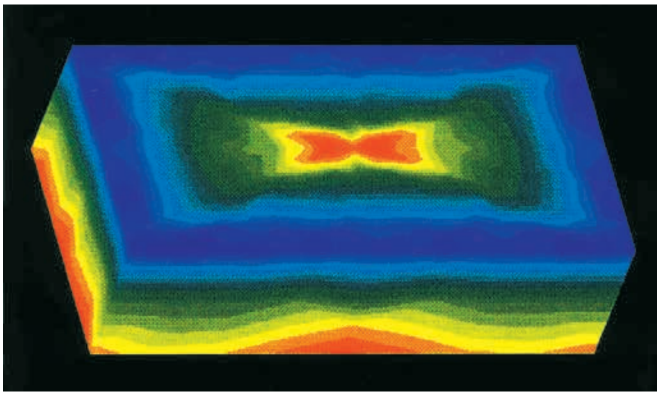
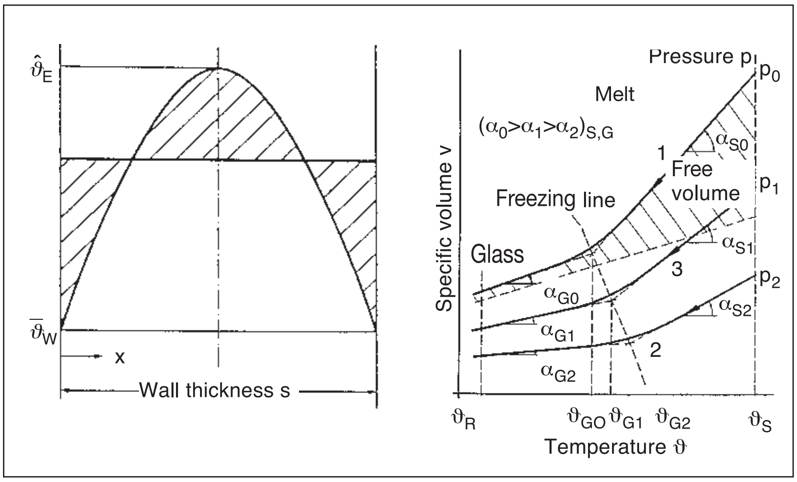
Process Variables as Production Cost Factors in the Injection Molding of Thermoplastics:

Melt, Mold and Demolding Temperature, Cycle Time, p-v-ϑ diagrams

Contents



$$t_K = \frac{s^2}{\pi^2 \cdot a_{eff}} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{\vartheta_M - \overline{\vartheta}_W}{\hat{\vartheta}_E - \overline{\vartheta}_W}\right)$$



1 Introduction

The injection molding of thermoplastics is a form of processing in which highly complex physical processes take place.

The thermoplastic to be processed first has to be melted, before being injected at high pressure into a "cold" mold. Since the mold is cooler than the compound, the shaped plastic part cools down and can be removed from the mold once it has solidified.

The individual process stages of melting, injection and cooling affect the quality of the subsequent molded part.

The temperature control system of the mold plays a central role in the quality-conscious and cost-efficient production of injection-molded parts. This control system is known to influence decisive quality features, such as surface appearance and warpage.

Efficient mold temperature control also helps to cut costs, however, since the cooling time, and hence the cycle time as well, can be optimized in this way.

In order to fully appreciate the importance of cooling in an injection mold, it is wise to take a look at the thermodynamic processes that prevail during the injection molding process.

This then supplies the answers to the following questions:

What sort of temperature changes occur in the molten plastic at the individual stages of the process, and what happens inside a polymeric melt as it cools? What is the difference between an amorphous plastic and a semi-crystalline plastic.

2 Melt temperature

2.1 Melt temperature during molded part filling

When thermoplastics are injection molded, granules are melted in a screw and conveyed into the screw antechamber.

Once the injection signal has been given, the screw moves forward and presses the molten plastic through both the machine nozzle and the runner/gate system into the cavity. The filling process frequently imposes a high level of mechanical and thermal stress on the melt. The chief parameters that affect this stress are the:

- Nozzle/gate geometry
- Wall thickness of the molded part
- Filling rate
- Molding compound temperature
- Mold wall temperature

The stress acting on the melt as it flows can lead to internal friction processes, which then cause the melt to heat up.

Experimental investigations into different gates and different materials [1] have shown that the mean temperature increase of $\Delta_{\overline{\vartheta}M}$ can be described in approximate terms as a function of the pressure loss Δp, whereby there is assumed to be no exchange of heat with the mold (adiabatic => $Q_{ab} = 0$).

$$\Delta\overline{\vartheta}_M = \frac{\Delta p}{\rho \cdot c_p}$$

$\Delta\overline{\vartheta}_M$ = Mean temperature increase in the melt
Δp = Pressure differential (pressure loss) in a flow section of the runner/gate system
ρ = Melt density
c_p = Specific heat capacity

The particular significance of this equation stems from the fact that it can describe the process independently of the geometry, the melt temperature, the wall temperature and the rheological material values. As has already been mentioned, there is no allowance made for the exchange of heat with the cold mold.

Looking more closely at the temperature of the melt as the molded part is being filled, it is seen that cooling can have a very considerable influence on the temperature of the melt. A temperature profile, which can be quite pronounced, forms over the cross-section of the flow channel as a result of the dissipation of heat via the mold wall. Figure 1 shows a typical temperature profile of a flowing plastic melt in a cooled injection mold.

Right next to the mold wall, the melt has already solidified, giving rise to a frozen edge layer. The thickness of this layer will be a function of the processing conditions (injection time, melt temperature and mold wall temperature). In the center of the flow channel, there is a uniformly high temperature distribution. Peaks such as those shown in the diagram can develop between the center of the channel and the mold wall. It is here that the shear stress acting on the melt is greatest and hence here that most heat is generated through internal friction.

The temperature profile can vary at different points of the cavity (close to the gate, far from the gate). Therefore, an increasingly large frozen edge layer can cause the maximum temperature (the temperature peaks in Fig. 1) to shift towards the center of the channel. This situation is depicted in Fig. 2.

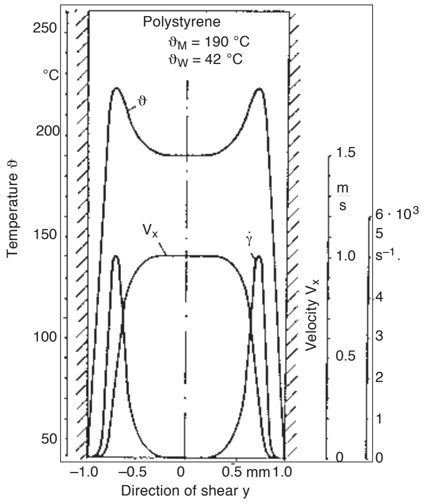


Fig. 1: Temperature profile in a flowing plastic melt [1]

2.2 Melt temperature in the holding pressure and cooling phases

Once the mold has been volumetrically filled, the holding pressure phase commences. In the course of this phase, melt is conveyed into the mold cavity for as long as possible, in order to offset volumetric contraction. Since the flow of melt is very small by comparison to the flow that prevails during the filling phase, there is no further increase in temperature as a result of internal friction. The temperature of the melt experiences a steady fall.

