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.

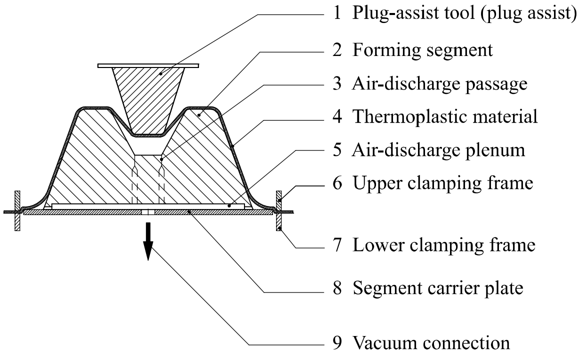


Figure 1.1 Concept of thermoforming

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.

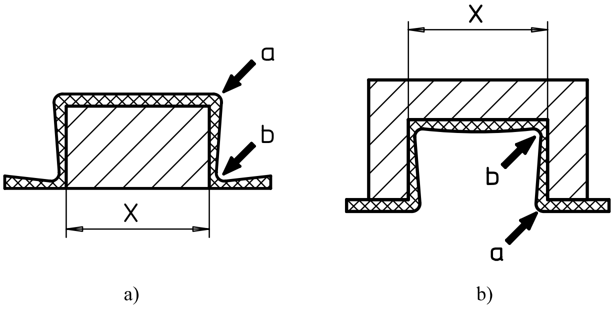


Figure 2.1 Positive and negative forming
a) Positive forming (schematic)
b) Negative forming (schematic)
X = molded dimension from mold

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

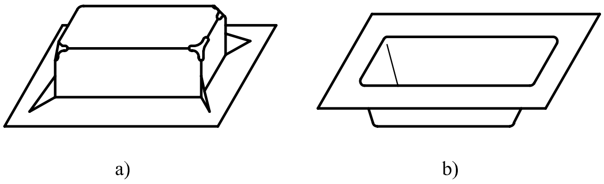

a) b)

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

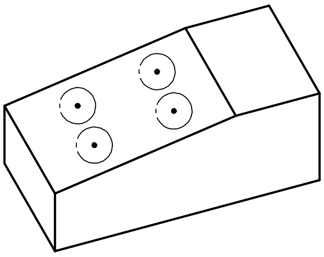

Circular marks surrounding the air-discharge ports, particularly conspicuous on clear transparent formed parts.

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

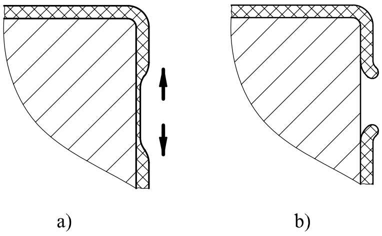


Figure 2.22
Separation and open tears
a) Separation on positive formed part
a) Open tear on positive formed part

■ 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.

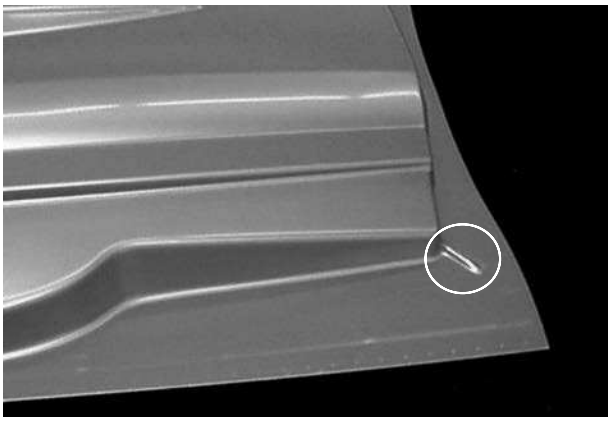
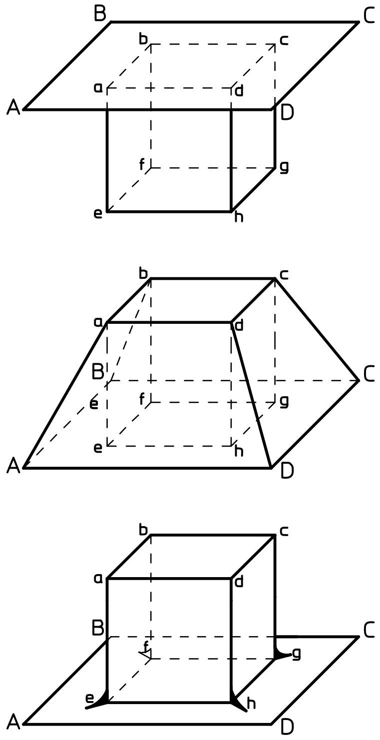


Figure 2.23 Wrinkle at corner of a positively formed part

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.

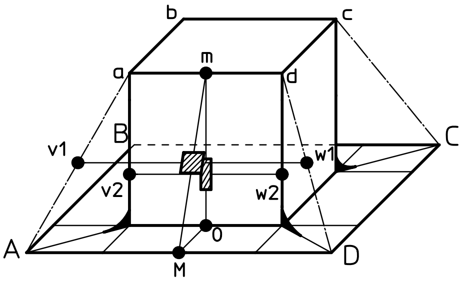


Figure 2.25 Schematic explanation of wrinkle formation on positive form

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.

