

work.info

Thermoforming, Hot-Forming, Bending

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1 Introduction

Within the industrial field, a number of processes have proved successful for the efficient forming of plastics. These processes, which are subject to constant development in line with technological advance, can be categorised as thermoforming, hot-forming and bending. Deep-drawing, vacuum forming and compressed-air forming are special methods of thermoforming [1].

Thermoplastics, either as basic materials or semi-finished parts, are particularly suitable for the various forming processes. This is due to the fact that they can be transformed to a high-elasticity state by warming and can subsequently be formed with the help of proven technology. After cooling in the mould the workpieces retain the shape they are given subsequent to warming. The formed part generally has a larger surface area than the semi-finished product, so a reduction in wall thickness is inevitable. This is taken into account prior to the thermoforming process, when selecting the actual wall thickness of the semi-finished product [2].

In order to achieve the desired shape of the formed part, it is necessary to rework the contour. In some cases, openings may have to be created by methods of machining. Nowadays this mainly takes place on CNC-controlled machines, for example on the basis of CAD data, but also by means of water-jet cutting or die-cutting processes.

In specific fields of application thermoforming competes with injection moulding and blow moulding. The benefits of thermoforming are the use of low-cost tools and machinery as well as the option of being able to process many different types of plastic. The semi-finished products used can have textured surfaces or printed sides. It is also possible to subject multi-layer materials to thermoforming. For example, they can be turned into hollow bodies by using the twin-sheet process.

Ultimately, the method of forming is determined by the price, quantity, shape and quality.

When selecting a process, it is important to take material properties and semi-finished product properties into account. Every material behaves differently with regard to softening temperature, restoring behaviour, recrystallisation and thermal expansion.

2 Materials

This work.info focuses on unfilled and unreinforced thermoplastics. Foamed/reinforced thermoplastics and thermoplastic blends are only described in brief.

2.1 Amorphous thermoplastics

Amorphous materials such as PVC-U or PETG are characterised by a high level of optical transparency, provided they are produced without additives.

In practice, they are used below the glass transition temperature T_G , as their fundamental strength is high in that range. As a result, machining is feasible and the strength required for use as a structural material is adequate.

Above the glass transition temperature T_G the mechanical properties tend to decrease substantially, and the material undergoes transition into the high-elasticity range, as illustrated in Fig. 1. After softening has commenced, resistance to breaking σ_B and the modulus of elasticity decline considerably, while elongation at break ϵ_B increases substantially. Within the high-elasticity range the material becomes extremely pliable, i.e. it can be formed with ease.

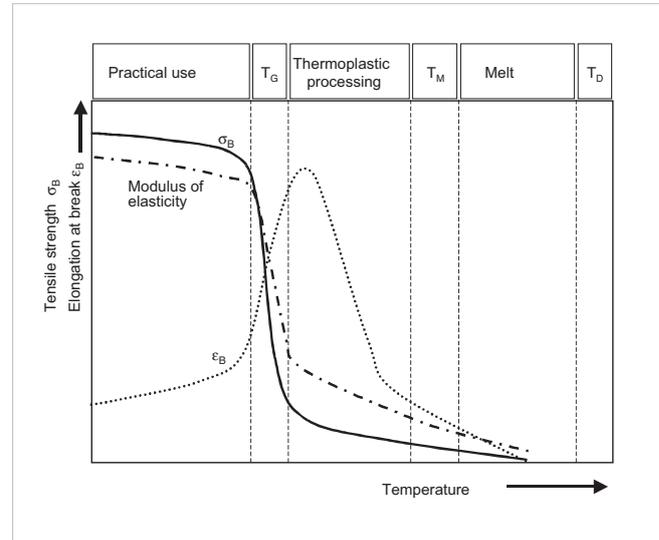


Fig. 1: Diagram of the mechanical properties of amorphous thermoplastics as a function of temperature (T_G = glass transition temperature, T_M = melting temperature, T_D = decomposition temperature)

If the material is heated further, the melting point T_M is reached. This marks the beginning of the plastic range in which the material is reshaped, i.e. extruded, injection-moulded or compression-moulded.

A further temperature increase leads to decomposition of the thermoplastic.

2.2 Semi-crystalline thermoplastics

Semi-crystalline materials, such as PE, PP, PVDF, ECTFE and PFA, are generally opaque to translucent. Below the glass transition temperature T_g they are extremely brittle and sensitive to impact (Fig. 2). Below T_g , semi-crystalline plastics are only used under special conditions.

Between T_g and the crystalline melting range T_c , resistance to breaking σ_B and modulus of elasticity decrease slightly, whilst elongation at break ϵ_B rises. It is in this temperature range that semi-crystalline materials are deployed.

Above the crystalline melting temperature, T_c , the mechanical properties such as tensile stress at break, σ_B , and the modulus of elasticity then decrease very considerably and tensile strain at break, ϵ_B , increases significantly. In this temperature range the materials become transparent due to crystalline-amorphous phase transformation and reach the high-elasticity state in which they can be formed with ease. If forming is conducted below T_c , crystalline areas remain in the part to be formed. Although they are formed, this leads to residual stress within the wall of the formed part. Rewarming of the material results in the deformation of the formed part [2].

If the temperature of the formed part is raised again, the material is plastified. It melts and can thus be used for primary forming.

Decomposition of the material takes place well above the melting temperature.

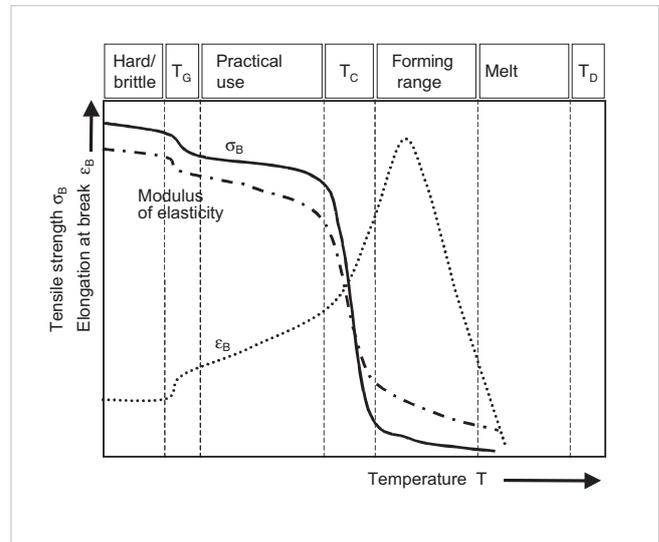


Fig. 2: Diagram of the mechanical properties of semi-crystalline thermoplastics as a function of temperature (T_g = glass transition temperature, T_c = crystalline melting temperature, T_d = decomposition temperature)

3 Material properties

Various characteristics of thermoplastics have to be taken into consideration when assessing their suitability for specific applications or forming processes. The thermodynamic properties determine the process parameters and tool designs as well as the properties of the formed part.