Immediately after the holding pressure phase comes the residual cooling phase. During this phase, the temperature of the molten plastic, which has now almost completely solidified, falls to the demolding temperature.

Fig. 3 shows computed temperature profiles over the cross-section of a molded part during the cooling phase (panel s = 3 mm, material ABS). The temperature profile flattens out increasingly with time. After approximately 16 s, the temperature in the middle has fallen to the demolding temperature.

It is evident from what has just been said that the melt temperature is subject to constant change during the injection molding process. Apart from the processing parameters of injection time, temperature of the injected compound and temperature of the runner/gate system, the mold cooling system also has a major influence on the temperature of the melt. The cooling of the mold, in particular, largely determines how uniformly and how rapidly heat is eliminated from the plastic in order to permit demolding.

What happens in a plastic melt as it cools? At what temperature does it freeze? How high is its heat content, i.e. how much heat energy is required to heat or cool plastics? The answers to these questions will be provided in the section that follows.

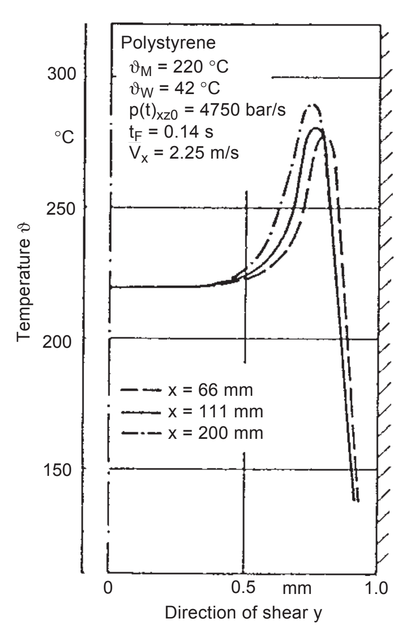


Fig. 2: Temperature profile at different flow locations at the time when the molded part is full [1]

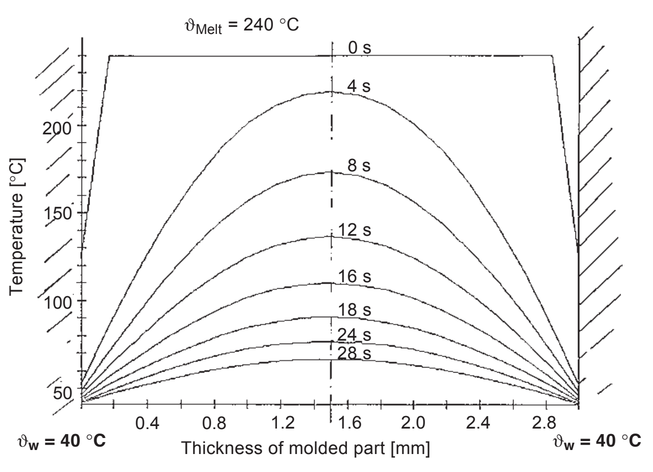


Fig 3: Temperature profiles in a cooling thermoplastic melt at different points in time (computed)

3 The cooling of thermoplastic melts, thermodynamic state curve

When heat is eliminated from a polymeric melt, the chains lose their mobility, and segment after segment is captured by the neighbouring secondary valence fields. The melt becomes highly viscous.

The “free volume theory” offers a particularly appropriate physical interpretation of polymeric melt cooling. According to this theory, it is possible to view a polymeric melt as a vacancy-saturated fluid (Fig. 4).

V_g = $V_m + V_f$
V_g = Overall volume
V_m = Partial volume of molecules (oscillation expansion volume)
V_f = Free volume (vacancy volume)

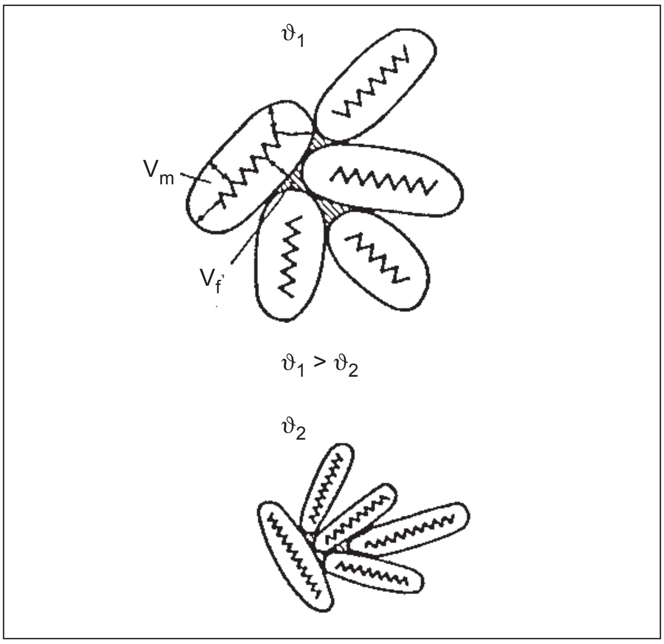


Fig. 4: Free-volume model according to [2]

The overall volume V_G is obtained from the sum of the partial volume of molecules V_m (oscillation expansion volume of molecules) and the vacancy volume, or free volume V_f. The change in the volume of the melt that results from a change in temperature can be illustrated by means of a pressure-volume-temperature diagram (p-v-ϑ diagram) (Fig. 5).

The bottom curve in Fig. 5 is the profile for a purely crystalline material. At the crystallization temperature, T_K, the material becomes fully crystallized. The free volume is then zero. In the further course of the process, only the oscillation expansion volume undergoes any change.

In the case of amorphous thermoplastics (top curve), the melt is seen to undergo undercooling as the temperature falls. Once the temperature has fallen below the glass transition temperature T_G, the specific volume falls less sharply (the straight lines have a low gradient). Below the glass transition temperature, the material is in the glassy state – a “supercooled fluid”. The free volume that exists at the glass transition temperature is frozen in and remains virtually constant in the glassy state.

