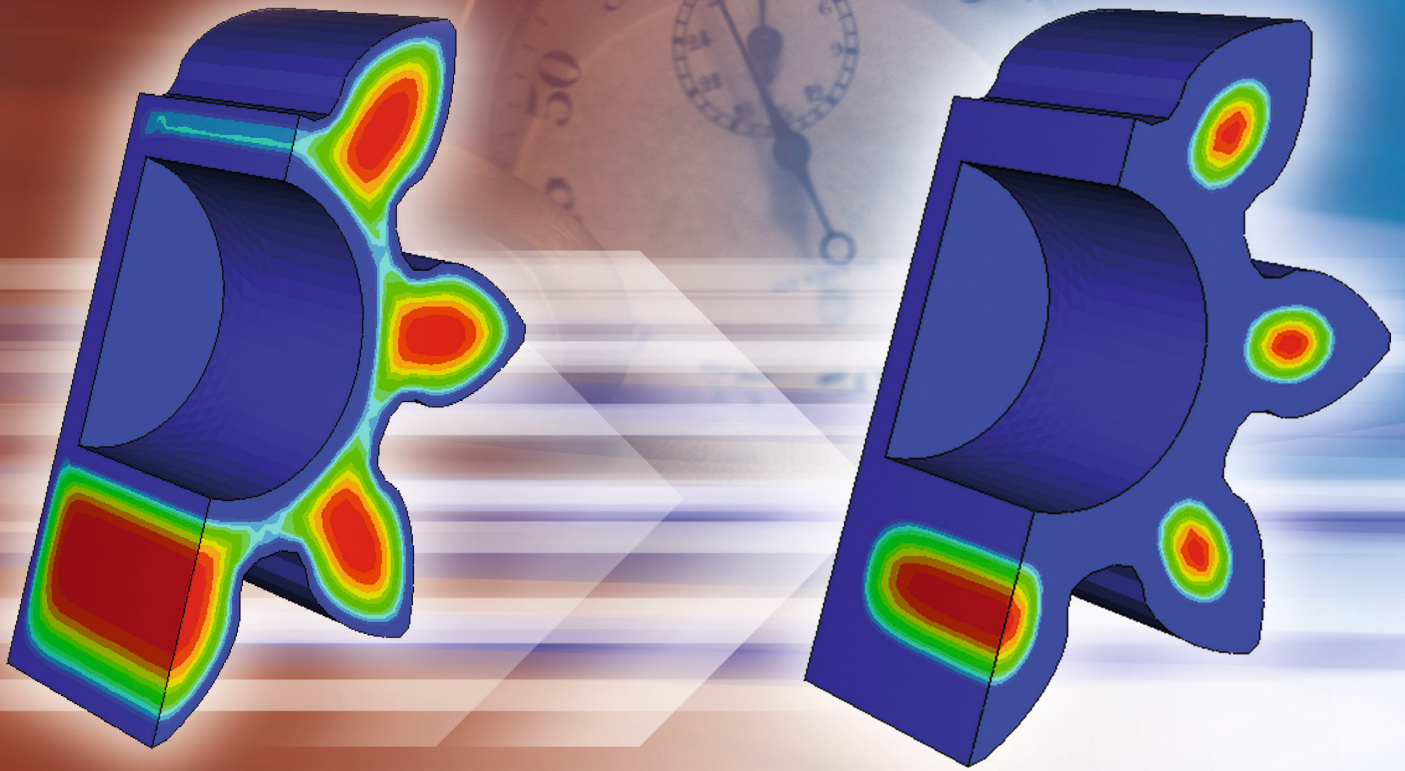


Estimating cooling times in injection molding

Technical Information





- Most of the injection molding cycle is taken up by cooling.
- The cooling time can be estimated with the help of a quantity known as the effective thermal diffusivity. The method of computation is described here.
- The amount of heat to be removed from the mold decreases linearly with decreasing wall thickness; the required cooling time decreases quadratically with decreasing wall thickness.
- For economic production, the relative dimensions of the feed system (sprue and runners) must be matched to the part's cooling time.

Once molten plastic has been injected into the mold cavity, it takes time before the molding has cooled and become sufficiently rigid to allow it to be demolded. This period is called the cooling time and often forms a significant part of the molding cycle.