3.1 Tension cracks

Tension cracks in thermoplastics occur upon contact with specific chemicals such as solvents, oils and oxidising media if they are simultaneously subjected to a mechanical load. The mechanical load may occur as a result of internal stresses if, for example, a material has been formed at a temperature which is too cold. In practical use, however, it can also be caused by stresses due to external loads (compressive, tensile and shear loads). Welding seams usually also contain relatively high internal stresses. Even if thermoforming processes are ideal, substantially stretched components are more susceptible to stress cracking than ones that have only been deformed slightly or not at all.

Stress crack corrosion can only be combated by reducing the level of stress (annealing the component) or by using chemicals that do not promote stress cracking as much.

3.2 Thermal properties

The processing capability and cycle times achievable are largely dependent on the thermal properties of the thermoplastic. Thermal parameters are of major importance for calculating the heating and cooling processes.

3.2.1 Specific heat capacity

Specific heat capacity C_p is a thermodynamic parameter which represents the amount of heat required to heat a material by 1 K. Heat capacity C_p can be determined from the change in enthalpy H (heat content) at temperature T and from enthalpy tables or charts (Fig. 3):

$$C_p = \frac{\Delta H}{\Delta T}$$

One experimental method of determining the temperature-dependent heat capacity is Differential Scanning Calorimetry (DSC). For this purpose, a small quantity (5 – 30 mg) is heated in a crucible under controlled conditions, and the heat flux required is measured in relation to a reference sample.

The heat capacity of amorphous thermoplastics is between 1 and 1.5 kJ/(kg·K) and that of semi-crystalline thermoplastics is between 1.5 and 2.7 kJ/(kg·K).

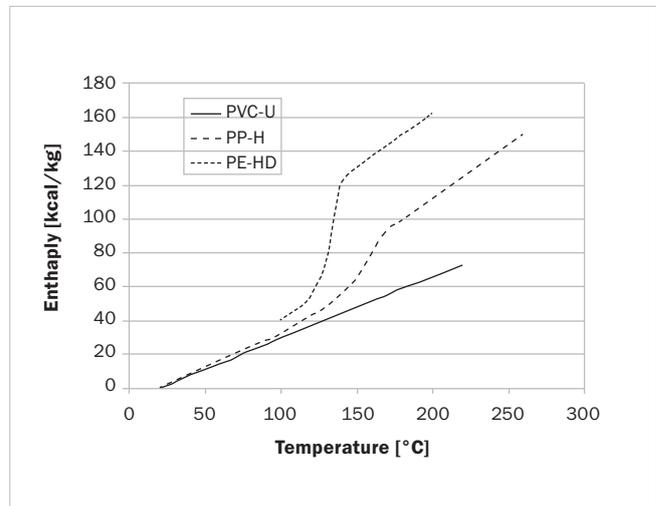


Fig. 3: Graph showing the enthalpy of some thermoplastics

3.2.2 Thermal conductivity

Thermal conductivity λ represents the transport of energy within the material. It is measured by determining the amount of heat which passes through a cross-section of 1 m^2 at a temperature gradient of 1 K in a period of 1 hour.

Thermal conductivity thus characterises the quantity of energy which can be transported through a material per unit of time.

The thermal conductivity of amorphous thermoplastics is in the range of 0.1 to $0.3 \text{ W/(m}\cdot\text{K)}$, while that of semi-crystalline thermoplastics is in the range of 0.2 to $0.6 \text{ W/(m}\cdot\text{K)}$. In some cases, it is heavily dependent on temperature and must be determined by experiment (additional data in [2]).

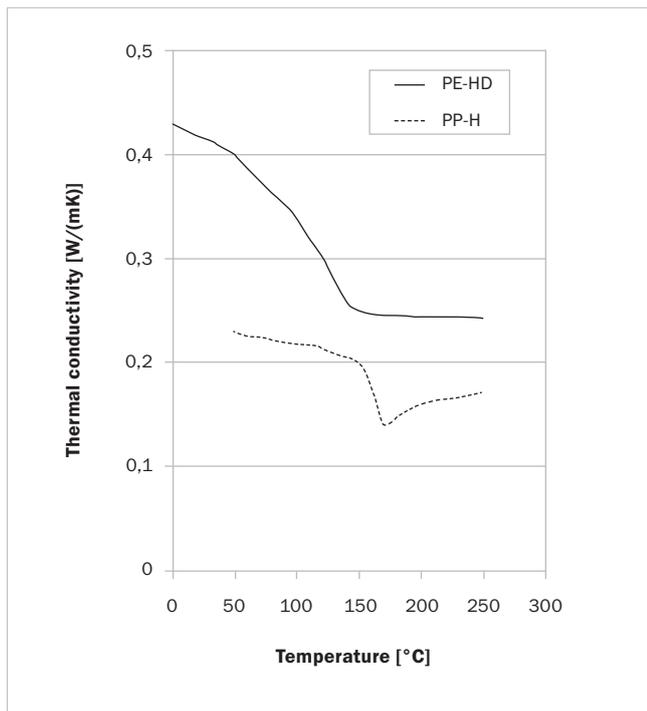


Fig. 4: Thermal conductivity of some thermoplastics as a function of temperature

3.2.3 Thermal diffusivity

The third important parameter for assessing the formability of thermoplastics is thermal diffusivity a , which constitutes a measure of the change in thermal conduction over time. It is dependent on thermal conduction λ , density ρ and specific heat capacity c_p :

$$a = \frac{\lambda}{\rho \cdot c_p}$$

For most unfilled plastics the thermal diffusivity is between 0.05 and $0.25 \text{ mm}^2/\text{s}$. Thermal diffusivity determines the internal warming of a thermoplastic sheet by superimposing an external temperature by radiation or direct contact. In the case of direct contact, heat penetration b is also of significance:

$$b = \sqrt{\lambda \cdot c_p \cdot \rho}$$

If b is known, contact temperature T_c can be calculated in the case of two bodies A and B touching each other:

$$T_c = \frac{b_A \cdot T_A + b_B \cdot T_B}{b_A + b_B}$$

Contact temperature T_c determines thermal flux between the tool and the semi-finished product during the forming process. With the aid of Table 1 the required coefficients can be calculated as a function of temperature.