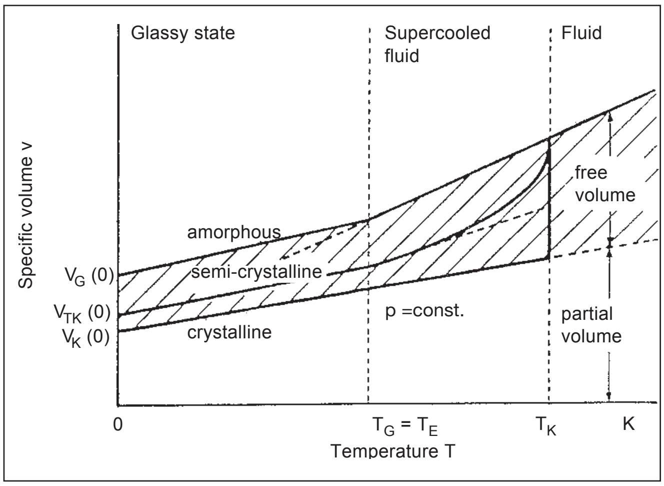


Fig. 5: Pressure-volume-temperature diagram (p-v-ϑ diagram)

The middle curve shows the volume/temperature behavior of a semi-crystalline material. In this class of material, some of the polymer chains are lined up closely in parallel during cooling and form submicroscopically small crystallites. Inside the crystallites, almost complete order prevails, with the exception of a few defects.

By contrast to purely crystalline materials, these materials have a crystallization interval instead of a crystallizing point. Apart from the semicrystalline domains, there are amorphous domains present too. Once the temperature falls below T_G, these assume the glassy state. The free volume is smaller than for purely amorphous materials – on account of the crystalline component.

The superposition of the state curves for amorphous and semi-crystalline thermoplastics that is shown in the diagram means that there is a certain amount of time at each temperature in which the respective specific volume can develop. The cooling or heating rate, and also the ambient pressure, have a major influence on the state curve.

3.1 Influence of ambient pressure

If a plastic melt is subjected to pressure and then cooled, lower specific volumes will result at each temperature. The glass temperature (in the case of amorphous thermoplastics) and the crystallization temperature (semi-crystalline thermoplastics) shift to higher temperatures.

Figure 6 shows the correlation between specific volume and temperature at different pressures for both an amorphous plastic (left) and a semicrystalline plastic (right). The Figure illustrates the differences that prevail between the two classes of material as of the transition from the molten state to the solid phase. The specific volume is generally lower for semi-crystalline materials than for amorphous thermoplastics on account of the crystallizing component of the structure.

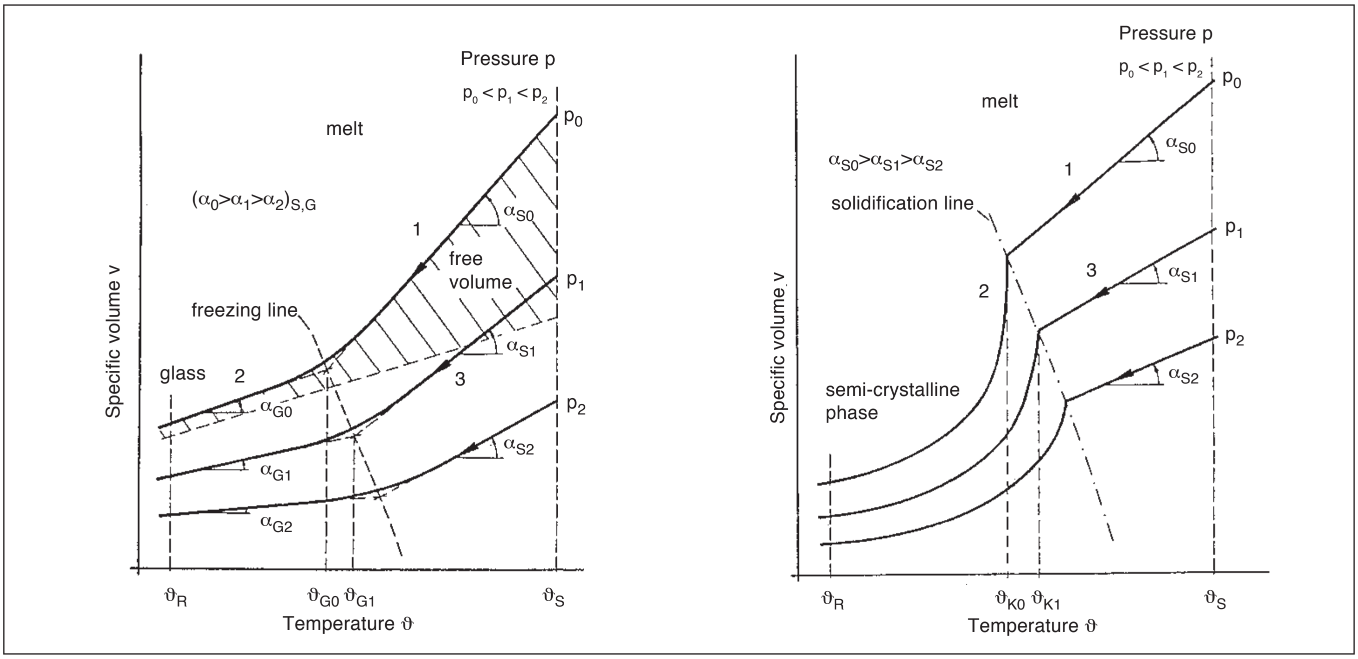


Fig. 6: p-v-ϑ diagram of a slowly cooling amorphous (left) and semi-crystalline (right) plastic (source: IKV)

With semi-crystalline materials, the curve displays a sharp kink. This sudden change in specific volume is due to the start of crystallization. The point of discontinuity marks the crystallizing point ϑ_K. Below this temperature, the reduction in specific temperature is due not only to the reduced thermal oscillation of the molecules, but also (and primarily) to the increasing crystallization. When both of these are superimposed, this leads to the parabolic curve profile for the semi-crystalline phase.

3.2 Influence of cooling rate

The specific volume that results at room temperature is similarly a function of the cooling rate. In the case of amorphous thermoplastics, the glass transition temperature will move towards high values at high cooling rates. The time that is available for an internal state of equilibrium to develop at each individual temperature becomes shorter. It is already impossible for a state of equilibrium to develop at high temperatures.

Fig. 7 shows the shift in glass transition temperature for an amorphous material at two different cooling rates. At the higher freezing temperature a larger free volume is frozen in, which means that the overall volume in the solid phase is greater.

Since the molecules are endeavouring to attain a state of internal equilibrium, it is possible for a "reduction" to occur in the excessively large free volume subsequent to production. This will occur all the more rapidly, the higher the service temperature of the finished component is – key word: "post-shrinkage".

As the cooling rate increases, no further increase comes about in specific volume, however, and there is no further change in the glass transition temperature. The specific volume and glass transition temperature. The specific volume and glass transition temperature strive towards a limit value.