There are two important reasons why we need the cooling time:

To help us design the mold's cooling system

We need to know how efficient the cooling system should be in order to remove a certain quantity of heat energy from the molten polymer in a given time.

To determine the cost of each molding

The cooling time is part of the overall cycle time, on which the molding-cost calculation is based.

In the following, a simple method of calculating cooling times will be described. Since the calculation produces only a rough estimate, it is important to understand what assumptions and simplifications are made in order to be able to interpret the results properly.

Removing heat from the mold

To allow a molded part to cool and solidify, heat must be removed from the mold. Figure 1 shows the path taken by the heat:

- a) Firstly, it flows from the molten core of the molding to the wall of the cavity; in doing so it has to pass through a frozen layer of polymer in contact with the cavity wall.
- b) From the cavity wall it passes through the mold heading for the cooling channels and following the temperature gradient.
- c) Finally it passes over from the mold into the cooling media and is transported away through the cooling channels.

The minimum achievable cooling time will depend on how fast heat can be conducted at each stage of its journey; the shortest achievable cooling time will therefore depend on the slowest stage. The first stage represents a bottleneck to the flow of heat since plastic is a relatively poor thermal conductor; the only way to speed up heat conduction is to lower the cavity wall temperature. However this is an unsuitable method because, for quality reasons, the cavity wall must be maintained at a certain temperature. For instance, if it is too cold, the molding will have a poor surface finish; in the case of semi-crystalline polymers, post-moldings shrinkage will result.

Given that nothing can be done to speed heat flow through the plastic without affecting quality, the only thing that can be done to achieve the minimum cooling time is to ensure the cooling system is capable of removing heat from the mold at the required rate; if it cannot, the cooling system itself becomes the heat bottleneck and the cycle time will be unnecessarily long.

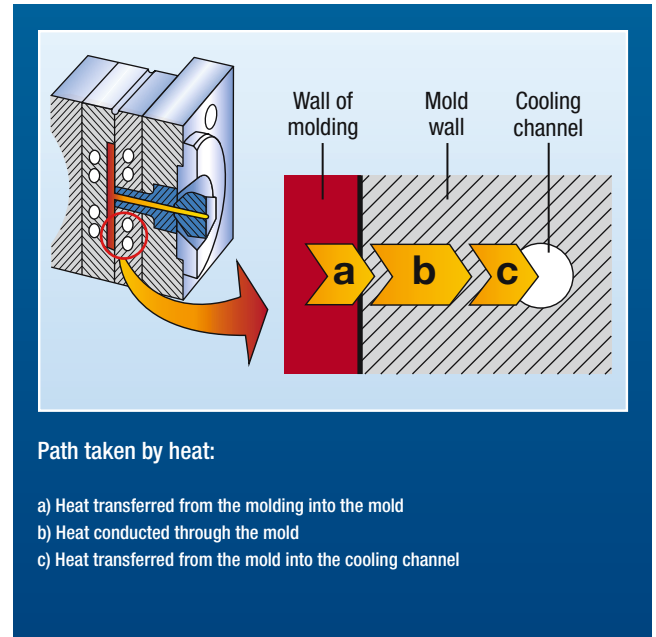


Fig. 1: Heat flow in the mold

And, as will be shown later, the thinner the wall of the molding, the more efficient the cooling system has to be if the cooling time is to be minimized. One reason for failing to achieve the minimum cooling time could be because the part is complex, making it difficult to locate cooling channels; others could be an inappropriate cooling system design, or a build-up of corrosion and lime scale in the cooling channels.

Demolding

To prevent distortion, moldings must have cooled and become sufficiently rigid by the time they are removed from the mold. That time is reached when the ejectors no longer cause permanent distortion or unacceptable stresses. Any stresses or deformation that occur during demolding will depend on the part's geometry, the ejection mechanism, the amount of shrinkage, and the friction between the part and the mold.

Deciding when to demold the part on the basis of the permitted distortion and stresses is far too complicated and impractical. Instead, a demolding temperature – Vicat temperature in the case of amorphous materials and a temperature derived from DSC measurements on the cooling melt in the case of semi-crystalline ones – can be chosen at which the plastic is sufficiently solid. Such a criterion only gives a rough estimate of the point when safe demolding is possible.

Alternatively a demolding temperature could be found by considering the material's stiffness as measured by its torsional modulus (Figure 2). Note that the measurement of torsional modulus on heated polymer specimens is likely to lead to higher demolding temperatures being chosen than would be the case if measurements were taken on cooling specimens.

