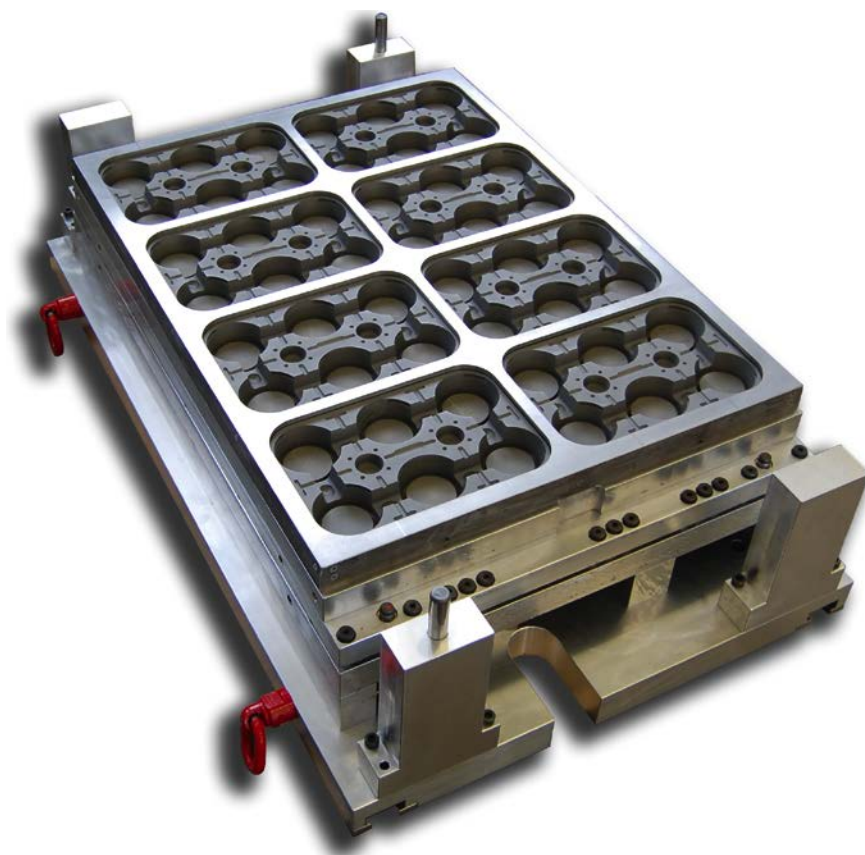


Molding Shrinkage is Calculable

Influence of Production and Material Parameter on the Molding Shrinkage

The molding shrinkage during thermoforming has a major influence on the function and quality of the moldings. In order to control the process as a whole, detailed knowledge is necessary of the material behavior and process technology in conjunction with the individual process steps.



The molding shrinkage of the molded part during thermoforming is always taken into consideration during mold making, depending on the material to be processed (figures: Illig)

The molding shrinkage (MS) expresses the deviation in size of the molding in relation to the dimensions of the corresponding mold cavity or mold segment (**Formula 1**).

This shrinkage starts with the demolding and continues with the further cooling of the molded part. According to DIN 16901, the molding and mold dimensions necessary for determination are measured after 16 hours' storage at 23 °C (room temperature); in practice, these dimen-

sions are generally measured after approx. 24 hours.

Further shrinkage occurring after this time is referred to as post-shrinkage (PS). The total shrinkage (TS) of a molding thus results from the sum of the molding shrinkage and the post-shrinkage (**Formula 2**).

There is no binding definition of the point at which the post-shrinkage is to be measured; it can be selected at random or by agreement.

What Happens After the Molding Process?

A thermoformed molding remains in the mold until it is rigid enough to be demolded without deformation. The demolding temperature is therefore selected such that the thickest point in the molding is sufficiently cooled. The temperature at the core of the thickest point then corresponds roughly to the maximum continuous working temperature of the molding, but cannot be measured directly. What is measurable is the surface temperature, but it is always lower than at the core of the molding due to the temperature gradient. Very thick-walled parts can have a considerable temperature gradient – and the more intensively a molding is cooled, the greater this temperature gradient becomes.