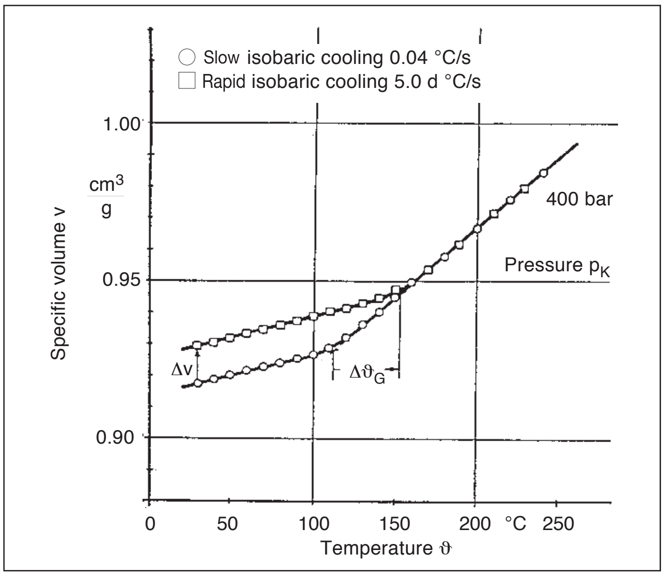


Fig. 7: Comparison of slow and rapid isobaric cooling of an amorphous thermoplastic (source: IKV)

Fig. 8 shows the correlation between the specific volume at RT, in a normal atmosphere, and the cooling rate and pressure during the cooling phase.

Although the specific volume becomes larger as the cooling rate increases, it relatively soon strives towards a limit value. This means that, with the standard cooling rates of > 20 °C/s that are encountered in practice, a constant increase in volume can be expected.

In the case of semi-crystalline plastics, a greater specific volume is similarly seen with higher cooling rates. The crystallization conditions deteriorate. The degree of crystallization is lower and the specific volume becomes larger. At an elevated cooling rate, however, the crystallization temperature remains virtually constant. With these high cooling rates, it must be born in mind that post-crystallization and hence a subsequent reduction in the specific volume can occur. This is frequently the cause of warpage and dimensional deviations in molded parts.

Efficient, uniform mold cooling is thus essential in the case of semicrystalline plastics. The properties of the molded part are determined by the “processing operation in the mold”. If, for instance, identical cooling rates are achieved in all the areas of the molded part, through identical cooling conditions, then this will mark a major step in the direction of identical molded part properties.

4 Melting temperature

It is clear from the p-v-ϑ diagram that thermoplastics do not possess a melting point in the sense of a specific temperature at which the material changes its aggregate state (melt -> solid). Thermoplastics have a melting range or a freezing temperature range.

This transition, or the start of the change from the molten phase to the solid phase, is known as the glass transition temperature or the freezing temperature for amorphous thermoplastics. The value of this temperature is a function of the cooling rate and the ambient pressure (see Figs. 6 and 7). In the case of semi-crystalline thermoplastics, reference is made to the crystallization temperature. This crystallization temperature is a function of the pressure and is hardly affected by the cooling rate (Fig. 9). There can, however, be differences in the cooling and melting of semi-crystalline thermoplastics.

Fig. 10 shows the difference between slow isobaric cooling and heating at ambient pressure, and at 400 bar, for a polypropylene grade. It is only when the crystallization temperature established in the slow cooling test has been surpassed by a considerable margin that the straightline curve for the melt is attained. The point of contact characterises crystallite melting, and is denoted as the crystalline melting point ϑ_{KS}.

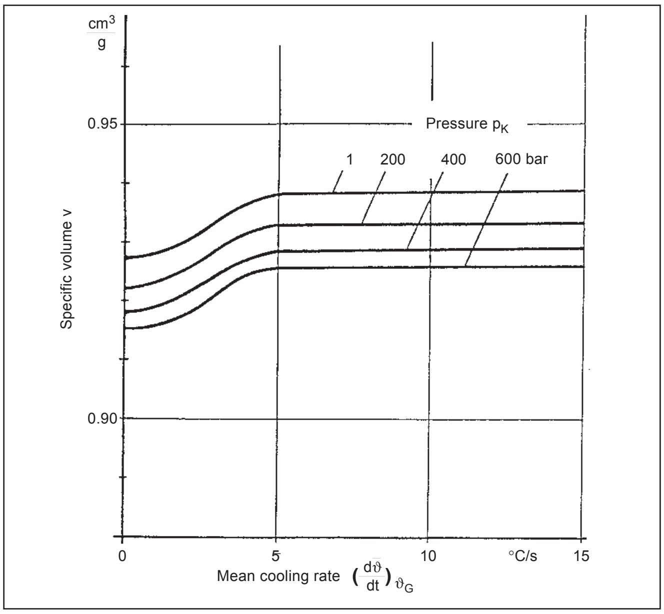


Fig. 8: Specific volume as a function of the cooling rate and pressure of an amorphous thermoplastic (Source: IKV)

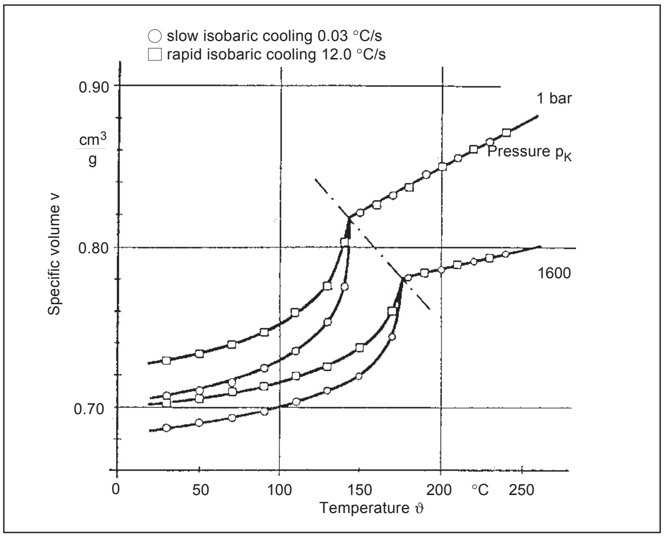


Fig. 9: Comparison of slow and rapid isobaric cooling of a semi-crystalline thermoplastic at two different pressures (source: IKV)

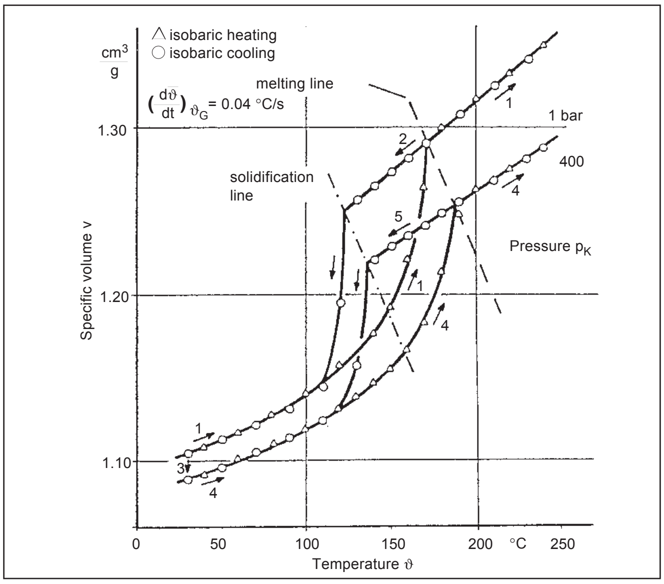


Fig. 10: Slow isobaric cooling and heating of a semi-crystalline thermoplastic (source: IKV)

The hysteresis between heating and cooling is due to suppressed crystallization during cooling. This suppressed crystallization occurs already at very low cooling rates [3]. In other words, crystallization sets in at lower temperatures.