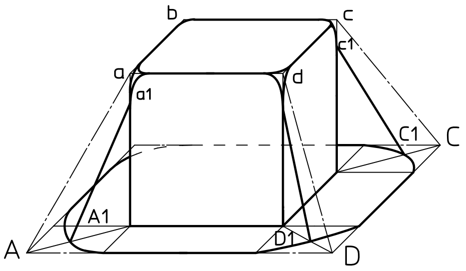


Figure 2.26 Preventing wrinkle formation in positive forming, schematic

Table 3.2 Table for the thermoformer (non-binding information) *(continued)*

Thermoplastics	Acronym	Density	Tensile strength	Elasticity modulus	Optical transparency	Linear heat expansion	Specific heat	Continuous-use temperature	
								Min.	Max.
	–	$\mathrm{g/cm^3}$	$\mathrm{N/mm^2}$	$\mathrm{N/mm^2}$	+ Yes – No	10^{-6} °C	kJ/kg·K	°C	°C
Cellulose acetate	CA	1.28	37	1800	+	110	1.6	–40	80
Cellulose diacetate	CdA	1.27	40	1000	+			–20	60
Cellulose acetate butyrate	CAB	1.18	26	1600	+	120	1.6	–40	60
Polyvinylidene fluoride	PVDF	1.78	43	1500	–	120	0.96	–40	120
Polyetherimide	PEI	1.27	105	2800	–	56			170
PET elastomer	TPE-E	1.17	28	55	–			–50	105
Thermoplastic styrenic elastomer (blends)	TPS blends	1.1–1.39							70–80
Polylactide acid **Polylactic acid**	PLA	1.21–1.43	10–60	3500	+		1.3	–20	60–70
Lignin	Lignin	1.3–1.4	25–61	1500–6670	+				85–120

Acronym	Pliability temperature	Crystallite melting range	Predrying of 1.5–2 h/mm panels	Thermoforming temperature		Material factor for heating time	Material factor for cooling time	Venting			
								Vacuum forming		Pressure forming	
				Pressure forming	Vacuum forming			Bore hole	Slot	Bore hole	Slot
–	°C	°C	°C	°C	°C	–	–	mm	mm	mm	mm
PS-GP	80	–	–	120–150	165–190	1.3	0.97	0.8	0.5	0.6	0.3
HIPS	80	–	–	120–160	150–200	1	1	0.8	0.5	0.6	0.3
SBS	90	–	–	115–125	140–140	1	1	0.8	0.4	0.6	0.3
OPS	99	–	–	115	115	1	0.7	0.8	0.6	0.6	0.4
ABS	100	–	75	130–160	160–220	1.3	1.3	0.8	0.5	0.6	0.3
ASA	90	–	85	120–160	160–190	1.3	1.3	0.8	0.5	0.6	0.3
SAN	95	–	–	135–170	165–190	1.6	1.12	0.8	0.5	0.6	0.3
PVC-U	90	–	–	120–140	155–200	1.7	2.55	0.8	0.5	0.6	0.3
COC	2)	–	–					0.6	0.3	0.3	0.2
PE–HD	105	125+15	–	140–170	170–200	2.5	2.5	0.6	0.3	0.4	0.2
PP	140	158+10	–	150–165	160–200	2.1	2.1	0.6	0.3	0.3	0.2
PMMA, ext.	95	–	70	140–160	160–190	1.5	1.5	0.8	0.6	0.8	0.5
PMMA, molded	100	–	–	140–170	170–200	1.6	1.6	1.0	0.8	0.6	0.3
POM	120	165+10	–	145–170	170–180	3.7	1.85	0.6	0.4	0.4	0.2
PC	150	–	100	150–180	180–220	1.5	0.9	0.6	0.5	0.6	0.3
PAR	170	–	110	180–210	210–235	2.6	2.21	0.8	0.5	0.6	0.3
PPE (PPO)	120	–	–	180–230	200–250	1.8	1.44	0.8	0.5	0.6	0.3
PA 6 GF15Z		222	110	230–240	240–250			0.8	0.5	0.6	0.3