Table 1: Coefficients for calculating heat penetration

	Coefficients for calculating heat penetration b [3]	
	$b = a_b T + b_0$ a_b	$[W \cdot S^{1/2}/m^2 \cdot K]$ b_0
PE-HD	1.41	441.7
PP-H	0.846	366.8
PVC-U	0.649	257.8

3.2.4 Moisture absorption

Depending on the raw material, modifications, processing equipment and reinforcement substances, plastics may absorb small quantities of moisture from the ambient air or on account of storage in a moist environment. In general, however, the quantities are so low that they do not have an adverse effect on the forming properties of semi-finished products.

In the case of PVC-U, PETG, electrically conductive thermoplastics or coloured thermoplastics, the quantities of moisture can become so high that blisters form on the surface when the semi-finished product is being heated. As regards reinforcement substances and dyes, the absorption of moisture is due to the hygroscopic properties of these additives.

In order to rule out any negative aspects, such plastics should be pre-dried in a forced-air oven (with exit air system). Please refer to Table 2 for a summary of drying conditions. During the drying process in the forced-air oven, care must be taken to ensure that the sheets are placed vertically or arranged in layers in order to ensure full circulation of air. If the semi-finished parts are protected against moisture during storage, pre-drying is generally not necessary.

Table 2: Conditions for drying thermoplastics that have absorbed moisture

	Temperature in °C	Duration in hours per mm wall thickness
PVC-U	55	1.5 - 2
PE-EL	80	
PP-EL	100	
PVDF-EL	100	
PETG	55	

3.2.5 Friction

The friction of a material is dependent on its surface morphology and substance properties. Owing to the low surface tension, plastics usually possess low coefficients of friction at room temperature. However, these properties change with temperature or surface modifications, but also when multi-layer materials are used. Friction can have a positive impact on the forming process or a negative one. If there is a high level of friction between the tool and the semi-finished product, drawing will be limited within the contact zone.

Friction can be influenced by the following parameters:

- Surface roughness of the tool
- Temperature
- Type of plastic

3.2.5.1 Electrostatic charge accumulation

Plastics can develop static if they rub against one another, for example. Such frictional electricity depends, amongst other parameters, on the level of humidity. Electrostatically charged surfaces are capable of attracting light particles of dirt, dust or plastic shavings, for example, which are deposited on the sheet surface. Such impurities appear on the surface lying between the mould and the sheet so they can have a detrimental effect on the visual appearance of the component. For this reason it is advisable to remove the surface charge and eliminate any other impurities, for example with carbon brushes or ionised compressed air.

3.2.6 Contraction and shrinkage

With plastics, as with other materials, the specific volume (volume per kg) increases with temperature on account of thermal elongation in all three directions. The volume of amorphous thermoplastics generally shows a quasi-linear rise in proportion to temperature. Crystalline thermoplastics, on the other hand, behave anisotropically, i.e. their properties are dependent on direction. A linear increase in volume is measured above the crystalline melting temperature T_c . Between the glass transition temperature T_g and T_c the increase in volume is non-linear (cf. Fig. 5).

In forming processes a distinction is drawn between contraction and shrinkage.

Contraction is the change in size of a semi-finished product after warm storage at a defined temperature:

$$\text{Contraction in \%} = \frac{\text{dimension before test} - \text{dimension after test}}{\text{dimension before test}}$$

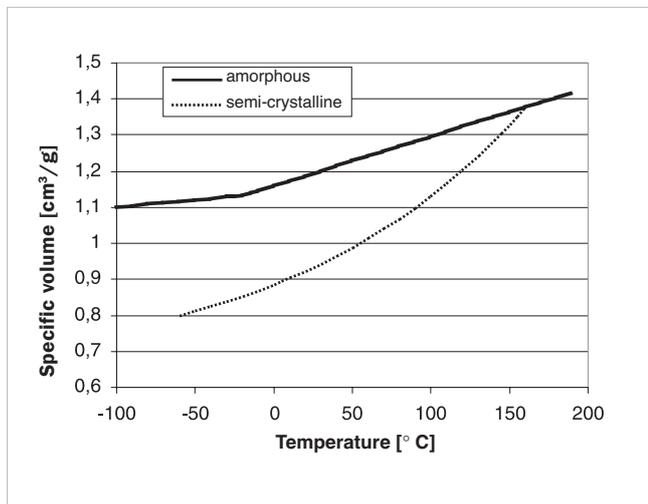


Fig. 5: Specific volume of amorphous and semi-crystalline PP [1]

In order to determine contraction during the forming process, a semi-finished product with defined dimensions should be heated to forming temperature in a forced-air oven on a Teflon sheet that has been sprinkled with talcum powder. In order to determine the anisometric properties, the levels of contraction can be measured in all directions, particularly in the direction of extrusion and at right angles to it.

Problems with regard to wrinkling, stripping from the frame and severe deformation when heating with contact heaters may be associated with contraction at a temperature which has been selected too high.

Shrinkage is the difference between the tool dimension and the dimension of the formed part when it has cooled down. A distinction is also drawn between processing shrinkage, post-shrinkage and total shrinkage:

$$\text{Processing shrinkage in \%} = \frac{\text{dimension of tool} - \text{dimension of part}}{\text{dimension of tool}}$$

The dimensions of the tool and the dimensions of the formed part should be measured after 24 hours of cooling to 23 °C.

$$\text{Post-shrinkage in \%} = 1 - \frac{\text{dimension of part after storage (days to weeks)}}{\text{dimension of part after cooling (24 h)}}$$

$$\text{Total shrinkage} = \text{processing shrinkage} + \text{post-shrinkage}$$

Accurate shrinkage values can only be determined by experiment using thermoforming tools which have similar contours to those of the parts to be manufactured. Approximate values for various thermoplastics are listed in Table 3. However, one must take into account the fact that contraction and shrinkage can also be dependent on the batch.

Shrinkage must be taken into consideration during rework on the formed parts because in many cases the parts in question have not yet cooled down completely. Shrinkage is generally influenced by the following factors:

- The type of plastic (with possible batch fluctuations)
- Rate of cooling: a high rate of cooling means less processing shrinkage
- High demoulding temperature results in higher shrinkage
- High stretching produces less shrinkage
- Male moulds produce less shrinkage compared to female moulds
- The direction of extrusion causes various amounts of shrinkage

4 Vacuum thermoforming

In single-stage thermoforming processes a basic distinction is made between male and female forming. The thermoforming process can be divided into two steps, pre-stretching and final forming.