With the cooling rates encountered in practice (>> 0.02 ° C/s) the fall in crystallization temperature is more or less constant (Fig. 11).

5 State curve during injection molding

Using the p-v-ϑ diagrams that have been presented, it is possible to show the thermodynamic state curve prevailing during injection molding for the three process stages of molded part filling, holding pressure phase and residual cooling phase.

This is done by transferring the pressures and temperatures that prevail during the different process stages to a p-v-ϑ diagram, on an isochronous basis. Figure 12 shows a measured pressure profile close to the gate and a computed mean temperature profile inside the molding in the course of the injection molding cycle. The numbered points are transferred to the material's p-v-ϑ diagram (Fig. 13).

The state points plotted on Figs. 12 and 13 indicate the following:

1 Start of mold filling (melt touches pressure sensor)
2 Mold is volumetrically full
3 End of compression phase
4 Switchover to holding pressure (partial discharge of cavity with melt flowing into melt antechamber)
5 Holding pressure level
6 Gate has frozen
7 Pressure has sunk to atmospheric pressure (start of shrinkage)
8 Mean melt temperature has attained freezing temperature
9 Demolding
10 Molded part has reached room temperature

Based on state curves like this, it is possible to make meaningful statements on the course of shrinkage and on the movement of the melt at each stage of the process. Point 7 on the Figures (the attainment of atmospheric pressure) is important for the start of shrinkage. This point can occur at different temperatures with different holding pressure profiles and cooling conditions. It is possible to influence shrinkage in this way.

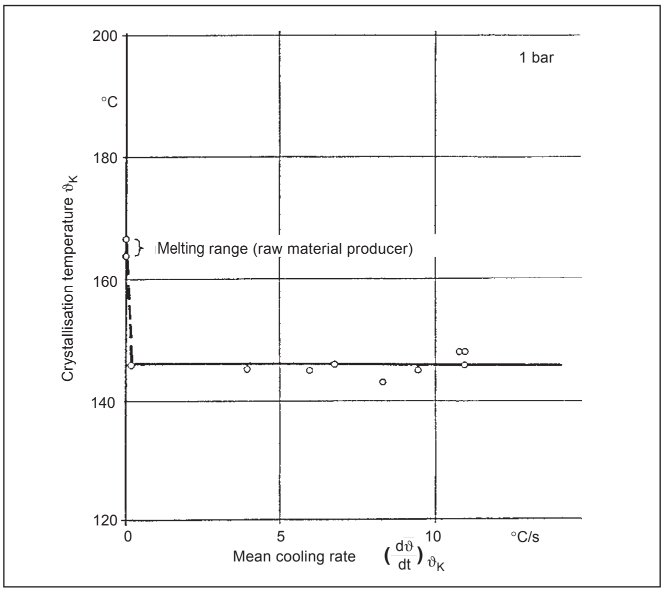


Fig. 11: Influence of cooling rate on crystallization temperature (source: IKV)

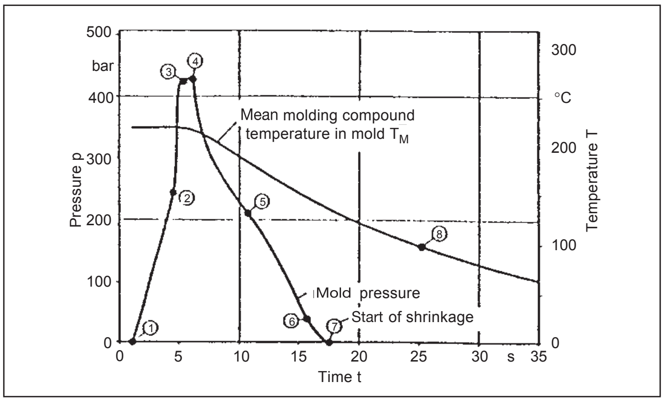


Fig. 12: Pressure and temperature profile during the injection molding cycle [4]

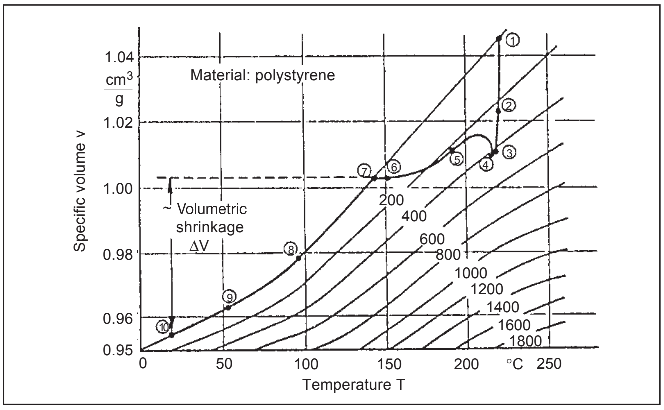


Fig. 13: State curve during injection molding [4]

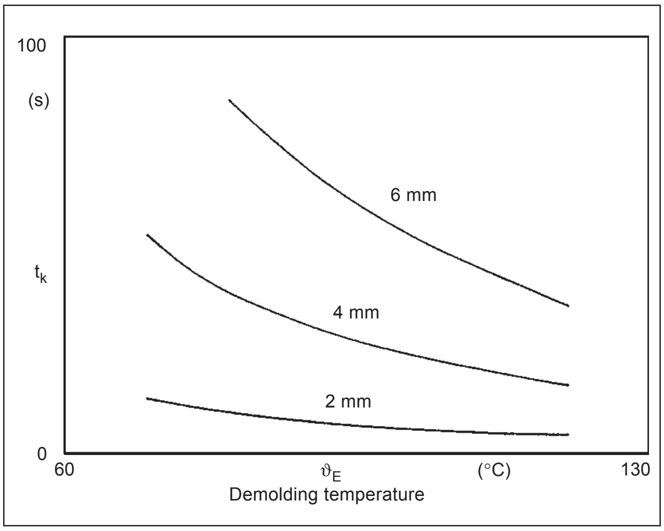


Fig. 14: Influence of demolding temperature on cooling time

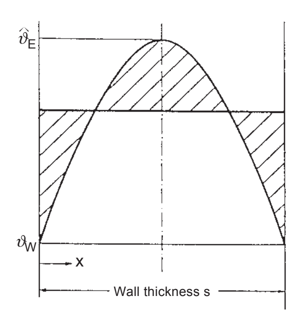


Fig. 15: Temperature profile in a thermoplastic molding at the time of demolding, demolding temperature $\hat{\vartheta}_E$ in the center

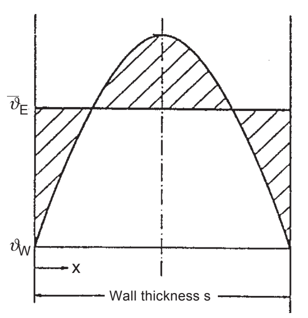


Fig. 16: Mean demolding temperature $\bar{\vartheta}_E$

Abbreviations	Thermoplastics	Mean demolding temperatures (°C) (Guide values)*
PC-HT	Apec® HT	150
(PC+ABS)	Bayblend®	110
PC	Makrolon®	130

*It may be necessary to deviate from the values in the table depending on the product grade.