Table 3.2 Table for the thermoformer (non-binding information) *(continued)*

Acronym	Pliability temperature	Crystallite melting range	Predrying of 1.5–2 h/mm panels	Thermoforming temperature		Material factor for heating time	Material factor for cooling time	Venting			
								Vacuum forming		Pressure forming	
				Pressure forming	Vacuum forming			Bore hole	Slot	Bore hole	Slot
–	°C	°C	°C	°C	°C	–	–	mm	mm	mm	mm
PA 12	150	175+10	80	160–180	170–180	2.5	2	0.8	0.5	0.6	0.3
PET–G	82	–	–	100–120	110–190	1.25	0.88	0.8	0.4	0.6	0.3
A-PET	86	–	65	100–120	110–120	1.25	0.88	0.8	0.4	0.6	0.3
C-PET	86	225+3	–	130–145	/	/	/	/	/	0.6	0.4
PSU	178	–	120	210–230	220–250	2.9	2.32	0.8	0.5	0.6	0.3
PES	220	–	180	230–270	265–290	–	–	0.8	0.6	0.6	0.3
PPS	260	280+8	–	260–270	260–275	3.5	0.87	0.6	0.3	0.4	0.2
A/MA/B	88	–	–	135–150	160–220	1.3	1.69	0.8	0.4	0.6	0.3
CA	98	–	65	145–170	165–180	1.5	1.5	0.8	0.5	0.6	0.3
CdA	70	–	60	115–130	120–140	–	–	0.8	0.4	0.6	0.3
CAB	120	–	90	140–200	170–200	1.5	1.5	0.8	0.5	0.4	0.2
PVDF	150	170+8	–	170–200	170–240	3	3	0.8	0.5	0.6	0.3
PEI	215	–	150[1]	230–290	240–330	2.7	0.62	0.8	0.5	0.6	0.3
TPE-E	108	–	–	–	135–143	1.5	1.5	0.6	0.5	/	/
TPS				120-140	140-165	1	1	1	0.4	0.6	0.3
PLA	58	–	–	80–100	90–110	0.9	0.8	0.8	0.4	0.6	0.3
Lignin				150-170	170-190	1	1.3	0.8	0.4	0.6	0.3

[1] Drying time 4 h/mm

[2] Depending on type, 70 … 160 °C

Acronym	Optimum temperature for the mold					Material for plug-assist tool					Molding shrinkage
						1 Wood 2 Felt 3 POM 4 PA (PA 6GGK) 5 Syntact. Foam …			6 Talcum-filled PU 7 Pertinax 8 Hy-tacB1X 9 PTFE		
	UA SB	RV(b) RD	RDKP RDK	RDM	HSA FS	UA SB	RV(b) RD	RDKP RDK	RDM	HSA FS	
–	°C	°C	°C	°C	°C	–	–	–	–	–	%
PS-GP	80	/	15	15	/	1, 2, 6, 7	/	2, 5	2, 5	/	0.5
HIPS	70	25	20	15	–/15	1, 2, 6, 7	1, 2, 5, 6	2, 5	2, 5	2, 5	0.5
SBS	50	25	20	15	40/20	1, 2, 3, 6, 7	1, 3, 5	3, 5	3, 5	3, 5	0.5
OPS	65	/	65	40	/	2, 5	/	2, 5	2, 5	/	0.5
ABS	85	35	20	15	–/15	1, 2, 4, 6, 7	1, 2, 4, 5	2, 5	2, 5	2, 5	0.6–0.7
ASA	85	–	20	15	–	1, 2, 4, 6, 7	–	2, 5	2, 5	–	0.3–0.7
SAN	85	–	–	–	–	1, 2, 4, 6, 7	–	–	–	–	0.4–0.7
PVC-U	25	25	20	15	35/15	1, 2, 6, 7	1, 2, 5, 7	2, 5	2, 5	2, 5	0.4–0.5
COC	–	–	–	–	35/15					3, 4, 5	
PE–HD	100	50	35	20	–	1, 4, 6, 7	1, 4, 5, 7	4, 5	4, 5	–	1.2–5.0
PP	90	(25)	25	15	–/15	1, 3, 4, 6, 7	3, 4, 5, 7	3, 4, 5	3, 4, 5	3, 4, 5	1.5–1.9

Effect of transport steps under a long heater

Every point on the surface of the semi-finished product must have a single temperature in the forming station. To obtain this result, it is necessary to ensure that each point in the advance-feed direction is heated with the same frequency as all others. If this is not the case, it remains possible to shield the surface from the radiant heat or to deactivate transverse heater element rows (Figure 4.14 and Figure 4.15).