Pre-stretching can take the form of mechanical pre-stretching by the mould or by an assisting plug as well as by means of pre-blowing or pre-suction. Pre-stretching creates a stretched preform that possesses an optimal, uniform wall thickness distribution at the final forming stage.

Final forming is carried out with a vacuum (vacuum forming) or compressed air (pressure forming). The assistance provided by the negative pressure during vacuum forming means that the semi-finished product is pressed against the mould at atmospheric pressure. The maximum contact pressure, however, is $1 \text{ atm} = 0.1 \text{ N/mm}^2$. The sheet or film is firmly clamped in a frame which is above the deep-drawing mould (= tool). After warming and stretching, which should be as uniform as possible, the air between the mould and the material is evacuated and the sheet is pressed against the deep-drawing mould by external atmospheric pressure. When it has cooled down the moulding can be removed.

The advantage of the vacuum forming process is that thin-walled, large-surface parts can be made with relatively simple tools. Tooling costs, capital expenditure and the cost of maintenance are significantly lower than with the injection moulding process. This method is particularly suitable for mass production. However, it also ensures profitability for small batch sizes.

Small items can be produced very efficiently by using multicavity moulds.

If greater detail is required on the formed part (i. e. the contour of the tool has to be reproduced more accurately), pressure forming is used, in which the heated semi-finished product is pressed against the mould at high pressure ($7 \text{ bar} = 0.7 \text{ N/mm}^2$ to $10 \text{ bar} = 1 \text{ N/mm}^2$).

All SIMONA® thermoplastics can be processed using standard methods of thermoforming, with thermoforming properties ranging from good to very good. The only exceptions to the rule are the high-molecular-weight PE versions PE 500 and PE 1000 as well as foamed thermoplastics, which are only suitable to a limited extent. All types of machine can be used. For sheets from a thickness of 3 mm upwards, however, it is advisable to heat the material from both sides or pre-warm it in an oven. The warming time is thus reduced and thermal damage to the surface is avoided.

It is also advisable to prevent the material from sagging – and thus from uneven heating – by supplying supporting air.

For the production of large batches, machines with automatic semi-finished parts feeding have proved particularly successful. Depending on the area of application, machines can be used with and without top force as well as with and without automatic mode for blank sizes of up to approx. 2 x 6 m.

For 1 mm wall thickness, a heating time of approx. 45 – 60 sec. is required for the semi-crystalline thermoplastics PE, PP and PVDF. In comparison, the time for PVC is approx. 25 sec.

Table 3: Approximate values for deep-drawing SIMONA materials^②

	Name	Maximum draw ratio ①③	Shrinkage in the direction of extrusion ^② in %		Processing temperature ^③ in °C	Tool temperature in °C
			Forming			
			male	female		
PE	PE-HD / PE 100	1 : 4	2 - 3	> 3	160 - 180	50 - 70
	SIMOLIFE PE ^④	1 : 5				
	PE-EL	1 : 3.5				
PP	PP-H AlphaPlus [®] / PP-H / PPs / PP-C / PP-R	1 : 3	1.5 - 2.5	> 2.5	170 - 200	50 - 80
	SIMOLIFE PP	1 : 2.5				
PVC-U	PVC-CAW / PVC-LZ	1 : 4	0.5 - 1	> 1	160 - 180	< 50
	PVC-MZ-COLOR ^⑤	1 : 5				
	PVC-GLAS / PVC-GLAS-SX	1 : 4				
PETG	SIMOLUX / SIMOLIFE PETG	1 : 4	0.5 - 1	> 1	160 - 180	50 - 60
PVDF	PVDF	1 : 3	2 - 3	> 3	190 - 200	60
ECTFE ^⑥	ECTFE	1 : 3	2 - 3	> 3	250 - 260	80 - 90
CPVC	CPVC	1 : 2.5	0.5 - 1	> 1	170 - 190	50 - 70

① Ratio between the area of the sheet and the area of the part to be formed

② Approx. half the value in the transverse direction

③ Surface temperature, not heater temperature

④ For extreme stretching conditions, especially for female forming

⑤ ECTFE has a very low elongation at break between 170 °C and 240 °C and cannot be processed within this temperature range

⑥ Dependent on operating staff and on the installation

⑦ The figures are values determined by experiment using a thermoforming unit from the Illig company, Type U100, with ceramic radiant heaters. The temperatures of the top heater were 550/500/450 °C. The temperature of the bottom heater was 400 °C.

For sheet thicknesses of 6 mm upwards, machines with a high heater power require reduced heater power or intermittent heating in order to improve internal warming.

To make sure plasticization reaches the clamping point, it is necessary to shield the sheet against draughts.

Uncoloured semi-crystalline thermoplastics such as SIMONA[®] PE-HD, PP-H natural and PVDF usually become transparent when the forming temperature has been reached (above the crystalline melting range).

Pre-stretching the sheet prior to forming results in uniform wall thickness distribution. This is achieved especially in the case of male forming.

After vacuum forming and solidification of the surface, air (with water added as well) can be used for further cooling. A high forming temperature, slow cooling rate, low demoulding temperature (40 °C) and immediate edge trimming will produce parts with minimal distortion.

Depending on mould design and processing conditions, contraction (difference between moulding dimensions and tool dimensions) is about 1% to 3%, mainly in the direction of sheet extrusion.

4.1 Male and female forming

The decision whether to use male or female forming depends on the desired effect for the formed part. In the case of male forming, for example, the mould's accuracy in terms of shape will be most noticeable on the interior surface of the formed part. This is because the interior surface of the semi-finished product makes contact with the tool. In addition, the tool surface, i.e. its detail, is reproduced particularly well on the side making contact.

Wall thickness distribution is also quite different. Where male moulds produce a thin spot, with female forming a thick spot is created.

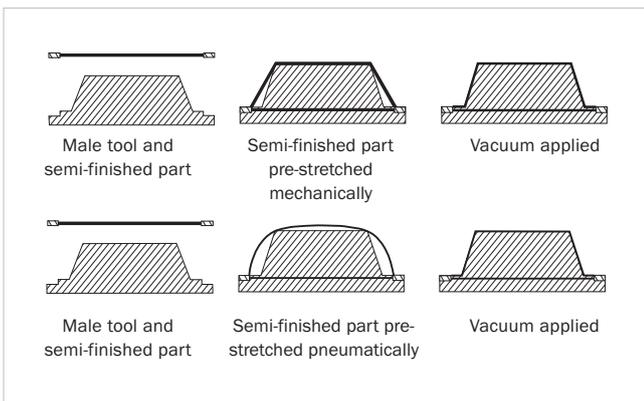


Fig. 6: Diagrams of male forming

Tool textures and production data can be reproduced very well on the part, particularly on PP. If specified tolerances are very small, the technique of choice is male forming because when the part is being cooled down it contracts onto the tool. Consequently the amount of shrinkage remains limited.