Until it is demolded, the dimensions of the molding are identical with the dimensions of the mold. The shrinkage process starts with the separation of the molding from the cavity wall or from the mold segment wall. If this takes place at temperatures in the maximum continuous working temperature range of the molding, shrinkage is essentially a temperature-dependent change in length

From Practice — for Practice

With this issue, **Kunststoffe** is starting a series of articles with practical know-how on thermoforming. The 15 articles planned here give answers to questions that have been asked for years in innumerable customer training seminars and practice-oriented further training courses. In general, each article covers one self-contained topic.

and can be calculated in advance with a good approximation.

Calculation of Molding Shrinkage

A general rule of thumb for the temperature-dependent change in length Δl of solids is **Formula 3** with the starting length l of the molding in mm, the coefficient of linear expansion α of the material in K^{-1} (per Kelvin), the temperature T_2 at the start of the change in length and T_1 on completion of the change in length, in $^{\circ}C$ in each case.

The molding shrinkage MS is thus calculated as a relative change in length with **Formula 4**.

What Influence Does the Heated Mold Have?

When determining the change in length, the starting dimension (l) corresponds to the dimension of the mold cavity or of the mold segment under production conditions. These conditions can differ widely, depending on the machine type. Molds in automatic roll-fed thermoformers, for example, are cooled so that their production temperature corresponds roughly to room temperature ($23^{\circ}C$). The molding starting dimensions with these molds are therefore equal to the production dimensions of the mold.

Molds in sheet processing machines, on the other hand, are generally heated (**Fig. 1**) so that their production temperature – at least for the standard plastics – is generally approx. $10^{\circ}C$ lower than the maximum continuous working temperature of the molding. Depending on the plastic type, the production temperature (mold temperature) can be well in excess of $100^{\circ}C$, for example $125^{\circ}C$ to $130^{\circ}C$ when processing polycarbonate (PC), $180^{\circ}C$ to $200^{\circ}C$ for high-tech plastics such as PPS (polyphenylene sulfide) or even $220^{\circ}C$ to $250^{\circ}C$ for PEEK (polyether ether ketone). The dimension of the mold at production temperature (i.e. in expanded state) then has to be taken as the starting dimension l for “exact” calculation of the molding shrinkage (Δl) of the molding (**Formula 5**). The factor which records the influence of the mold temperature is thus calculated as **Formula 6**.

For an aluminum (Al) mold with a production temperature of $200^{\circ}C$, we thus have **Formula 7**.

This means that the calculated molding shrinkage of a molding, allowing for the expansion of the mold at $200^{\circ}C$, is only 1.004 times (0.4%) larger than the molding shrinkage calculated for a cold production mold ($23^{\circ}C$). The influence of the mold temperature is therefore low and negligible in practice, so that the production dimension of the mold at $23^{\circ}C$ is taken as the starting dimension for the molding when determining the molding shrinkage even with heated molds.

Examples of Calculated Molding Shrinkage

For HIPS (high impact polystyrene) with a coefficient of thermal expansion α of approx. $70 \times 10^{-6} K^{-1}$, a demolding temperature during production (max. continuous

working temperature of the molding) of approx $90^{\circ}C$, and a room temperature of $23^{\circ}C$ we obtain a relative molding shrinkage of 0.47% (**Formula 8**).

■ From experience we know that the molding shrinkage of amorphous HIPS lies in the range of 0.4% to 0.5%.

For PP with α of approx. $200 \times 10^{-6} K^{-1}$ (mean value of $\alpha = 150 \times 10^{-6} K^{-1}$ to $250 \times 10^{-6} K^{-1}$), a demolding temperature of $115^{\circ}C$, and $23^{\circ}C$ room temperature we obtain a relative molding shrinkage of the molding of 1.84% (**Formula 9**).

■ The molding shrinkage of partially crystalline PP normally lies in the range of 1.8% to 2.1%.