The mere use of a temperature value as the demolding criterion is the biggest weakness in the estimation of cooling time since no account is taken of the part's geometry, shrinkage, frictional forces, ejector geometry or material stiffness. Also, it is sometimes possible to demold thick-walled parts safely without having to wait until they have fully solidified; it is therefore very easy to overestimate the necessary cooling time in such cases.

Molding trials can be carried out to determine demolding temperatures more accurately; however, the results can only be transferred to other parts that are similar.

Another consideration is that, although a part may be sufficiently rigid to demold, it is usually possible, by extending the cooling time, to reduce warpage caused by an uneven temperature distribution in the mold cavity. The use of a simple demolding criterion like temperature obviously does not take such situations into account.

Estimating the cooling time

For simplicity, it is assumed that cooling only starts once the mold has been completely filled. It is further assumed that the melt has the same temperature throughout the cavity at the start of cooling, and that the cavity wall temperature remains constant throughout the cooling process. The cooling process can be described by the following equation due to Fourier:

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \quad (1)$$

Where a , called the thermal diffusivity is given by

$$a = \frac{\lambda}{\rho \cdot c_p} \quad (2)$$

The thermal diffusivity is a variable quantity since λ , ρ and c_p (the thermal conductivity, density and specific heat capacity) all depend on temperature and, to a certain extent, on the rate of cooling. However, in order to solve the above differential equation analytically, the thermal diffusivity has to be assumed to be constant.

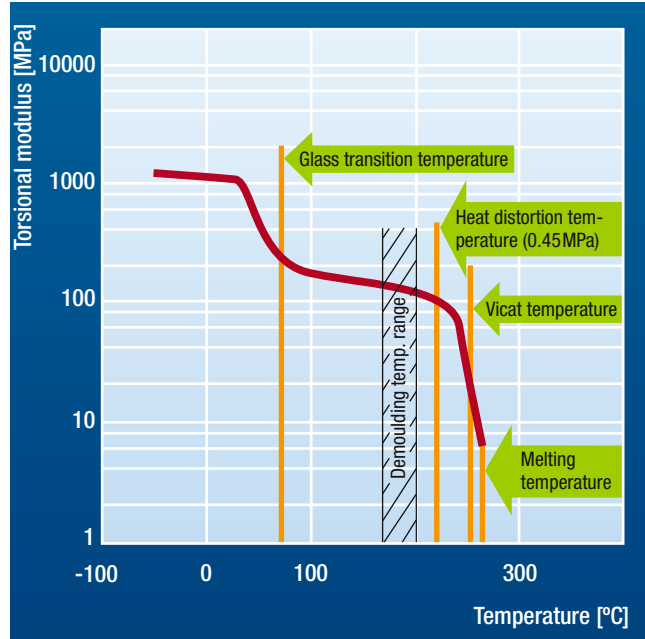


Fig. 2: Torsional modulus of a Ultramid® A3K (polyamide) as a function of temperature

Effective thermal diffusivity

The value for the thermal diffusivity is not derived from equation (2) but chosen so that the computed cooling time matches that obtained from injection molding trials; by doing so, the effect of temperature and cooling rate on the thermal diffusivity is taken into account. The value chosen is called the effective thermal diffusivity a_{eff} to distinguish it from that in equation (2).

The effective thermal diffusivity is not solely characteristic of the material, but depends to some extent on the molding conditions (Figure 3). In addition, a_{eff} is only valid for describing the cooling behaviour close to the freezing point of the melt.

Estimating cooling times for specific geometries

Table 1 gives cooling-time equations (derived from the Fourier differential equation) for three geometries: a plate, a long cylinder and a short cylinder. One question that arises is what melt temperature to use in the equation.

The answer depends on the part's wall thickness. For thin-walled parts we can take the maximum temperature of the melt; for thick-walled parts we can take the mean temperature of the melt (as mentioned previously, these are often rigid enough to demold even if some of the molding has not reached the set demolding temperature) (Figure 4). In the latter case the cooling time calculated must be regarded as the absolute minimum, since the inside of the part may still be soft at demolding time.

Again, comparison of the results obtained from molding trials can help decide what type of melt temperature (maximum or mean) is appropriate. The choice also depends on what the cooling time is to be used for. If it is for calculating the production costs, then it is the best to choose a value that produces a longer cooling time; on the other hand, when designing the cooling system, it is the best to err on the safe side and choose a value that gives a shorter cooling time.