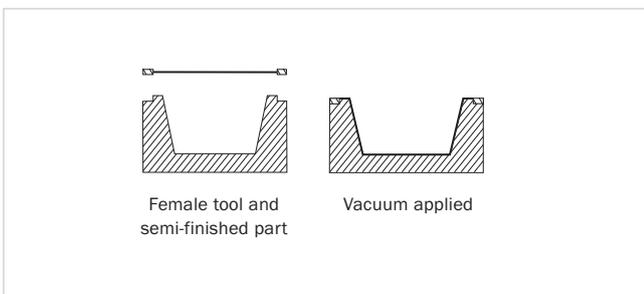


Fig. 7a: Diagram of female forming without mechanical or pneumatic pre-stretching

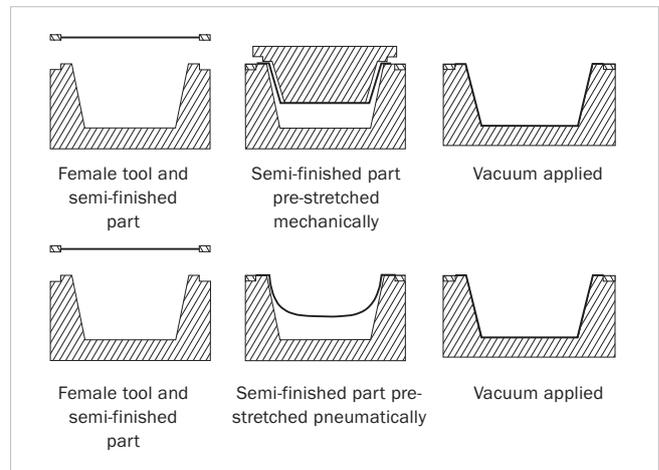


Fig. 7b: Diagram of female forming with mechanical or pneumatic pre-stretching

When the material is completely plasticized, in the tool cavity it should be pre-blown to an appropriate height, or pre-stretched in the case of female forming. Otherwise there may be a risk of wrinkling. Pre-stretching should be performed at approx. $\frac{2}{3}$ of the height of the tool. Then the tool is moved into the pre-stretched sheet and a vacuum is applied. Owing to rapid cooling, further forming is limited at points where the plastic makes contact with the tool.

Air should be used for subsequent cooling. Spray water should only be used when the surface has cooled down sufficiently so that no stresses are introduced. With this method of processing the wall thicknesses are more uniform and internal stresses are reduced.

For efficient manufacturing of top-quality deep-drawn polyethylene, PVDF and polypropylene parts it is absolutely essential that the item has cooled down completely – after demoulding the parts whilst they are still warm – in separate frames in order to avoid distortion.

It is recommended that cooling be performed in a frame with the same geometry as that of the tool. In many cases, it is possible to use old tools or moulds made of wood.

4.2 Tools

The materials chiefly used for tool construction are wood, aluminium, casting resins and laminating plastics. The choice of material for mould making is determined by the

- Required quality of deep-drawn parts to be manufactured (e.g. surface quality)
- Number of forming processes
- Favourable processing capability
- Thermal conductivity
- Wear resistance
- Cost

When making the tools the mould shrinkage of the thermoplastics and the direction of extrusion of the sheets must be taken into consideration.

A material with high thermal conductivity and cooled moulds tend to increase cost-effectiveness and result in more uniform forming conditions.

Uniform batches and short, efficient cycle times can be achieved with temperature-controlled tools.

The advantage of sand-blasted surfaces is that in vacuum forming the air can be withdrawn entirely and no nests of air can form. Vacuum channels should be no larger than 1 mm, for polyolefins preferably smaller than 0.8 mm. Otherwise, their structure will be reproduced too intensely on the material in its plastic state. It is advisable to coat the moulds with a release agent (talcum powder, Teflon spray, wax or soap). In male forming one will usually be able to achieve slightly more uniform wall thicknesses on account of the possible pre-stretching of the heated sheet.

The edge radii may be relatively sharp in the case of polypropylene and PETG. The minimum radii at the specified forming temperature are roughly equal to the sheet thickness. In the case of PE-HD, PVC and PVDF, we recommend larger edge radii (about 2 – 3 times the sheet thickness).

The use of male moulds requires a draft (degree of taper) of 5° to 10° for semi-crystalline materials (PE, PP, PVDF, ECTFE) and a draft of approx. 5° for amorphous thermoplastics (PVC, PETG). In the case of female moulds, this is not necessary because the deep-drawn part is separated from the mould during the cooling process.

4.3 Pre-heating

To optimise machine utilisation (increase cycle times), we recommend preheating the sheets in a forced-air oven to just below the softening range (PE-HD 110 °C, PP 125 °C, PVC 50 – 55 °C, CPVC 70 – 80 °C, PETG 60 – 70 °C, PVDF 140 °C, ECTFE 140 °C). When heating up the oven, one should use a reduced level of heating power. The surface of the sheet is thus largely preserved. Ultimately, by using this approach, one will achieve a longer service life of the parts.

Plastication up to the edge is essential in order to avoid considerable deformation in the deep-drawn parts. We strongly recommend screening the deep-drawing machine from draughts on all sides.

4.4 Heating the semi-finished parts

Heating the semi-finished parts is one of the most important process steps in thermoforming. The semi-finished part should be heated in such a way as to ensure maximum efficiency, i. e. it should be heated to the forming temperature required with minimal energy in a short space of time. Generally speaking, care must be taken to ensure that heating of the surface of the semi-finished part is uniform. Only in special cases does non-uniform temperature have any advantages in thermoforming.

When heating, the “processing window” consisting of the lower and upper forming temperatures must be taken into account. They are dependent on the material and are listed in Table 3. Heating must be controlled in such a way that the temperature of the semi-finished part is within that processing window. A temperature gradient within the wall thickness is unavoidable in practice. However, care must be taken to ensure that the internal segment of the semi-finished part has exceeded the lower temperature limit in order to avoid stresses in the part.

If the heater temperature is very high, the surface of the semi-finished part, for example, will be heated too quickly and too intensely. As a result, the surface may start decomposing, or other property changes may occur. The interior of the semi-finished part may, due to low thermal conduction, not follow the surface temperature, and its temperature will therefore be too low for forming. This leads to stresses, while the long-term stability of the part is impaired on account of excess surface stress.