The values calculated here are standard values that are taken as the basis for the design of molds for the processing of these plastics. »

$$MS[\%] = \frac{\text{Dimension at mold} - \text{Dimension on molding}}{\text{Dimension at mold}} \cdot 100$$

Formula 1

$$\text{Total shrinkage } TS = \text{Molding shrinkage } MS + \text{Post-shrinkage } PS$$

Formula 2

$$\Delta l = l \cdot \alpha \cdot (T_1 - T_2)$$

Formula 3

$$MS = 100 \cdot \frac{\Delta l}{l}$$

Formula 4

$$\Delta l_{\text{Molding}} = l_{\text{Mold at production temperature}} \cdot \alpha_{\text{Plastic}} (T_{\text{Demolding of part}} - 23)$$

$$\Delta l_{\text{Molding}} = l_{\text{Molding at } 23^{\circ}C} \left(1 + \alpha_{\text{Al}} (T_{\text{Molding during production}} - 23) \right) \alpha_{\text{Plastic}} (T_{\text{Demolding of part}} - 23)$$

Formula 5

$$1 + \alpha_{\text{Al}} (T_{\text{Molding during production}} - 23)$$

Formula 6

$$1 + \alpha_{\text{Al}} (T_{\text{Mold during production}} - 23) = 1 + 23 \cdot 10^{-6} (200 - 23) = 1.004$$

Formula 7

$$MS = 100 \cdot 70 \cdot 10^{-6} (90 - 23) = 0.47\%$$

Formula 8

$$MS = 100 \cdot 200 \cdot 10^{-6} (115 - 23) = 1.84\%$$

Formula 9

Formulas for the calculation of molding shrinkage having regard to production and material parameters



Fig. 1. Examples of molded parts produced with heated molds on platen machines

Calculations Provide Only Reference Values

The arithmetically determined molding shrinkage can only provide an approximate value, as the coefficient of linear expansion of the material and the temperature difference between demolding temperature and room temperature required for the calculation generally have to be entered as mean values. Furthermore, intrinsic stresses in the intermediate used (films, sheets) also have an effect as they cannot always be completely relieved during heating to molding temperature. Nevertheless, the calculation equations shown here illustrate clearly the main influencing parameters for the molding shrinkage.

In practice, the molding shrinkage is determined in tests rather than being calculated. For this, a pilot-series mold is required with which the moldings can be produced under near-production conditions. For the exact design of a mold, the molding shrinkage in all three molding axes – longitudinal, transverse and in molding height – has to be known.

Influences on the Molding Shrinkage – from Coefficient of Linear Expansion α ...

- Figures indicated in tables for the coefficient of linear expansion α are always average values. The coefficient of linear expansion can vary, depending on the raw material, the masterbatch incorporated into the intermediate or the filler content.

- For amorphous plastics such as HIPS, α is roughly constant in the range of the continuous working temperature.
- For partially crystalline plastics, α is not constant. For PP, for example, the coefficient of linear expansion changes from approx. $150 \times 10^{-6} \text{ K}^{-1}$ at temperatures in the range of 20°C up to $250 \times 10^{-6} \text{ K}^{-1}$ at the continuous working temperature of approx. 110°C .

... through the Demolding Temperature ...

- One example: In a cup molded with solid phase pressure forming, the molding temperature of the film is approx. 154°C to 158°C , the measured surface temperature is immediately after demolding (on opening the mold) approx. 115°C at the thick points and approx. 55°C at the thinner walls (Fig. 2). Already this significant temperature gradient alone results in differences in the molding shrinkage within the PP cup.
- Experience has shown that for a round PP cup, a molding shrinkage of approx. 1.85% to 2.1% has to be assumed for the thicker edge area, and approx. 1% for the side wall.

... and the Plastic Type ...

- Moldings of amorphous plastics have practically no or very little post-shrinkage.
- Partially crystalline plastics, on the other hand, are characterized in some cases by a quite pronounced post-shrinkage. Depending on the storage time and storage temperature, the post-shrinkage of the moldings can be as high as 50% of the molding shrinkage.
- The period over which moldings of partially crystalline plastics undergo post-shrinkage is roughly one week. Depending on the storage temperature, however, this period can be significantly longer.

