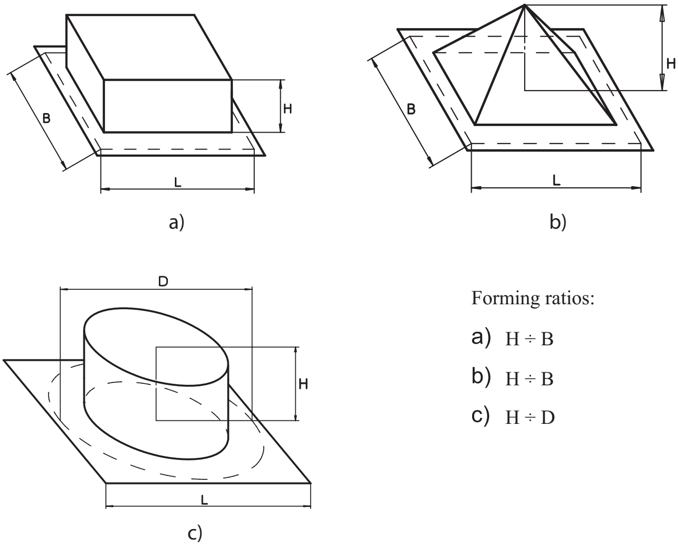


Figure 2.30 Double positive mold with downholder in upper clamping frame and upholder in lower clamping frame

2.11 Forming and stretching ratio

The forming ratio is the ratio between the height *H* and the width *B* of the formed area. The forming ratio does not provide precise information regarding stretch.



Forming ratios:

a) H ÷ B

b) H ÷ B

c) H ÷ D

Figure 2.31 Forming ratio

The stretching ratio defines the relationship between the total surface of the part created with stretching and the initial surface prior to stretching. The clamped edge is not included as part of the generated surface or of the initial surface.

$$\text{Stretching ratio} = \frac{F_2}{F_1} \tag{2.1}$$

F_1 = Forming surface

F_2 = Surface of the formed part

2.12 Draft angles

The angle between the sidewall and the demolding direction constitutes the draft angle.

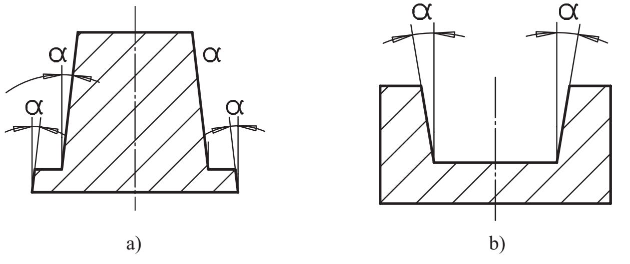


Figure 2.32 Draft angles α
a) Positive mold
b) Negative mold

Demolding proceeds as soon as the temperature in the thickest portion of the formed part cools to below the pliability temperature. The longer the wait before demolding, the greater the cooling in the formed part. Owing to the change in length, the positively formed part shrinks onto the forming tool. With a single mold, a negatively formed part shrinks away from the wall of the tool.

The formed part must be stiff enough to allow secure demolding. The formed part must not become too cold, especially in positive forming. The demolding time is always a portion of the cycle time and must remain as short as possible. During demolding, it is important to monitor the incoming air between the wall of the tool and the formed part. The formed part must not be allowed to distort during demolding. The draft angles are needed to satisfy all of these criteria. The selected draft angle should always be as large as possible. As draft angles increase, so does the speed with which demolding can proceed – and this also reduces the cycle time. A large draft angle reduces the risk of deformation in the formed part during demolding. Preferred draft angles for positive molds and for multiple negative molds:

- α = 3 to 5°
- $\alpha < 0.5°$ for shrinkage < 0.5% and slow demolding

Demolding a positively formed part with a draft angle α of 0° is possible under the following conditions:

- The demolding temperature is only just below the pliability limit temperature, meaning that the formed part must be as hot as possible during demolding.
- It must be possible to adjust the demolding process in two steps at the machine:
  - First step: Release with compressed air.
  - Second step: Demold at low speed; in this process, precise metering of demolding air and demolding speed must be available.

2.13 Vent cross-sections

During vacuum forming, the air between the material and the mold is extracted through the vent cross-sections in the mold in order to press the heated material onto the surface of the mold during forming. In pressure forming, the air is pressed out through the vent cross-sections.

Sample versions of vent cross-sections are bore holes, slots and slotted nozzles. As an alternative, porous materials can be used in production of the mold.

Reference figures for designing vent cross-sections are provided in Table 3.2 “Table for the thermoformer”, in Chapter 3 “Semi-finished thermoplastic materials”.

The vent cross-sections from the surface of the mold are joined by a system of air-discharge passages.

Design of air-exhaust system, see Chapter 21 “Thermoforming tools”, Section 21.9.4 “Tool venting, air-discharge cross-sections”.

2.14 Calculating wall thickness

Assuming that the weight of the unmolded blank and the finished formed part remain equal, then the ratio of the finished product’s wall thickness to the material’s initial thickness is equal to the ratio of the material’s initial surface area to the stretched surface of the formed part.

Since the wall thickness can be reproduced during thermoforming, but the thickness is not equal at all positions on the finished part, a deviation of the smallest and the largest wall thickness from the average wall thickness of ±30% can be assumed.

$$s_2 = \frac{F_1}{F_2} \times s_1 \quad (2.2)$$

F_1 = Surface of material without clamped edge

F_2 = Surface of the thermoformed part

s_1 = Thickness of the material

s_2 = Theoretical average wall thickness of the thermoformed part

Thinnest location = 0.7 s_2

Thickest location = 1.3 s_2