The optimum temperature distribution point in the semi-finished part will depend on the thermodynamic properties of the semi-finished part used and the method of heating.

Accurate calculation of heating parameters is extremely complex because the full range of the thermodynamic properties of the semi-finished part, tool and heating system have to be determined.

It is more practicable to determine the parameters with the respective semi-finished part and tool by experiment. Determining the surface temperature distribution with a contactless temperature measuring instrument (IR thermometer) or temperature measuring strips has proved particularly successful. Using these methods, it is also possible to determine the temperature distribution of the heating units.

4.4.1 Contact heating

With contact heating the semi-finished sheet is placed on a heated plate with parting film (Teflon film) and backing layer to improve the contact or between two heated plates each with parting film and kept in that position until the semi-finished part has reached the contact temperature of the heating plates. Heating is performed by pure thermal conduction in the sheet. In practice, care should be taken to ensure a uniform distribution of temperature within the heating plates in order to prevent temperature peaks which would subject the semi-finished part to undue stress.

4.4.2 Convection heating

Convection heating is the heating of semi-finished parts in a forced-air oven which has been heated to forming temperature. This method is used, for example, with thick PETG sheets, which are subsequently stretch-formed.

4.4.3 Radiation heating

Radiation heating is an interaction between an electromagnetic radiation source and a surface which absorbs the radiation in the form of heat. The radiation is characterised by its wavelength. Plastics chiefly absorb radiation in the infrared (IR) range, in the wavelength range of 0.8 to 10 μm .

Absorption of radiation depends on thickness, the colour of the plastic and the wavelength of the radiation source. Whereas virtually all the radiation energy is absorbed in the surface, no direct heating of the sheet interior takes place in the wavelength range. If the wavelength is between 1 and 1.4 μm , the penetration depth of the radiation is several millimetres. Wavelengths above 2.5 μm chiefly heat the surface, so the heating of a relatively thick sheet may, under certain circumstances, take a very long time due to the inferior thermal conduction.

In practice, there is no heater that regulates monomodally, i. e. only with one wavelength. Commercially available radiation sources emit throughout the entire IR range and have their radiation maximum at various wavelengths depending on the type (Fig. 8).

It is clearly evident that the ceramic heater has a very wide wavelength spectrum and thus also covers the range in which most plastics possess a high absorption capacity.

Bright radiators, on the other hand, have a very pronounced radiation maximum. Thus, the principal energy is emitted between 0.5 and 2 μm . That is precisely the range in which penetration depth is very high, so absorption is at a minimum. Consequently, the heating process is not solely performed by thermal conduction from the surface to the interior. Rather, on account of the penetrating radiation, the interior of the sheet is heated directly.

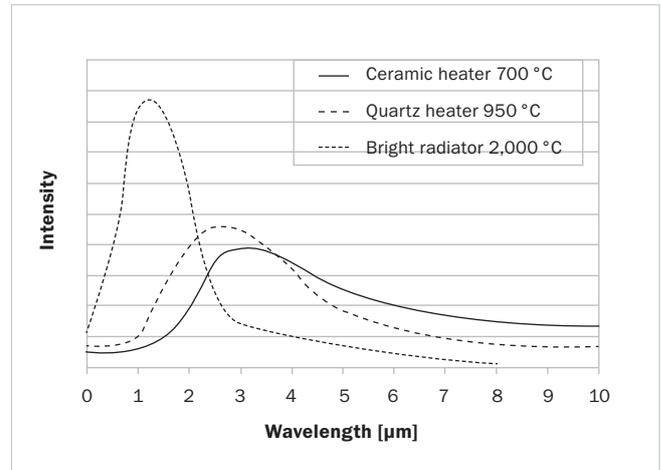


Fig. 8: Radiation characteristic of various commercial IR heaters

As the radiation temperature increases, the radiation maximum shifts towards shorter wavelengths. The energy to be introduced to a semi-finished part is also dependent on heater temperature, which can shorten cycle times considerably.

The next generation of heaters, with a radiation maximum at 1 μm (halogen heaters), are said to guarantee an even faster heating phase [4]. However, there are physical limits to heat transfer in the form of the absorption characteristic of the plastic. Bright radiators cannot always be used because they heat the surface too intensely, and the interior of the sheet is unable to “follow” this temperature. As a result of too intense heating, the surface of the semi-finished part may be damaged permanently. The damage has a detrimental effect on service life and colour consistency, especially when exposed to weathering.

4.5 Orientation – influence of extrusion direction

The contraction test is suitable for determining the orientation and stretching of the macromolecules in a semi-finished part. High orientations, as usually occur in the direction of extrusion, have a very substantial effect on wrinkling. In the direction of sheet extrusion the shrinkage is generally much higher than in the transverse direction. In the case of multiple tools with segments at equal distances or with moulds containing segments which are longer than they are wide and which are repeated a number of times (Fig. 9), the direction of extrusion should be parallel to the length of the segments in order to avoid wrinkling. This becomes all the more important if the direction perpendicular to extrusion possesses negative contraction.

General rule of thumb: longitudinal direction of the sheet = longitudinal orientation of the deep-drawn part. For special deep-drawing applications we recommend the use of PVC-T.

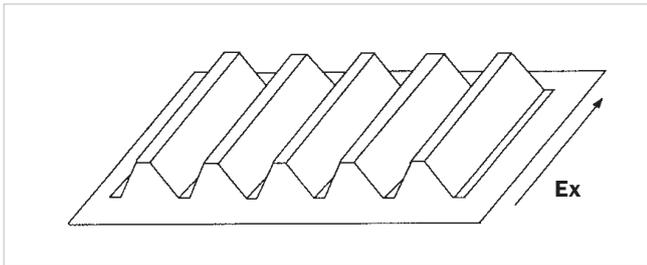


Fig. 9: In the case of formed parts with distinct orientation, the direction of extrusion of the semi-finished part should be in the direction of the longitudinal orientation of the individual segments.

4.6 Calculation of the wall thickness of deep-drawn parts

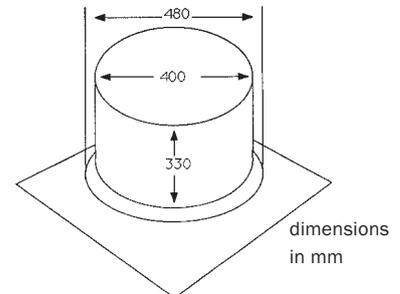
The deep-drawing ratio is regarded as the quotient of the surface area of the base (O_1) and the surface area of the drawn part (O_2).