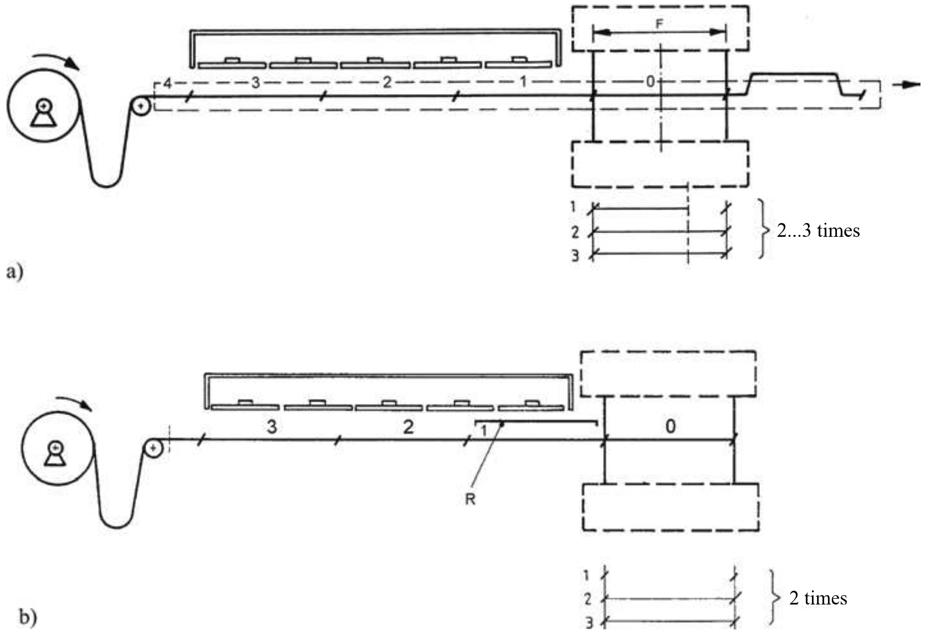


Figure 4.14 Checking the heating through a whole number of advance-feed cycles (2 or 3 times)
Case: Machine tables widths wider than the mold
0, 1, 2, 3, 4 steps (countdown) in transporting
F: Forming surface (advance feed)

If the machine's table width is wider than that of the mold, then there will be differences in how the blank is heated before it arrives in the forming station (Figure 4.14 a). If the sector of the heater in front of the forming station is covered, then all points on the blank will be heated exactly two times (Figure 4.14 b).

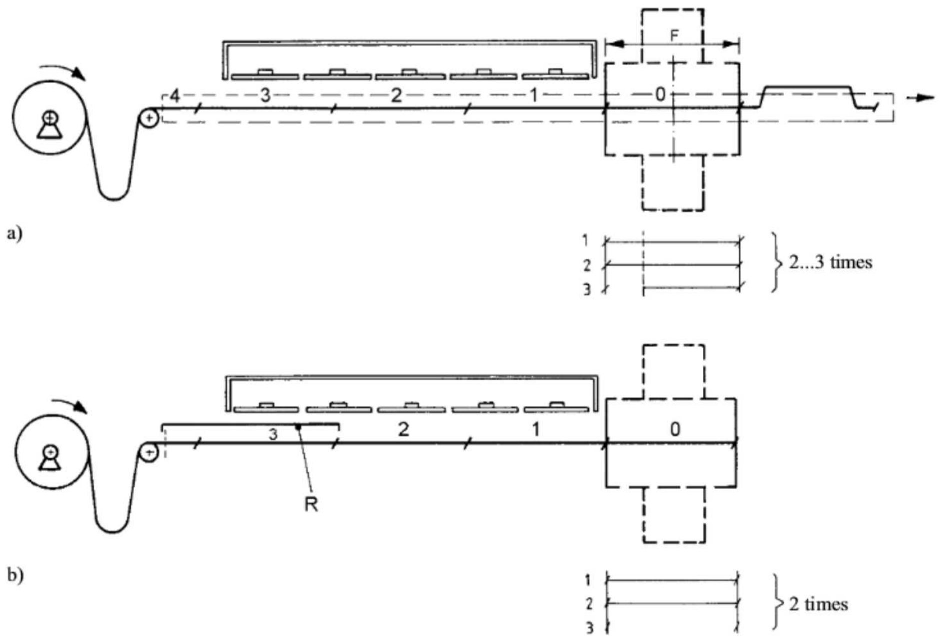


Figure 4.15 Checking the heating with a whole number of advance-feed cycles (2 or 3 times)
Case: Machine table widths narrower than the mold
0, 1, 2, 3, 4 steps (countdown) in transporting
F: Forming surface (advance feed)

If the machine's table width is narrower than that of the mold, then there will be differences in how the blank is heated before it arrives in the forming station (Figure 4.15 a). If the sector of the heater in front of the forming station is covered, then all points on the blank will be heated exactly two times (Figure 4.15 b).

The schematic explanation in Figure 4.14 and Figure 4.15 only applies to the upper heater deflection panel. In actual real-world application, there will also be a lower heater deflection panel. The procedure for heating with an upper heater and lower heater is similar, even if two heater deflection panels are not of equal length or are not perfectly aligned above each other in the advance-feed direction.

Cross-over effect with radiant heaters

When a heater panel travels from its standby position to its heating position at the start of each cycle and then returns to its standby position once the heating time has elapsed, this leads to the cross-over effect, meaning that the semi-finished product is heated for different amounts of time because the heater crosses over it. More rapid heater travel motion corresponds to reduced cross-over effect and vice versa.

8 Thermoforming process on sheet-processing machines

The thermoforming process can be subdivided into two steps – preforming or prestretching/drawing, and the actual contour-molding process. In many cases, unassisted contour molding with vacuum or compressed air will not be able to achieve satisfactory wall-thickness distribution, and for this reason, preforming will be necessary. The objective behind preforming is to obtain a contour that comes as close as possible to the contour of the finished part. The molding's final contour definition is produced during finish molding. In most cases, preforming has a greater influence on wall-thickness distribution than contour molding.