... up to the Production of the Intermediate

- Internal stresses in the intermediate (films and sheets) generally have no major influence on the molding shrinkage. In practice, tolerances of max. $\pm 10\%$ are observed, depending on the extrusion parameters for the intermediate production and depend-

The Author

Dipl.-Ing. Peter Schwarzmann is division manager sheet processing machines at Illig Maschinenbau GmbH & Co. KG, Heilbronn, Germany, and publicly appointed and sworn expert of the Heilbronn-Franconia Chamber of Trade and Industry (IHK), Germany, for thermoforming; peter.schwarzmann@illig.de

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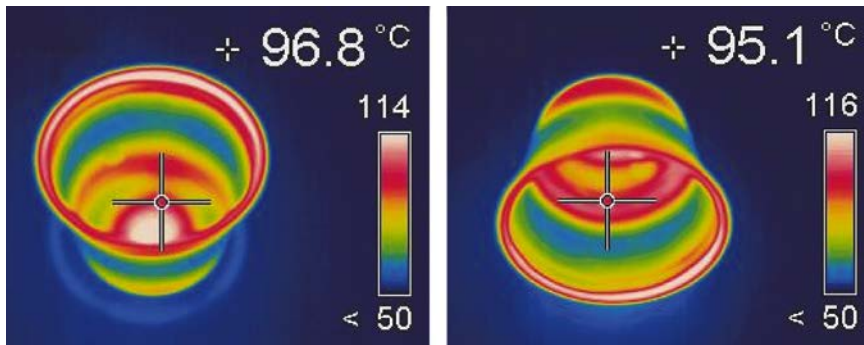


Fig. 2. Temperature distribution in a PP plastic cup with sealing edge after demolding: The hot-test points in the edge and base have a temperature of approx. 115°C, the coldest points in the side wall only approx. 55°C

ing on the degree of concatenation of the production line, i.e. whether it operates inline or offline.

Tips and Advice on Determining the Molding Shrinkage ...

- When determining the molding shrinkage, all the influencing parameters have to be defined and documented (mold, machine, settings, molding and demolding temperatures).
- One of the biggest problems is the documentation of the tested intermediate, as sufficient data are generally not available. Retention samples and a test of the free shrinkage of the delivered intermediate are therefore always to be recommended.
- When determining the dimensions for calculation of the molding shrink-

age, care must be taken that no deformation is measured in the process. If, for example, a round cup is deformed into an oval shape after molding, the measured values have to be converted for "round". Or, to put it in simple terms: The cup has to be "pressed into the round shape" before measurement.

... and in General

- Due to the spread of the property values of thermoformed parts, no statements should be made on dimensional tolerances whose values are less than $\pm 10\%$ of the molding shrinkage. One calculation example for HDPE with a molding shrinkage (MS) of approx. 2%: With 1,000 mm molding length, the molding shrinkage is $0.02 \times 1,000 \text{ mm} = 20 \text{ mm}$;

the mold cavity or mold segment is therefore designed for a molding length of $1,000 + 20 = 1,020 \text{ mm}$. For a dimensional tolerance of at least $\pm 10\%$ of the MS: $\pm 0.01 \times 20 \text{ mm} = \text{at least } \pm 2 \text{ mm}$; the tolerance specification for the 1,000 mm long HDPE molding is thus $\geq \pm 2 \text{ mm}$.

- If punching is carried out in a separate station on a thermoforming machine after molding, the short-term shrinkage has to be taken into consideration.

One example for the molding of PP on an RDKP thermoforming machine with separate molding and punching: In order that the punched parts achieve their finished dimension according to the molding shrinkage of 1.85%, a short-term shrinkage of 1.1% is taken into consideration for the tools of the punching station.

- If fits between two molded parts are demanded, the fit test during running-in of these molds may only be performed after the end of the molding shrinkage, i.e. after at least 24 hours.
- If very closely toleranced technical parts are paired together (e.g. by clipping) and the parts to be paired are also made of different materials, attention must be strictly paid to the use of materials with more or less the same molding shrinkage.
- If moldings are to be fitted into one another (e.g. bonded) and the time for the sequence for this reworking is defined, the working procedure must be strictly observed. ■



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