Assuming wall thickness distribution is as uniform as possible, here are two examples of calculations.

Cylindrical tank

Specified:

Deep-drawing frame with mask	$D_1 = 48 \text{ cm}$
Cylinder	$D_2 = 40 \text{ cm},$ $h = 33 \text{ cm}$
Required wall thickness	$s_1 = 3 \text{ mm}$



Sought:

Initial wall thickness	$s_2 = x \text{ mm}$
------------------------	----------------------

Solution:

Surface area of the base	$O_1 = r^2 \pi = 24^2 \pi$	$= 1,809 \text{ cm}^2$
Generated surface area	$M = D_2 \pi h = 40 \pi 33$	$= 4,147 \text{ cm}^2$
Surface area of the drawn part	$O_2 = O_1 + \text{gener. surface area}$	$= 5,956 \text{ cm}^2$

Draw ratio $s_1 : s_2 \approx O_1 : O_2 \approx 1 : 3.3$

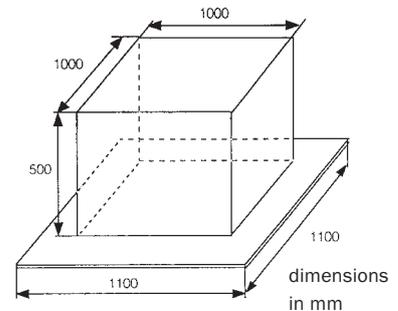
Conclusion:

In order to obtain a 3 mm wall thickness for the part, sheets with a thickness of at least 10 mm must be used.

Square tank

Specified:

Deep-drawing frame with mask	$= 1.1 \cdot 1.1 \text{ m}^2$
Square tank	$= 1.0 \cdot 1.0 \cdot 0.5 \text{ m}^3$
Initial wall thickness	$s_2 = 5 \text{ mm}$



Sought:

Wall thickness of finished part	$s_1 = x \text{ mm}$
---------------------------------	----------------------

Solution:

Surface area of the base	$O_1 = 1.1 \cdot 1.1 \text{ m}^2$	$= 1.21 \text{ m}^2$
Generated surface area	$M = 4 \cdot 1.0 \cdot 0.5 \text{ m}^2$	$= 2.00 \text{ m}^2$
Surface area of the drawn part	$O_2 = O_1 + M$	$= 3.21 \text{ m}^2$

Draw ratio $s_1 : s_2 \approx O_1 : O_2 \approx 1 : 2.5$

Conclusion:

The wall thickness on the part to be drawn will be no larger than approx. 2 mm (for reasons of caution it is advisable to calculate on the basis of 1.5 mm).

4.7 Troubleshooting in vacuum thermoforming – processing flaws [5]

	Lack of detail	No mould contact	Chill marks	Bead along the edge	Ragged surface	Air inclusions	Arching	Blisters	Thin areas	Uneven wall thickness	Wrinkles	Material torn open on mould contact	Material clings to tool	Cracks in the drawn part	Crazing	Wrinkling on heating	Drawn part resumes original shape	Drawn part bent	Drawn part unstable	Material heats up unevenly
Possible cause																				
Material too hot			x			x		x	x		x	x								
Material too cold	x	x										x								
Demoulded too warm	x						x										x	x		
Demoulded too cold														x	x					
Release agent may be required												x	x							
Too much release agent					x															
Vacuum too early			x								x	x								
Vacuum too late											x									
Vacuum too fast											x									
Vacuum too slow	x	x		x																
Final vacuum inadequate	x	x																		
Vacuum not switched off													x							
Vacuum switched off too early	x																			
Cooled down too early	x	x																		
Pre-blowing omitted/inadequate			x						x	x		x								
Excessive pre-blowing							x		x	x	x									
Material touches mould on warming										x	x					x				
Material sags on heating										x	x									
No hold-up plate											x									
No hold-down plate									x	x	x									
Hold-down plate not balanced	x																			x
Cooled for too long															x					
Cycle time too slow	x																			
Draught	x																			x
Demoulding air irregular							x						x	x	x					
Mould moves in too fast									x											
Mould moves out too fast													x	x	x					
Cooled down too late				x																
Cooled down in parts														x					x	
Material warmed too fast								x				x								
Clamping rim cut off too late																				x
Parts jammed																				x
Material not cleaned					x															
Top force absent/too slow									x											
Top force too small									x											
Top force too large									x											
Top force too rough									x											
Top force too early									x											
Top force too cold									x											
Top force not centred										x										

Flaw in mould, machine, material or design

	Lack of detail	No mould contact	Chill marks	Bead along the edge	Ragged surface	Air inclusions	Arching	Blisters	Thin areas	Uneven wall thickness	Wrinkles	Material torn open on mould contact	Material clings to tool	Cracks in the drawn part	Crazing	Wrinkling on heating	Drawn part resumes original shape	Drawn part bent	Drawn part unstable	Material heats up unevenly
Possible cause																				
Mould too cold		x	x									x		x						
Mould too hot						x	x										x	x		
Mould too smooth				x		x														
Mould too rough					x				x			x	x	x						
Not tapered											x		x	x						
Mould with undercut													x							
Edges and corners too sharp			x						x		x	x		x						
No vent/suction													x	x	x					
Mould board too high, no seal	x																			
Mould hollow, suction flow too high	x																			
No suction/suction inadequate	x	x						x												
No suction over area		x	x			x	x				x									
Uneven suction, hole distribution		x		x			x		x	x										
Suction too high									x		x									
Mould dirty					x															
Stretching excessive (drawing edge too small)	x								x			x								
Drawing edge too large											x									
Segment spacing too small									x											
Clamping frame too large											x			x						
Clamping frame too small	x								x			x								
Clamping frame not tight	x																			
Clamping frame not balanced	x															x				x
Not tight (rubber seal)	x																			
Heating uneven								x			x	x				x		x		x
Heating too intensive								x				x								
Table too slow or too fast			x							x		x		x	x					
Vacuum filter soiled	x	x																		
Material not stored properly (vertically)																				x
Material selected is too thin									x											x
Material thickness uneven		x								x										
Inclusions in the material					x															
Material stretched on one side				x												x		x		
Shrinkage too large													x	x						
Narrow forming range	x	x										x								
Material does not retain heat		x																		
Stretch ratio unfavourable									x										x	
Attach ribbing																				x
Walls too vertical											x			x						
Corners too sharp											x			x						
Form reinforcements																				x

5 Hot-forming

A distinction is made between heating on the deep-drawing machine plus vacuum stretching, and heating in an oven plus forming with male and female dies/blowing at positive pressure. As opposed to thermoforming, where the material is clamped and heated at a high heater temperature on one side or both sides, the heating process for hot-forming takes place much more conservatively in a forced-air oven.