Preforming is always a prestretching process and can assume various forms:

- Mechanical prestretching with the actual mold
- Mechanical prestretching with a plug assist (prestrecher)
- Pneumatic prestretching with preblow or presuction
- Combination of mechanical and pneumatic prestretching

Depending on the machine's equipment and the configuration of the forming tool, molding relies on:

- Vacuum (vacuum forming)
- Compressed air (compressed-air forming)
- Vacuum and compressed air
- Bilateral vacuum application (e. g., for foams)
- Supplementary stamping, crimping, calibrating, usually restricted to limited surface areas

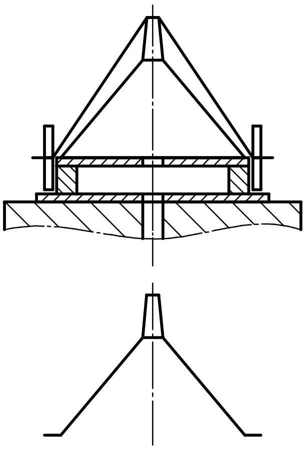
Mechanical tools such as slides and plugs usually are intended to prevent wrinkles during molding. In some cases, forming relies on mechanical stretching only, without molding using vacuum or compressed air. This is the origin of what we call free-form surfaces.

The forming processes cited below will all be explained in the following combination:

- Sketch of forming process
- The essential steps in the process sequence
- Important instructions/to be observed
- Possible intervention by the machine's operator with the resulting effect on the molding
- Required machine equipment

8.1 Positive forming

8.1.1 Positive forming with mechanical prestretching



Preforming:
– Prestretching with the mold
– With or without preblow

Contour molding:
– With upper forming table vacuum on

Figure 8.1 Process sequence – without preblow, without upper table

Please note

- Wall-thickness distribution in the vicinity of the tip

Table 8.1 Positive forming

Operator intervention	Effect on the molding
▪ Bubble height = 0 ... low	▪ Tip thick
▪ Bubble height corresponds to 2/3 of forming height	▪ OK
▪ Bubble height corresponds to forming height	▪ Wrinkle formation risk on the surface
▪ Cold mold	▪ Tip thicker
▪ Hot mold	▪ Tip thinner
▪ Low table speed	▪ Tip thicker
▪ High table speed	▪ Tip thinner
▪ Cold mold and low table speed, without preblow	▪ Thickest tip
▪ Hot mold and high table speed with preblow	▪ Thinnest tip

Required machine equipment

This forming procedure can be performed on all thermoforming machines with basic equipment.

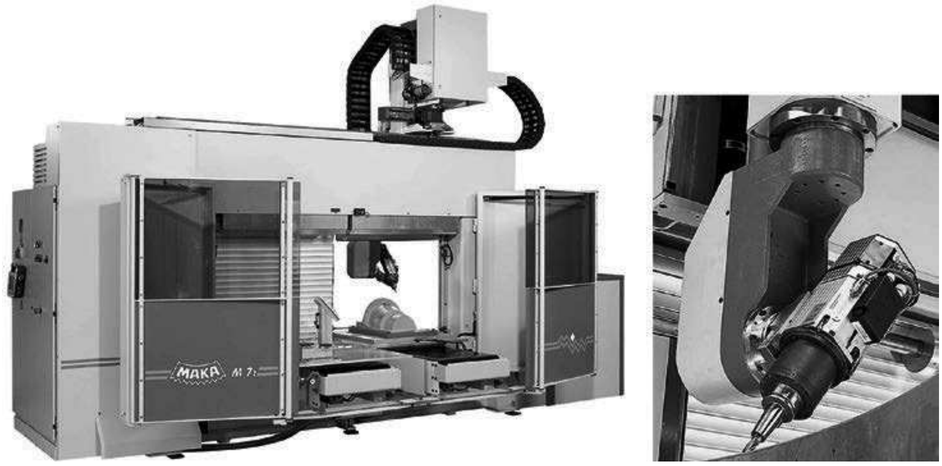


Figure 17.3 Left: 5-axis milling machine (illustration provided by MAKA)
Right: Milling spindle

17.2 Deburring

No deburring is necessary following punching with the steel rule die, punch and die trimming tool, shear cutting or laser cutting. Deburring is performed in response to a coarse cut:

- After sawing with a cut-off saw
- After milling in some cases
- after abrasive jet machining in many cases

Deburring is carried out by hand with a deburring cutter, with electric deburring brushes, or in a fully automated process (i. e., on multi-axis machines).

17.3 Connecting

Welding

Various welding processes are available for use with thermoplastic materials:

- Friction welding
- Ultrasonic welding
- Vibration welding (angular motion friction welding)

- Hot-tool welding (butt welding with heat reflectors)
- Hot-gas welding
- High-frequency welding
- Induction welding

The following welding technologies are applied with thermoformed parts:

- Ultrasonic technology
- Vibration technology
- HF (high-frequency) technology
- Hot-tool welding

Not all plastics are suitable for ultrasonic and high-frequency welding.

Adhesive bonding

Suitable, standard commercial adhesives are available for bonding. The surfaces being bonded must be clean and grease-free and should also be roughened. Plastics with "adhesive-resistant" surfaces, such as PE, PP, POM, require extensive surface pretreatments (flame treatment, electric surface discharges or chemical pretreatments). Information regarding selection of adhesives, see Chapter 3 "Semi-finished thermoplastic materials", with the plastics discussed at this location. An adhesive manufacturer should be consulted as the need arises.

