Technical manual, January 2005

Makrolon®
Solid Polycarbonate Sheets

Forming

1. Cold forming

Cold bending
All Makrolon® sheets, with the exception of Makrolon®AR, can be subjected to cold bending with a minimum radius of 150 times sheet thickness.

Minimum radius ≥ 150 x sheet thickness

Thermoforming is recommended for smaller radii.

Cold folding
Makrolon® sheets can be cold folded. To achieve good results, the following guide values should not be exceeded:

Sheet thickness in mm	Bending radius in mm	Maximum folding angle
1 to 2.5	2	90°
3 and 4	3	90°
5 and 6	4	60°

The relaxation immediately following the cold folding process means that the sheet has to be overstretched by approximately 25°. The internal and external stress levels take a few days to become balanced with the parts only then taking on their final shape.

Bear in mind that cold folding places high stress on the edge areas of the material.

Avoid the use of aggressive chemicals, particularly with cold folded and cold bent parts.

The use of cold folding should be restricted to thin Makrolon® sheets.

2. Thermoforming

Protective Masking
Makrolon® sheets are provided with a PE masking film to protect the smooth surfaces from damage during transport and fabrication.

Please leave the film on the sheet during machining. Solar radiation and weathering may influence the properties of the film and make it very difficult to remove later on (possible formation of adhesive residues).

Our **standard protective masking film is not suitable for exposure to thermal loads**, and does not allow thermoforming with good results. The film should therefore be removed from the sheets before processes such as drying, hot line bending and/or thermoforming.

We have specially manufactured, unprinted grades of film that allow the sheets to be fabricated with the protective masking left on.

Pre-drying
Makrolon® sheets absorb only small amounts of moisture from their surroundings. Nevertheless, we recommend drying the sheets prior to forming. Insufficient pre-drying leads to the formation of bubbles during the heating process, impairing the optical quality of the finished part.

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A circulating air oven should be set at a temperature of 120 to 125 °C to ensure thorough pre-drying. The drying times vary according to the thickness of the Makrolon® sheets.

Sheet thickness (mm)	Drying time at 125 °C (h)
1	1.5
2	4
3	7
4	12
5	18
6	22
8	30

Once the protective film has been removed, the sheets can be hung up in the oven or laid in a frame. Make sure that the sheets are spaced 20 to 30 mm apart to allow the air to circulate freely.

To cut the heating time and save energy when using the thermoforming machine, the pre-dried Makrolon® sheets should be kept in the drying oven until processing.

Makrolon® sheets that are cooled to room temperature after the drying process should be processed within a maximum of ten hours (depending on ambient conditions) unless redried.

When cutting the sheets it is important to remember that there will be one-off shrinkage upon initial heating to above the glass transition temperature of 145 °C.

Shrinkage values of max. 6 % for sheets up to 3 mm thick and of max. 3 % for thicker sheets can be expected.

Prior to thermoforming, Makrolon® sheets should be thoroughly cleaned using an anti-static detergent or ionized compressed air thus avoiding surface defects e.g. embedded particles of dust on the finished part.

Hot folding

Hot folding is a relatively easy forming process for the production of uniaxially formed parts. The Makrolon® sheet simply requires local heating to 150 to 160 °C so that pre-drying is generally not required.

The Makrolon® sheet is heated using IR heaters or heating elements in a linear manner (see Fig. 1). As soon as the desired temperature is reached, the sheet is removed from the heating element, folded, placed in the mold and clamped into position. The desired shape should be fixed until the material becomes stiff.

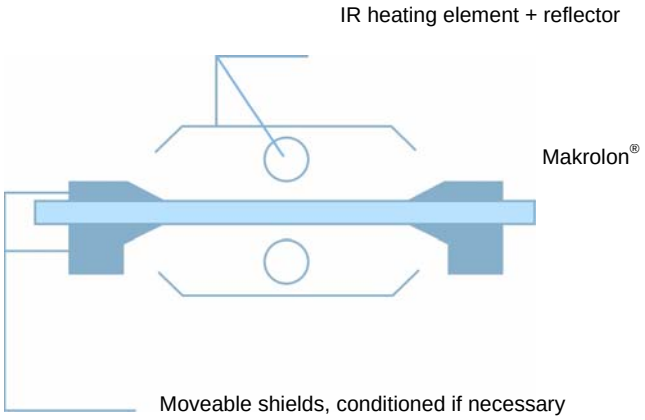

Fig. 1: Hot folding

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If using one-sided heating, the Makrolon® sheet must be turned over several times to guarantee even heating on both sides. With sheet thickness of 3 mm or more and when producing large numbers of units, we recommend simultaneous heating of both sides using a sandwich heating appliance. By adjusting the heating width using the shields (see Fig. 1), various different bending radii can be achieved, although a minimum bending radius of 3 times the sheet thickness should not be undershot.