In the case of hot-forming, too, the thermoplastic semi-finished part is heated into the high-elasticity range in order to minimise forming forces and residual stress in the component after cooling.

For forming, the semi-finished part is cut to size, heated, laid round the mould and kept on or in the mould by a vacuum or by mechanical means until it has cooled down sufficiently for it to have adequate rigidity.

In order to ensure the dimensional accuracy of the fittings, preliminary tests should be performed directly using the production tool or a tool comparable to the mould. In addition, the forming temperature should be determined by experiment because the characteristic of the mechanical properties can vary enormously depending on temperature. This becomes evident when one assesses PVC-U (Fig. 10). The elongation at break of PVC-U has a minimum at 135 °C. Therefore, depending on the mould, a temperature outside the temperature range that is common for PVC-U, from 110 °C to 140 °C, can also be suitable for thermoforming.

SIMONA offers, specially for hot-forming, semi-finished parts such as SIMONA® PE-HD, which owing to the special production conditions have shrinkage values that are suitable for hot-forming.

The sheet format required should be cut to size taking contraction into consideration. An additional small allowance for length is to be recommended for the purposes of reworking.

The sheet sections are best heated in a forced-air oven which can be controlled accurately. The thermoplastic sheets should be placed on shelves horizontally in order to ensure that they are heated on all sides.

The following figures are to be seen as a rough guide for the temperature of the sheets to be formed:

■ PE-HD	125 – 150 °C
■ PP-H	160 – 190 °C
■ PP-C	160 – 175 °C
■ PVC-U	110 – 140 °C
■ CPVC	140 – 160 °C
■ PETG	140 – 170 °C
■ PVDF	175 – 200 °C
■ ECTFE	260 – 270 °C
■ PFA-M	310 – 325 °C
■ PFA	320 – 340 °C

Higher temperatures are possible in order to increase the cycle rate. In this case, the surface must be observed and the surface temperature measured accordingly.

The duration of heating depends on the temperature in the forced-air oven, the degree of movement of the ambient hot air, the wall thickness of the sheet to be heated and, last but not least, the type of plastic. The following figures have proved reliable as guidance for workshop use:

■ Polyolefine and PVDF	Heating time in minutes: 6 times sheet thickness (mm)
■ PVC	Heating time in minutes: 3 times sheet thickness (mm)
■ PETG	Heating time in minutes: 3 times sheet thickness (mm)

One must bear in mind that for hot-forming all parts of the sheets must be heated uniformly throughout (visual inspection). This minimises the risk of “restoring” when cooling down after forming. One criterion in the case of uncoloured materials is the complete transparency of the material.

The selection of mould material depends on the desired service life and the stresses, i.e. the number of intended formings as well as the surface quality of the finished part. The moulding tool can be made of gypsum, casting resin, wood, plastic or metal. If the mould is made of gypsum, however, care should be taken to minimise residual moisture because otherwise chill will occur on the tool.

Generally speaking, two tool parts are used (male and female moulds). In some cases, one part of the tool is replaced by a cloth, the heated blank is thus wound round a core and held firmly until it has cooled down.

5.1 Hot-forming with backed materials

SIMONA® liner materials are all thermoformable without exception. They can be processed by various types of hot-forming.

The main ones are:

- Vacuum deep-drawing
- Deep compression-moulding with male/female mould (with vacuum assistance where necessary)
- Hot-forming, e.g. beading

The sheet, which is usually clamped in a frame, is heated to about 175 °C in a hot-air oven (for backed PVDF, temperature may vary for other thermoplastics). To achieve a short dwell time (3 to 4 min/mm) it is advisable to use a forced-air oven and temperatures around 200 °C. The time between removal of the sheet from the oven and the forming process should be kept short. In blowing, the use of preheated air is beneficial.

In this way, stretch-backed PVDF sheets are processed to make dished boiler ends and other parts with a low stretch ratio. Stretch ratios that can be achieved in the stretching process are 1:1.4 max. Stretch-backed sheets may only be heated on one side if radiators are used.

Although the stretch fabric can be stretched two-dimensionally, wall thickness distribution cannot be as uniform as with unbacked sheets, owing to the different surface temperatures.

Pressure and vacuum forming processes, as often applied for forming dished boiler ends, can also be used with SIMONA® ECTFE. The glass fabric backing of SIMONA® ECTFE has adequate multi-axial stretchability for the application, even though the stretch ratio is lower than in the case of stretch backings. With fabric-backed sheets it is generally only possible to achieve reduced degrees of stretching. The figures indicated are for guidance only and may vary according to machinery and tooling.

Table 4: Deep-drawing parameters of ECTFE

	Two-sided heating	One-sided heating
Top heating in °C	450 – 550 (depending on zone)	–
Bottom heating in °C	400	400
Heating time in sec./mm sheet thickness	45 – 50	100

ECTFE has a highly reduced level of expansibility in the temperature range between 170 °C and the melting range. Forming tests in this range lead to cracking or brittle fracture, especially if the radius is small or if the shaping is complex. Conventional processes such as hot bending, beading and folding can be performed without any problems provided this fact is taken into account.

For compression forming of backed sheets the optimal procedure is to anneal the sheets at 180 °C in a forced-air oven. In this process the temperature of the forming tools should be at least 80 °C.

To form flange faces, the procedure is to bead round liner pipes. Notch-free cut edges are heated to a temperature in the melting range by means of a hot-air gun, oil bath or glycerin bath and are then formed using forming tools preheated to 80 °C.

For further information on backed materials and processing thereof, please contact our Technical Service Centre (tsc@simona.de).

5.2 Hot-forming in orthopaedics

For the construction of orthotic devices and prostheses SIMOLIFE products are also hot-formed after the heating of sheets. The deep-drawing of such prostheses and orthotic devices is described in detail in the SIMOLIFE product brochure.

6 Bending

Apart from whole-piece heating and forming, it is also possible to heat individual areas, e.g. in order to make edges or angles. The linear bending zone of a sheet can be heated in various ways on one or both sides:

- without contact
- with heaters (infrared or quartz heaters)
- with glow wires or heating rods
- with a hot-air blower
- with direct contact
- with flat heating elements

After adequate warming, the plastic sheet is bent at the angle specified and locked until the material has solidified again. Blowing with compressed air accelerates cooling.

The minimum bending radius can be assumed to be double the wall thickness of the sheet.

7 Appendix

Literature

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8 Legal note and advice

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