Riveting, threaded connections

Since the strength of plastics is not as high as that of metals, the employed diameters and pressure surfaces should be correspondingly larger, in a situation mirroring that encountered with wood.

Special plastic screws are available for connecting plastics.

Reinforcement

The rigidity of a formed part depends on:

- The employed plastic (Young's modulus)
- The wall thickness produced during thermoforming
- The geometry of the formed part (length, width, height, radii, ribs, etc.)
- The application temperature

Reinforcement is logical if:

a) the rigidity obtained during thermoforming is not adequate,

b) subsequent reinforcement is more economical than application of thicker or more expensive initial material,

c) no reinforcement is supplied by a subsequent process, such as insulation, adhesive bonding, welding.

Various reinforcement options are available:

- Lamination with fibreglass
- Foam backing with integral or PU foam
- Bonding reinforcement elements
- Applying poured material (e.g., in thin corners with epoxy resin)

Surface treatment

The options for treating surfaces of formed parts are:

- Grinding, polishing
- Painting
- Embossing
- Metallising
- Galvanising
- Flocking
- Antistatic treatment (antistatic spray, antistatic bath, rinse with detergent solution)

17.4 Recycling

Direct on-site recycling of materials represents the current state of technology. Edge trim cuts during production of sheet material and presorted waste are returned for remelting and sheet extrusion following post-production granulation. Problems can arise when contamination is present if different types of plastic are mixed or when waste materials have different colours.

Mixed plastic waste, including that from recycling centres, can be processed with extrusion or pressing to produce parts for less demanding applications, primarily for garden and landscaping, but also for industry and commercial uses.

Most suppliers of sheet material on reels or in sheet panels accept returned plastic waste. In any case, it is essential to negotiate with the supplier regarding acceptance of returned waste material when requesting information on materials and placing orders. Waste materials, possibly in granulated form, are secondary raw materials and are utilised.

■ 18.4 Factors affecting the punching process

Influences on the plastic being punched

Property	Effect on …
Plastic type	▪ Specific punching force, see Section 18.7 "Punching forces" ▪ Service life of die tool ▪ Abrasive bulking agents in the sheet material and abrasive print colours on the sheet material reduce the residence time ▪ Angel-hair formation

Influences on the formed part being punched and the design of the formed surface

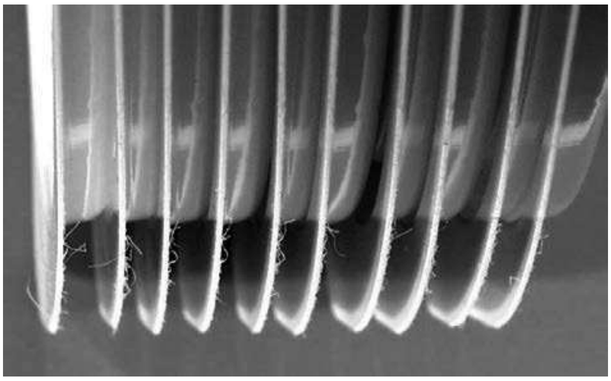
Property	Effect on . . .
Material thickness on the punched part	Punching force
Total cut length	Punching force Other factors requiring consideration: ▪ Number and size of radii per m: Small radii increase the displacement forces and thus the required punching force. ▪ Proportion of cut length with narrow parallel cut lines (below 12 mm) of total cut length increases punching force
Punched edge tolerance	Selection of punching procedure
Cut quality (haptics)	Selection of punching procedure

Effects of the machine/Punching station

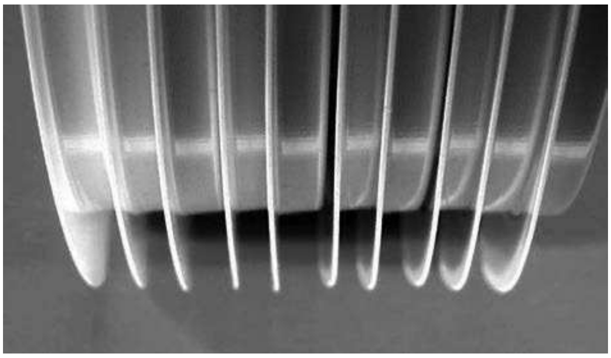
Property	Effect on . . .
Punching force	Punched length/Design of formed surface/Machine output
Punched surface	Punched length/Design of formed surface/Machine output
Punching station rigidity	With blade cut in separate punching station: Effect of the residence time of the cut line
Punching speed (cutting speed)	Effect of the heated punch line when the blade edge cuts more slowly
Blade cut adjustment mechanism (position of transverse and angular position of the die tool relative to the direction of production flow)	Punched edge accuracy Adaptive possibility with distortion (deformation) in the formed sheet-material strip

18.5 Angel-hair formation

Figure 18.22 shows punched edges with and without punched material strands (angel hair).