Fig. 17: Recommended mean demolding temperatures for a number of thermoplastics [5]

6 Demolding temperature and cooling time

An injection molded part cannot, or should not be demolded until it has cooled to the point where it is dimensionally stable. The ejector pins and their holes should not be allowed to leave pronounced marks on the molding.

If the target of a short cycle time is to be fulfilled, then it is essential for the material-dependent demolding temperature to be known. Moldings are frequently left in the mold for too long, in order to be on the safe side, although the cooling time to the demolding temperature has long since lapsed.

Knowledge of the demolding temperature is important on economic grounds. Fig. 14 shows the influence of the demolding temperature on the expected cooling time. The lower the demolding temperature is, the longer the cooling time will be.

The demolding temperature, by definition, is the temperature that prevails at a point of the molded part in the central layer of the wall thickness at the time of demolding. Fig. 15 shows a temperature profile in a thermoplastic molding at the time of demolding.

Alongside this, a mean demolding temperature, ϑ_E, is frequently to be found. This is the integral mean value of the temperature profile at the time of demolding.

How can the correct demolding temperatures for a specific case be established?

First of all, the raw materials manufacturers issue recommendations as to the mean demolding temperatures for their products (Fig. 17).

If there is no recommended guide temperature available for demolding, it can be established from the shear modulus curve of the material in question [6]:

To ensure successful demolding, the mean temperature $\bar{\vartheta}_E$ or temperature in the center of the molded part $\hat{\vartheta}_E$, must not lie within the range where the plastic "yields" and is not able to absorb any force. It is possible to establish this temperature from shear modulus curves. Figure 18 shows the shear modulus curve for an ABS. Above a temperature of some 106 °C, the shear modulus falls sharply, which means that dimensional stability is no longer guaranteed. The maximum possible demolding temperature is thus approximately 106 °C.

ϑ_E max = 106 °C

If no shear modulus curves are available, then the maximum permitted demolding temperature for a given material can be determined from the p-v-ϑ diagrams described above. In the case of amorphous materials, this can be the softening temperature or glass transition temperature and, in the case of semi-crystalline materials, the crystallization temperature. For the ABS shown in Fig. 18 (shear modulus curve), a temperature of approximately 110 °C is obtained as the softening temperature from the p-v-ϑ diagram. This tallies well with the value from the shear modulus curve.

If no curves are available, then the demolding temperature can be taken as being equivalent to the heat deflection temperature (Vicat temperature).

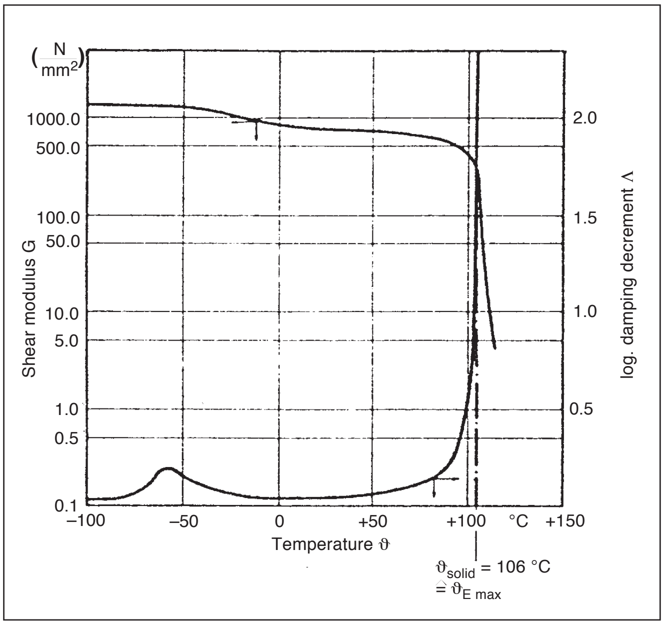


Fig. 18: Determination of the maximum demolding temperature from a shear modulus curve, material ABS

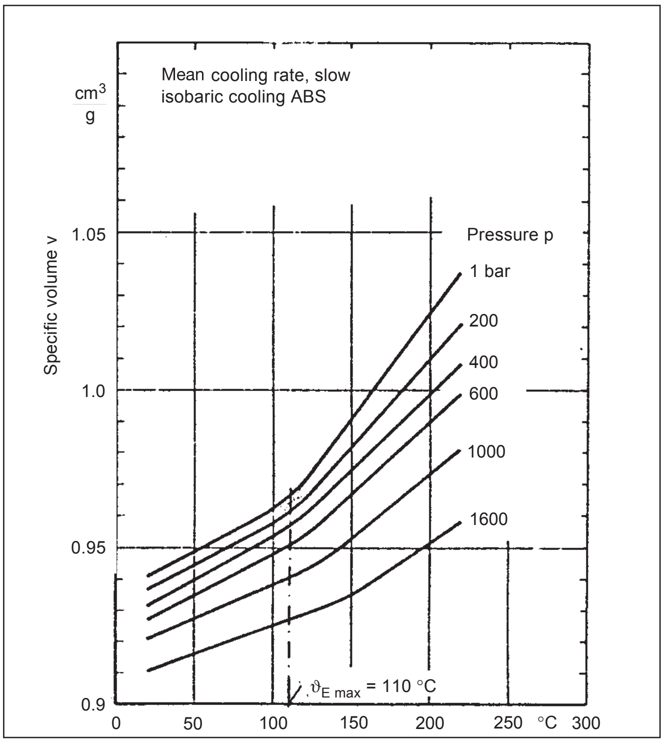


Fig. 19: Demolding temperature from the p-v-ϑ diagram, material ABS

Measurement of the demolding temperature [7]

As has already been mentioned, the demolding temperature represents a key criterion for both the requisite cooling time and the dimensional stability of the demolded part. This should therefore be verified as precisely as possible on a part that has just been demolded.