Figure 5 shows the effect of wall thickness on the cooling times of a plate molded from semi-crystalline polymers. The maximum and minimum cooling times for each polymer are found by using the recommended maximum and minimum melt and cavity wall temperatures respectively.

The curves clearly show that the wall thickness is the dominating influence on the cooling time. If the temperature terms and the effective thermal diffusivity in the cooling time equation are gathered up to form a constant term, the equation for the plate becomes:

$$t_k = \text{const} \cdot s^2 \quad (3)$$

Figure 6 shows, for various resins, ranges in which the proportionality constant can lie in practice.

Finding the average cavity wall temperature

Although assumed to be constant for the purpose of calculating the cooling time, the temperature of the cavity wall in reality varies throughout the molding cycle. From a set value at the start of injection, it climbs to a maximum and then falls back to the set value by the end of the cycle. The average wall temperature is required when calculating the cooling time; this can be taken to be the arithmetic mean:

$$T_w = \frac{1}{2} (T_{w \max} + T_{w \min}) \quad (4)$$

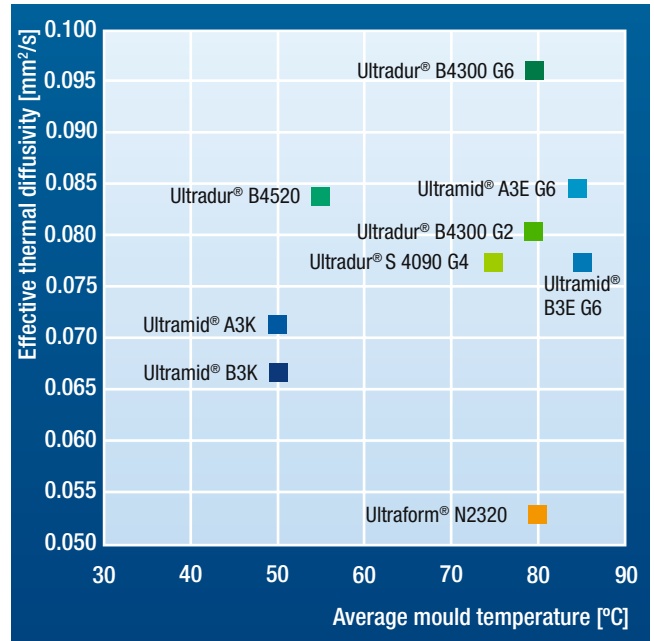


Fig. 3: Effective thermal diffusivities of semi-crystalline thermoplastics

Table 1: Equations for calculating the cooling time		
Geometry	Cooling times based on the maximum temperature in the molding	Cooling times based on the average temperature in the molding
Plate	$t_k = \frac{s^2}{\pi^2 a_{\text{eff}}} \ln \left(\frac{4}{\pi} \frac{T_M - T_W}{T_E - T_W} \right)$	$t_k = \frac{s^2}{\pi^2 a_{\text{eff}}} \ln \left(\frac{8}{\pi^2} \frac{T_M - T_W}{T_E - T_W} \right)$
Cylinder ($L \gg D$)	$t_k = \frac{D^2}{23.14 a_{\text{eff}}} \ln \left(1.602 \frac{T_M - T_W}{T_E - T_W} \right)$	$t_k = \frac{D^2}{23.14 a_{\text{eff}}} \ln \left(0.692 \frac{T_M - T_W}{T_E - T_W} \right)$
Short cylinder	$t_k = \frac{1}{\left(\frac{23.14}{D^2} + \frac{\pi^2}{L^2} \right) a_{\text{eff}}} \ln \left(2.04 \frac{T_M - T_W}{T_E - T_W} \right)$	$t_k = \frac{1}{\left(\frac{23.14}{D^2} + \frac{\pi^2}{L^2} \right) a_{\text{eff}}} \ln \left(0.561 \frac{T_M - T_W}{T_E - T_W} \right)$