Punching threads at edge = "angel hair"



Edge without punching threads

Figure 18.22 Punched edge of a container in HIPS, edge thickness 0.6 mm

22.7.1 Material quantity being cooled (material throughput)

$$m = L \cdot B \cdot s_1 \cdot \rho_m \cdot \frac{3600}{T_Z} \cdot 10^{-6} \tag{22.1}$$

m = Material throughput per hour in kg/h.

L = Length (advance feed length or panel length), in mm (Important: Only the length being cooled, without the uncooled clamped edges)

B = Width (e. g., roll-fed sheet-material width or panel width), in mm (Important: Only the width being cooled, without the uncooled clamped edges)

s_1 = Exit thickness of the semi-finished material (sheet material or panel), in mm

ρ_m = Density of the semi-finished material (sheet material or panel), in g/cm^3

T_z = Cycle time, conversion of cycles per minute to cycle time in s.:

$$T_Z = \frac{60}{\text{cycles per minute}}$$

Example:

$L = 1200\,\text{mm}$

$B = 800\,\text{mm}$

$s_1 = 5\,\text{mm}$

$\rho_m = 1.05\,\text{g/cm}^3$

$T_z = 65\,\text{s}$

$$m = 1200 \cdot 800 \cdot 5 \cdot 1.05 \cdot \frac{3600}{65} \cdot 10^{-6} = 279.14\,\text{kg / h} \tag{22.2}$$

22.7.2 Required cooling power during production

$$Q = m \cdot \Delta H \cdot k \cdot S \tag{22.3}$$

Q = Cooling power, in kJ/h

m = Material throughput per hour in kg/h

ΔH = Enthalpy difference during the cooling period, in kJ/kg
See graphic in Figure 22.3 or the values in tabular form

k = Factor for proportional cooling through contact with the forming tool (without air cooling)

- For machines without air cooling (RDM, RDKP, etc.) $k = 1$
- For machines with air cooling (UA) $k = 0.5 \ldots 0.7$

S = Factor reflecting heat loss

- for tool temperature of 15 … 50 °C, $S = 0.1 \ldots 0.95$
- for tool temperature of 50 … 100 °C, $S = 0.95 \ldots 0.85$
- for tool temperature of 100 … 140 °C, $S = 0.85 \ldots 0.75$

When a tool is extremely hot, it will lose a portion of its heat to the environment. Accordingly, less cooling power must be conducted to the tool in the cooling water.

Example (continued):

$m = 279.14\,\text{kg/h}$

$\Delta H = 198\,\text{kJ/kg}$

$k = 0.6$

$S = 0.9$

$$\begin{aligned} Q &= m \cdot \Delta H \cdot k \cdot S \\ &= 29.845\,\text{kJ}\,/\,\text{h} = 8.3\,\text{kW} \end{aligned} \tag{22.4}$$

It is now possible to examine the cooling power of an available cooling device using the calculated cooling power. This value can also be employed to evaluate the heat exchanger if the heat from the forming tool is not directly discharged with the cooling water, but instead with the heat exchanger of a temperature-control unit. This is indicated under "cooling power" for temperature-control units with heat exchangers. If the total heat is discharged through two or more temperature-control units, then this fact must also enter consideration.

22.7.3 Cooling-water requirement for tool cooling

The required cooling water can be calculated with the following formula:

$$V = \frac{1}{60 \cdot \Delta T_M} \cdot \frac{Q}{c_M \cdot \rho_M} \tag{22.5}$$

For water:

$$V = \frac{1}{250.8} \cdot \frac{Q}{\Delta T_M} \tag{22.6}$$

V = Total volumetric flow rate for cooling water, in litres/min.

Q = Cooling power, in kJ/h

ΔT_M = Difference in entry and exit temperatures of cooling medium (water), in °C
  - For forming and punching tools (RDM) ΔT_M = 1 to 2 °C
  - For other forming tools (UA, RV, RDKP, etc.) ΔT_M = 3 to 10 °C

c_M = Specific heat of heat-transfer medium, in kJ/kg K
  - For water, c_M = 4.18 kJ/kg K

ρ_M = Density of cooling medium in g/cm^3
  - For water, ρ_M = 1 g/cm^3

Example (continued):

$Q = 29{,}845\,\mathrm{kJ/h}$

$\Delta T_{\mathrm{M}} = 7.5\,°\mathrm{C}$

$$V = \frac{1}{250.8} \cdot \frac{Q}{\Delta T_{\mathrm{M}}} \qquad (22.7)$$
$$= 15.9 \text{ litres / min}$$

22.7.4 Contact surface required for the cooling water

The cooling water's contact surface can be calculated with the following formula. The calculations apply only for clean cooling passages without deposits.

$$A = \frac{Q}{3600 \cdot \alpha} \cdot \frac{1}{\Delta T_{\mathrm{MF}}} \qquad (22.8)$$