After ejection, the surface temperature of the molded part rises fairly rapidly to reach a peak value and then falls gradually (Fig. 20). This increase is due to the equalization of the temperature profile that developed during cooling (and is particularly pronounced with larger wall thicknesses).

The maximum value measured should be taken as the demolding temperature, since this ultimately constitutes a measure of the mean molded part temperature. Measuring the demolding temperature is important not only for optimizing the cooling time but also for monitoring the temperature of the mold. With an effective form of mold temperature control (which presupposes no major differences in wall thickness over the molded part), the mean demolding temperature measured should be as constant as possible over all the different regions of the molding. Any differences would suggest that the mold temperature control has not been efficiently configured.

Temperature-controllable contact sensors or noncontact infrared measuring cells can suitably be used for measuring the demolding temperature.

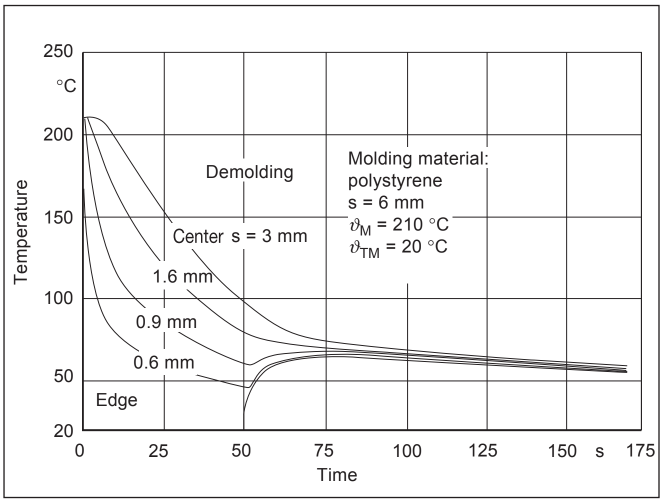


Fig. 20: Temperature profile in a plastics molding before and after demolding

7. Cooling time

Strictly speaking, the cooling phase in injection molding commences with the injection signal and ends with the "open mold" signal. This is because as soon as the hot molten plastic comes into contact with the cooler mold wall at any point in the mold, cooling then commences in this region.

Measures should be taken, however, to prevent the mold from freezing during the filling phase. The loss of heat to the mold wall should be offset by the flow heat. Most heat is released during the residence time (holding pressure phase and residual cooling phase).

Simple cooling equations can be used to estimate the cooling time, or the time by which the demolding temperature (see above) will have been attained. In the case of a flat panel, where an exchange of heat only takes place over the panel thickness, the following equation can be used to estimate the cooling time (for further cooling time equations see Technical Information "Optimized Mold Temperature Control").

$$t_K = \frac{s^2}{\pi^2 \cdot a_{eff}} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{\vartheta_M - \overline{\vartheta}_W}{\widehat{\vartheta}_E - \overline{\vartheta}_W}\right)$$

t_K = Cooling time
s = Wall thickness
a_{eff} = Effective temperature conductivity
ϑ_M = Molding compound temperature at end of filling phase
$\overline{\vartheta}_W$ = Mean mold wall temperature
$\widehat{\vartheta}_E$ = Demolding temperature at center of molded part

The fact that the correct demolding temperature also has a decisive influence on the cost efficiency of production has already been mentioned in the previous chapter. A simple example will be given to illustrate this.

The recommended demolding temperature for a molded part in ABS is approximately 100 °C. How is the cooling time affected if the part is demolded at approximately 80 °C instead of at 100 °C?

Example: "Demolding temperature"

Panel with a wall thickness of:	s = 3 mm
Effective thermal diffusivity of ABS:	a_{eff} = 0,08 mm²/s
Polymer melt temperature after filling:	ϑ_M = 240 °C
Mean mold wall temperature:	ϑ_W = 50 °C
Demolding temperature at center of molded part:	$\widehat{\vartheta}_{E1}$ = 100 °C $\widehat{\vartheta}_{E2}$ = 80 °C

Cooling time 1:

$$t_{K1} = \frac{3^2\ \text{mm}^2}{\pi\ 11.3986\ \text{mm}^2/\text{s}} \cdot \ln\left(\frac{4}{\pi} \cdot \frac{240\ °\text{C} - 50\ °\text{C}}{100\ °\text{C} - 50\ °\text{C}}\right)$$

$$t_{K1} = 11.3986 \cdot 1.5766$$

$$t_{K1} = 18\ \text{s}$$

Cooling time 2: $\left(\frac{4}{\pi} \cdot \frac{240\ °\text{C} - 50\ °\text{C}}{80\ °\text{C} - 50\ °\text{C}}\right)$

$$t_{K2} = 11.3986 \cdot \ln\left(\frac{4}{\pi} \cdot \frac{240\ °\text{C} - 50\ °\text{C}}{80\ °\text{C} - 50\ °\text{C}}\right)$$

$$t_{K2} = 11.3986 \cdot 2.0874$$

$$t_{K2} = 24\ \text{s}$$

Even if just an estimate, this simple example serves to show that if too low a demolding temperature is selected, this will have a pronounced effect on the cooling time. In the example given, the 20 °C lower demolding temperature extends the cooling time by some 30%!

The length of the cooling time is influenced not only by the demolding temperature but also by the mold wall temperature (for the influence of the wall thickness s and the melt temperature, and also the influence of the mold temperature on the quality of molded parts, see Technical Information "Optimized Mold Temperature Control".

Figure 21 shows the computed mold surface temperature on the nozzle side for a box-shaped molded part. The temperature distribution shown is obtained as a result of the cooling channel positions and the other temperature control conditions (cooling medium temperature, flow rate). The temperature control for the top and lateral surfaces of the molded part is not optimally configured.

The box has a uniform wall thickness yet, despite this, different cooling times result for the different regions on account of the dissimilar mold surface temperatures.

The example already set out above will be used once again to show how the cooling time can be estimated for the different wall temperatures.

Example: "Mold temperature"

Wall thickness:	s = 3 mm
Effective thermal diffusivity of ABS:	a_{eff} = 0.08 mm²/s
Demolding temperature:	ϑ_E = 100 °C
Melt temperature after filling:	ϑ_M = 240 °C
Wall temperature 1 – Center of top and lateral surfaces:	$\vartheta_{WD} \approx$ 50 °C
Wall temperature 2 – Edge of top:	$\vartheta_{WR} \approx$ 30 °C

Employing the cooling time formula and the conditions specified, two cooling times are obtained for the two wall temperatures:
Center of top and lateral surfaces: $t_{WR} \approx$ 18 s
Edge of top: $t_{WD} \approx$ 15 s

Since the demolding temperature ϑ_E = 100 °C applies to both, the cycle time is increased by approximately 20 % through the longer cooling time that is required for the center of the top and the lateral surfaces.

Different mold wall temperatures mean different cooling rates and hence different properties, such as shrinkage, surface appearance, structure and warpage.