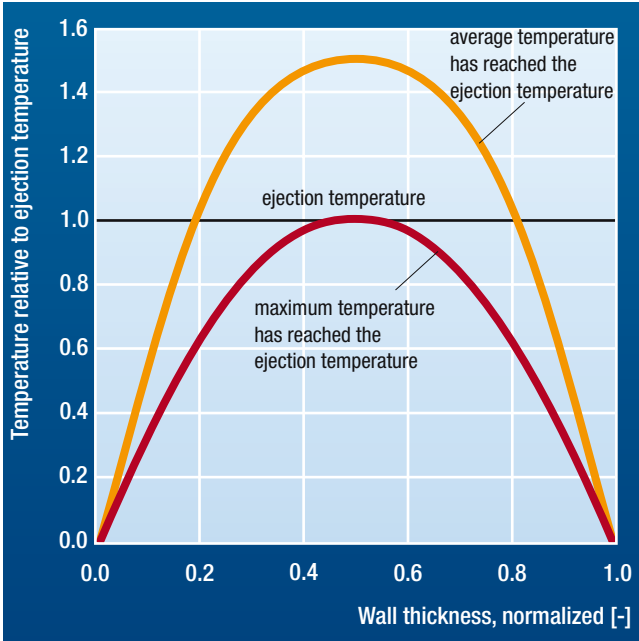


Fig. 4: Temperature distribution through the wall of the molding at demolding time

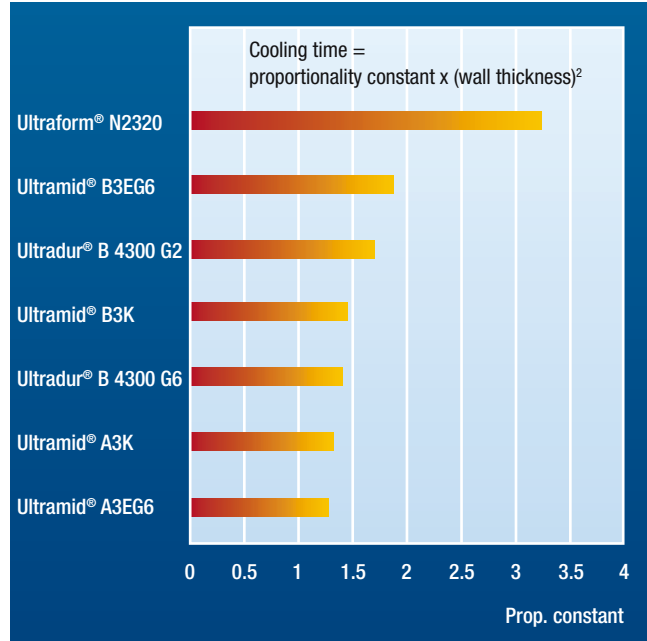


Fig. 6: Ranges for the proportionality constant relating cooling time and the square of the wall thickness

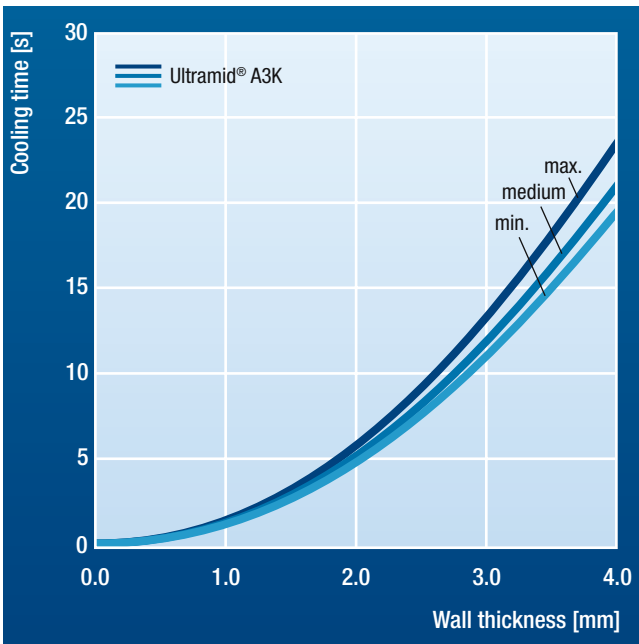


Fig. 5: Cooling time for a plate (here the maximum temperature of the melt is used in the cooling-time equation)

The problem is that we still do not know the maximum cavity wall temperature, which is usually some 5 to 20 degrees above the minimum temperature can be found approximately from the following equation.

$$T_{W \max} = \frac{b_W T_{W \min} + b_M T_M}{b_W + b_M} \quad (5)$$

$T_{W \min}$ can be taken to be the same as the coolant temperature. b , called the heat penetrability, is given by:

$$b = \sqrt{\rho \lambda c_p} \quad (6)$$

The heat penetrability is a measure of a material's ability to conduct heat under transient conditions. Such cases need to take into account the material's heat storage capacity, which is done by including density (ρ) and specific heat capacity (c_p) in the expression. Table 2 gives heat penetrability values for a number of materials.