Local heating creates stresses in the finished part. Care should be taken when using chemicals with bent formed parts.

Heating the Makrolon® sheet

To achieve compliant formed parts, the Makrolon® sheets should be heated evenly as part of a controlled process to a temperature of 175 to 205 °C. The best forming precision of the parts is achieved at the upper end of the forming temperature range. Given that the forming temperature is very high and Makrolon® sheets cool quickly, it is better in practice to heat the sheets directly on the forming machine and not – as is frequently done with other thermoplastics for example – in separate circulating air ovens.

For heating the Makrolon® sheets we recommend IR heating systems, if possible two-sided, which can be heated up relatively quickly.

The advantage of two-sided heating lies in the more even and quicker heating of the material. This enables shorter cycle times and is more economical. The heating time increases in linear proportion to the thickness of the Makrolon® sheets and should be calculated by means of trials on the forming machine.

To avoid any significant loss of heat at the sheet edges during the heating process or uneven cooling, which could create internal stresses and warping, we recommend that the clamping device be conditioned. To improve the thickness flow, the sheets may be hot formed with mechanical pre-stretching.

Cooling the finished part

Makrolon® sheets cool quickly, with the result that the forming process must be rapid. At the same time, however, the high heat resistance means that short cooling cycles can be achieved. As soon as the formed part is dimensionally stable (at approx. 135 °C) it can be removed from the tool.

Male forming

Simple, uniaxially formed parts with large radii of curvature can be stretch formed. The Makrolon® sheets are heated to the right temperature in a circulating air oven and quickly transported to a tool heated to between 80 and 100 °C.

The sheet's own weight or light pressure applied with gloves or cloth is enough to form the sheet over the male tool.

The sheets then need to be cooled in fresh air. Make sure there are no draughts, which can cause distortions or stresses in the formed part.

We recommend removing the protective film before heating the sheets in an oven.

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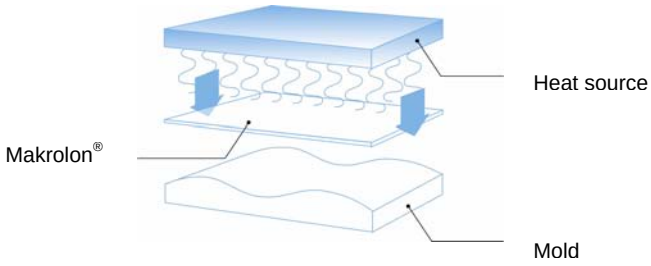

Fig. 2: Thermoforming using a male tool

Thermoforming Tools

To produce large numbers of units and/or to achieve optimum surface quality, use should be made of conditioned (120 to 130 °C) aluminium or steel tools with silk-matt surfaces. A mold angle of between 4 and 6° will facilitate the release process.

When constructing forming molds, allowance should be made for shrinkage of 0.8 to 1 %. Provision should be made for sufficient and correctly placed vents with a diameter of no more than 0.5 to 0.8 mm to avoid impressions on the molded part. To improve ventilation, the hole may be back-drilled with a larger drill (see Fig.3). Special materials are available for producing porous forming tools without vents.

The radii should be measured as generously as possible and at least correspond to the wall thickness of the Makrolon® sheet to attain a higher level of stiffness and to avoid any dilution or wrinkle formation during forming.

Male and female tools

The decision on whether to use a male or female tool depends on the application. To achieve a better surface quality on the outer side of the finished part, use of a female tool is recommended to attain greater detail (see Fig. 4).