A = Contact surface of cooling water, in m^2

Q = Cooling power, in kJ/h

α = Heat transfer coefficient, in kW/m^2 °K

- For water, α = 2.3 to 3.5 kW/m^2 °K

ΔT_{MF} = Temperature differential between tool surface and heat-transfer medium (°C)
The temperature differential varies according to the tool material, the distance between the tool's surface and the cooling passage, and the ratio of cooling time to cycling time. The recommended temperature differentials for thermoforming tools lie between 8 and 15 °K with sheet-processing machines and between 12 and 25 °K with automatic roll-fed machines

This can be used to calculate the product for round passages of $d \cdot l$:

$$\left(d \cdot l_{\mathrm{total}}\right) = \frac{Q}{3.6 \cdot \pi \cdot \alpha} \cdot \frac{1}{\Delta T_{\mathrm{MF}}} \qquad (22.9)$$

$(d \cdot l_{total})$ = auxiliary parameter, in mm · m; here, the definitions are d for the cooling passage diameter in mm and l_{total} for the total length of the cooling passage

Q = Cooling power, in kJ/h

α = Heat transfer coefficient, in kW/m^2 °K

- For water, α = 2.3 to 3.5 kW/m^2 °K

ΔT_{MF} = Temperature differential between tool surface and heat-transfer medium (°C)

Table 24.3 Faults during thermoforming (vacuum and pressure forming)

Cause …		Material											
		Inadequate impact resistance in material	Low melt resistance (pronounced sag)	Material damp, must be dried	Gassing during heating	Excessive linear expansion during heating	Material displays excessive longitudinal shrinkage	Material displays excessive transverse shrinkage	Shrinkage of material in direction of wrinkles too great	Material part has excessive thickness tolerances	Material displays inadequate ductility when heated	Surface of the multi-layered material too sticky	
Faults during heating	1												1
Sheet material breaks during unwinding	2	x											2
Material is (demonstrably) not warmed consistently	3									x			3
Material too cold in vicinity of edge	4									x			4
Material displays considerable sag	5		x										5
Material sags more on one side	6									x			6
Bubbles on the surface of the material	7			x	x								7
Material wrinkles during heating	8					x							8
Material produces considerable gaseous emissions	9												9
Errors during transport	10												10
Material slips from toothed chain during transport	11							x					11
Material greatly constricted in transport direction	12						x						12
Material escapes from clamping frame	13						x	x					13
Material displays excessive sag	14		x			x							14
Faults during preforming	15												15
Unilateral bubble formation (preblow)	16									x			16
Bubble formation too small (despite maximum preblow settings)	17										x		17
Material tears upon contact with tool	18												18
Material adheres during tool immersion	19											x	19
Faults during molding	20												20
Molding contours with inadequate definition	21										x		21
Edge zone or parts in edge zone not well defined	22												22
Creases on the surface (“surface wrinkles”)	23		x			x							23
Creases in the corners (“corner wrinkles”)	24												24
Terminal vacuum not reached (vacuum forming)	25												25
Forming air escapes (pressure forming)	26												26
Markings from plug-assist tool	27												27

Table 24.3 Faults during thermoforming (vacuum and pressure forming) *(continued)*

Cause …		Heating																			
		No roller preheating (automatic reel-fed machine)	Roller preheat temperature too low	Poor heating pattern	Heaters display excessive output disparities	Poor reflection around edges	Heater temperature too low in edge zone	No pneumatic assist during heating (sheet-processing machine)	Excessive heater temperature (heat radiation too intense)	Insufficient heating consistency in material	Forming temperature too low	Heating time too long	Heating time too brief	Material too hot	Material too cold	Contact surface of material against forming tool too hot	Contact surface of material against forming tool too cold	Contact surface of material against plug-assist tool too hot	Stretch too low in direction of sheet-material transport	Heated length not aligned with advance feed length	
Faults during heating	1																				1
Sheet material breaks during unwinding	2	x	x																		2
Material is (demonstrably) not warmed consistently	3			x	x	x	x													x	3
Material too cold in vicinity of edge	4				x	x	x												x		4
Material displays considerable sag	5	x	x	x	x			x	x			x		x					x		5
Material sags more on one side	6			x	x				x			x		x							6
Bubbles on the surface of the material	7								x					x							7
Material wrinkles during heating	8		x																		8
Material produces considerable gaseous emissions	9								x			x		x							9
Errors during transport	10																				10
Material slips from toothed chain during transport	11																				11
Material greatly constricted in transport direction	12																				12
Material escapes from clamping frame	13																				13
Material displays excessive sag	14	x	x	x	x				x			x							x		14
Faults during preforming	15																				15
Unilateral bubble formation (preblow)	16			x	x															x	16
Bubble formation too small (despite max. preblow settings)	17												x		x						17
Material tears upon contact with tool	18									x					x						18
Material adheres during tool immersion	19													x		x					19
Faults during molding	20																				20
Molding contours with inadequate definition	21	x	x		x	x	x			x	x				x						21
Edge zone or parts in edge zone not well defined	22			x		x	x														22
Creases on the surface ("surface wrinkles")	23							x													23
Creases in the corners ("corner wrinkles")	24																				24
Terminal vacuum not reached (vacuum forming)	25										x		x								25
Forming air escapes (pressure forming)	26										x		x								26
Markings from plug-assist tool	27																				27