Table 2: Heat penetrability value	
Material	Heat penetrability at melt temperature [kg/(s ^{3/2} · K)]
Ultraform®	560
Ultramid® A	785
Ultramid® A3...G6	805
Ultramid® B	730
Ultramid® B3...G6	800
Steel X40CrMoV51	9 445
Steel X155 CrVM121	10 387
Steel X35CrMo17	8 214
Steel X5CrNiCuNb1744	7 620
Aluminium alloy AlMg3	18 500
Aluminium alloy AlMg4.5MN	17 000
Aluminium alloy AlMg Si1	21 500
Aluminium alloy AlCuMg1	20 000
Aluminium alloy AlCuMg2	18 500
Aluminium alloy AlCuSiMn	20 500
Aluminium alloy AlZnMgCu0.5	18 500
Aluminium alloy AlZnMgCu1.5	18 500
Zamak 430 zinc alloy ZnAl4Cu3	16 900
Copper/Beryllium. CuBe2	18 390
Copper/Beryllium. CuCo2Be	26 227

Wall thickness and the required cooling capacity

In practice, the actual value of the demolding temperature, that goes into the cooling time equation is dictated by the molding process, and so is not really a variable. Of the three remaining variables – melt temperature, cavity wall temperature and wall thickness the latter has the largest influence as it is a squared term. Since the cooling time is proportional to the square of the wall thickness, we can say for two flat parts of wall thicknesses s_1 and s_2 :

$$t_{k2} = t_{k1} \frac{s_2^2}{s_1^2} \quad (7)$$

In other words, the time to demolding decreases quadratically with decreasing wall thickness. However, the amount of heat to be removed decreases only linearly with decreasing wall thickness. Thus:

$$Q_2 = Q_1 \frac{s_2}{s_1} \quad (8)$$

Also, the thinner the wall gets, the more heat that must be removed per unit time in order to achieve the minimum cooling time. This can be expressed as:

$$\frac{Q_2}{t_{k2}} = \frac{s_1 Q_1}{s_2 t_{k1}} \quad (9)$$

This means the capacity of the cooling system must be improved accordingly. Figure 7 shows the relationship between the minimum theoretical cooling time and the required cooling capacity.

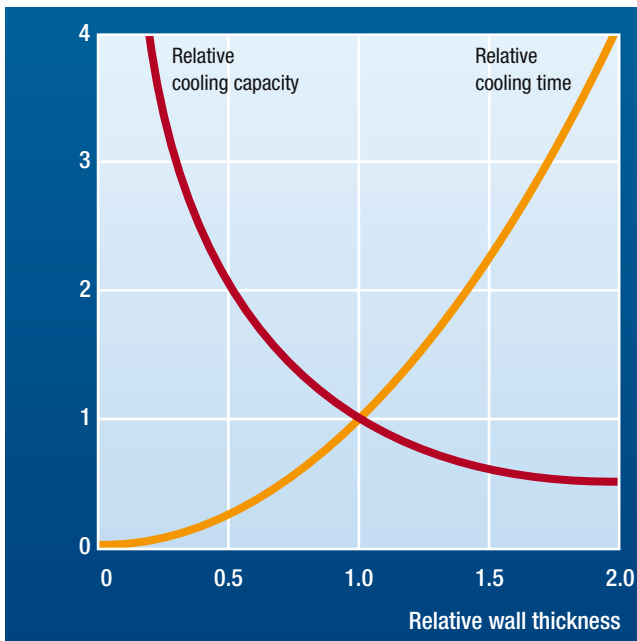


Fig. 7: Effect of wall thickness on cooling time and the required cooling capacity