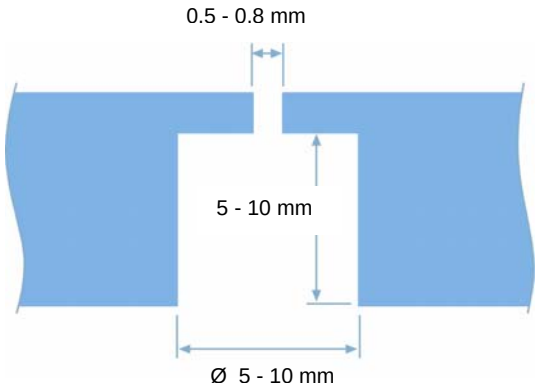

Fig. 3: Sketch of vents during thermoforming

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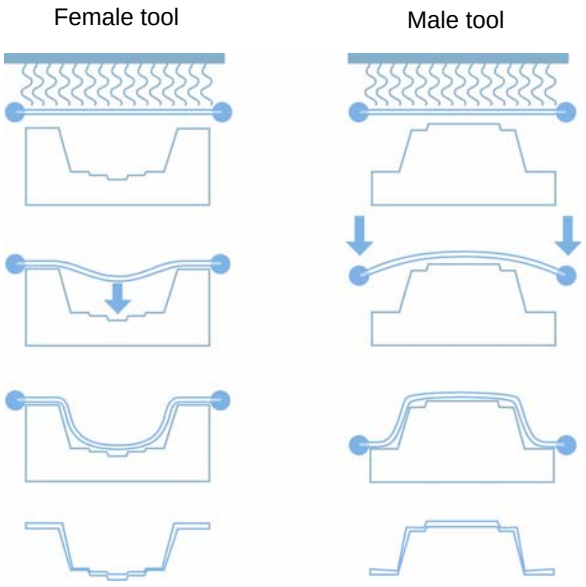

Fig. 4

Blowing or thermoforming without countermold
This technique is used to form domes. Blowing without a countermold involves working with air pressure whilst the thermoforming process without a countermold is carried out in a vacuum. To produce perfect moldings, the sheets should be evenly heated. Avoid any draughts in the workshop that could lead to uneven heating. At a sheet temperature of approx. 135 °C, the part retains its desired shape and can be removed.

Other methods
Other thermoforming methods involve combinations of the above processes.

High-pressure forming
Compressed air is used to increase the atmospheric air pressure in a closed mold, stretching the softened sheet across the mold. This results in precise reproduction of detail and sharp edges.

Twin-sheet forming
Two heated sheets are placed between two female tools. Using compressed air, blow moldings are produced with a high degree of structural stiffness and lightweight construction. This method can be used to form and join two sheets during one process.

Conditioning
Makrolon® sheets should be processed under optimum conditions as far as possible so avoiding high internal stress in the sheets, which could result in a need for subsequent heat treatment.

Conditioning means heating parts, keeping them at their temperature and then slowly cooling them again.

Internal stresses in Makrolon® sheets can be largely removed by conditioning in a hot cabinet. The parts are evenly heated to 120 to 130 °C and kept at this temperature on the basis of 1 hour per 3 mm of thickness. It is important that the parts are then cooled without any extreme temperature fluctuations, preferably in an oven.

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Tips for Thermoforming

Problems	Possible causes	Solution	Hot Bending	Stretch forming	Thermo-forming	Blowing / thermo-forming without counter-mold
Bubbles in the sheet	Moisture	Pre-drying	•	•	•	•
	Excess heating	Reduce heating	•		•	•
Badly formed parts	Sheet too hot	Reduce heating			•	•
	Tool too cold	Raise tool temperature			•	
	Part not released soon enough	Shorten cooling cycle			•	
	Vacuum too fast	Limit vacuum			•	
	Sharp edges	Round off edges			•	
	Sheet surface too small	Use larger sheets			•	
Wave formation	Uneven heating	Monitor hot areas and shadow areas			•	
	Too small a distance between molds	Min. distance = 2 x thickness			•	
	Vacuum too fast	Limit vacuum			•	
	Sheet surface too large	Distance between clamp & tool < 50 mm			•	
Reduced or incomplete details	Insufficient vacuum	Check for lack of tightness or add vents			•	
	Sheet temperature too low	Increase heating			•	
Molding sticks to mold	Tool too hot	Reduce tool temperature			•	
	Part not released soon enough	Release sooner			•	
	Release angle too small	Release angle > 4 to 6°			•	
Impressions	Mold surface too smooth	Slightly matt tool			•	
	Sheet temperature too high	Reduce heating time	•	•		
	Vents badly positioned	Re-evaluate vent positioning			•	
Surface defects	Dust on sheet or mold	Clean with ionized compressed air		•	•	
	Vents badly positioned	Re-evaluate vent positioning			•	
Uneven finished parts	Tool/clamp too cold	Increase pre-heating			•	
	Heating/cooling	Check for draughts; check heating	•	•	•	•
	Release too late	Release sooner			•	