These two examples have shown just how sensitively the cooling time responds to the processing conditions and how important temperature control in the mold and optimum processing conditions are for cost-efficient production.

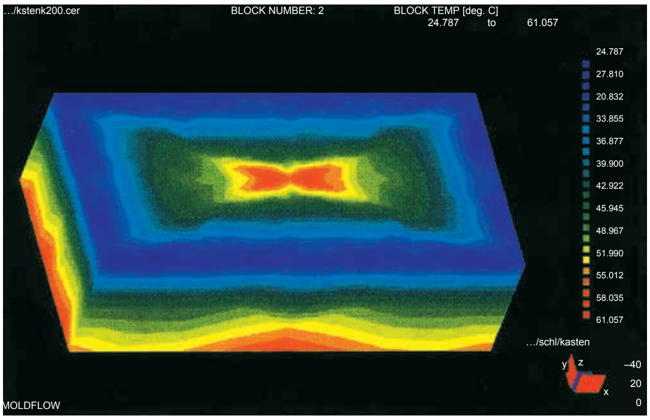


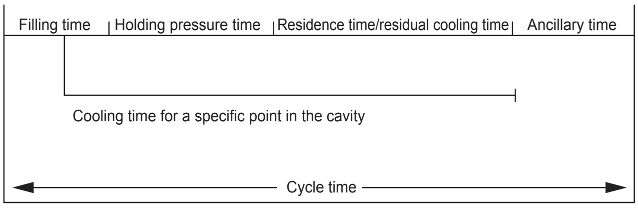
Fig. 21: Calculated mold surface temperature on the nozzle side of a box-shaped molded part

8 Cycle time

The cycle time is the time interval at which the production sequence is periodically repeated. It is made up from the individual production steps and the ancillary time.

Cycle time = filling time + holding pressure time + residence time (residual cooling time) + ancillary time (opening and closing of the mold, ejection, switchover time and, where appropriate, plasticization time).

The cycle time can be shown in graphic form as below:
The different times can be of different lengths as a function of the processing conditions.
Normally, however, the residence time or residual cooling time accounts for the largest time span.



9 Heat content of a molten plastic

Before the requisite cooling capacity of the mold temperature control system can be established, it is necessary to know the heat content that is released by a molten plastic.

The mean quantity of heat to be eliminated per time unit is

$$Q_{Pl} = \frac{m \cdot \Delta h}{t_{Zyl}}$$

$\dot{Q}_{Pl}$ = Heat flow of the molded part
m = Mass of molded part
t_{Zyl} = Cycle time
Δh = Specific enthalpy differential between the melt and the demolding temperature

The term specific enthalpy denotes the mass-related heat content of a material as a function of temperature and pressure. The enthalpy values for plastics are frequently found in diagram form, with the enthalpy plotted as a function of temperature. Figure 22 shows specific enthalpy diagrams for a number of amorphous and semicrystalline thermoplastics. Since the pressure dependence of the specific enthalpy plays only a minor role by comparison to its temperature dependence (order of magnitude approximately 10 %/1000 bar), the diagrams measured at p = 1 bar can suitably be applied in practice.

A comparison of the two classes of material shows that semi-crystalline materials have a considerably higher heat content than amorphous materials in the molten range. Approximately twice the capacity is required to melt or cool semi-crystalline molding compounds in the same period of time as amorphous ones.

While amorphous thermoplastics display a more or less steady decrease in their specific enthalpy, there is a sharp bend in the curve for semi-crystalline thermoplastics in the crystallization interval.

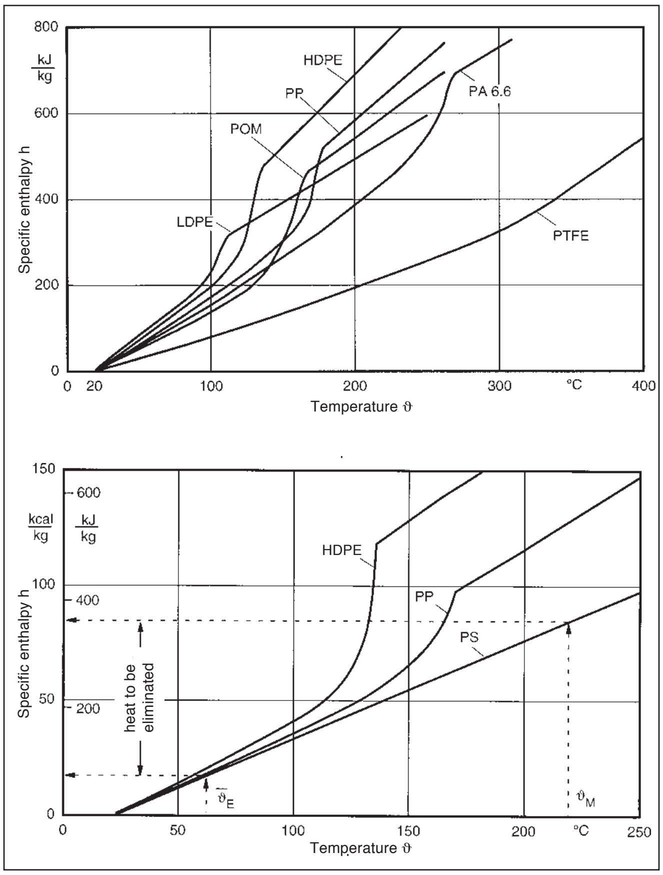


Fig. 22: Specific enthalpy as a function of temperature for a number of thermoplastics; p = 1 bar

10 Summary

The thermoplastic being processed passes through different thermodynamic states in the course of the injection molding process. Knowledge of the state curve during processing makes it easier to selectively control the processing sequence and exert a positive influence on it.

The cooling behavior of the melt can be influenced to a pronounced extent by the cooling in the mold. Different mold surface temperatures can lead to dissimilar cooling times inside the molded part. The solidification behavior, i.e. the level of the glass transition or crystallization temperature, is a function of the ambient conditions (pressure, cooling and heating rate), where with amorphous and semi-crystalline thermoplastics, elevated cooling rates relatively soon lead to specific volumes that remain constant. The position of the cooling channels also has an influence here. If the part is not cooled uniformly then a dissimilar structure can develop inside it, leading to dissimilar shrinkage and warpage behavior.

A carefully selected demolding temperature makes temperature contributes to more cost-efficient production.

Knowledge of the material's state curve during processing – and particularly during the cooling phase – is especially important when engineering thermoplastics are to be processed into highly-stressed, high-grade molded parts.

11 References

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Typical value
These values are typical values only. Unless explicitly agreed in written form, they do not constitute a binding material specification or warranted values. Values may be affected by the design of the mold/die, the processing conditions and coloring/pigmentation of the product. Unless specified to the contrary, the property values given have been established on standardized test specimens at room temperature.

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