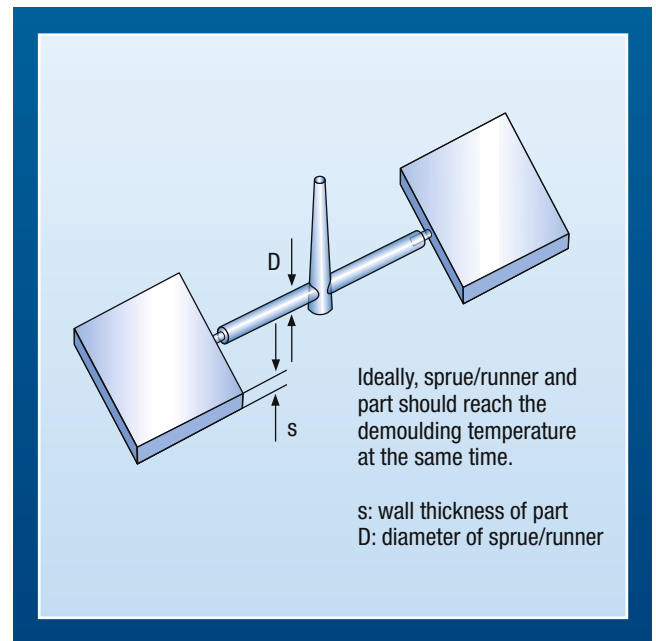


Fig. 8: For economic molding, the dimensions of the runner system must be compatible with the part's cooling time

Making the feed-system dimensions compatible with the cooling time

A balance has to be struck between the freezing time of the feed system (sprue and runners) and that of the molding. If the feed system freezes too early, no holding pressure can be applied; this results in poor quality parts. On the other hand, production time will be wasted if we have to wait too long for the feed system to freeze before the part can be demolded. The dimensions of the feed system should therefore be matched to the part's cooling time.

To find the runner diameter/wall thickness ratio that produces equal cooling times, we equate the appropriate cooling time equations. For the flat part in figure 8, we can use the cooling time equations for the plate and cylinder given in table 1. The ratio is then:

$$\frac{d_{\text{sprue}}}{s_{\text{max}}} = 1.53 \cdot \sqrt{\frac{\ln\left(\frac{4}{\pi} \frac{T_M - T_W}{T_E - T_W}\right)}{\ln\left(1.602 \frac{T_M - T_W}{T_E - T_W}\right)}} \quad (10)$$

s is the wall thickness of the part near the gate as it is this region that determines the duration the holding pressure can be applied. The above ratio is only dependent on the melt, cavity wall and demolding temperature; it always lies in the following range, irrespective of the type of resin:

$$1.1 \leq \frac{d_{\text{sprue}}}{s_{\text{max}}} < 1.53 \quad (11)$$

If product-specific temperatures are included, the following is true for the most resins:

$$1.4 \leq \frac{d_{\text{sprue}}}{s_{\text{max}}} \leq 1.46 \quad (12)$$

As already mentioned, one consequence of falling below the ratio (for instance, by reducing the runner diameter) may be an inability to apply effective holding pressure. And of course, by doing so, no reduction in the part's cooling time is achieved.

List of symbols used

- a thermal diffusivity [m^2/s]
- a_{eff} effective thermal diffusivity [m^2/s]
- b_M heat penetrability of plastic material [$\text{kg}/(\text{s}^{3/2} \cdot \text{K})$]
- b_W heat penetrability of mold material [$\text{kg}/(\text{s}^{3/2} \cdot \text{K})$]
- c_p specific heat capacity [$\text{J}/(\text{kg} \cdot \text{K})$]
- D diameter of cylinder [m]
- L length of cylinder [m]
- Q quantity of heat energy [J]
- s wall thickness [m]
- t time [s]
- t_k cooling time [s]
- T temperature [$^{\circ}\text{C}$]
- T_E demolding temperature [$^{\circ}\text{C}$]
- T_M melt temperature [$^{\circ}\text{C}$]
- T_W mean cavity wall temperature [$^{\circ}\text{C}$]
- x distance [m]
- λ thermal conductivity [$\text{W}/(\text{m} \cdot \text{K})$]
- ρ density [kg/m^3]

Selected Product Literature:

- Ultramid® – Product Brochure
- Ultramid® – Product Range
- Ultradur® – Product Brochure
- Ultradur® – Product Range
- Ultraform® – Product Brochure
- Ultraform® – Product Range
- Ultrason® – Product Brochure
- Ultrason® – Product Range
- Ultramid®, Ultradur® and Ultraform® – Resistance to Chemicals
- Ultrason® – Resistance to chemicals

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