

Giving Pressure Greater Weight

Often Overlooked: The Injection Pressure Influences the Melt Flow Behavior in Injection Molding

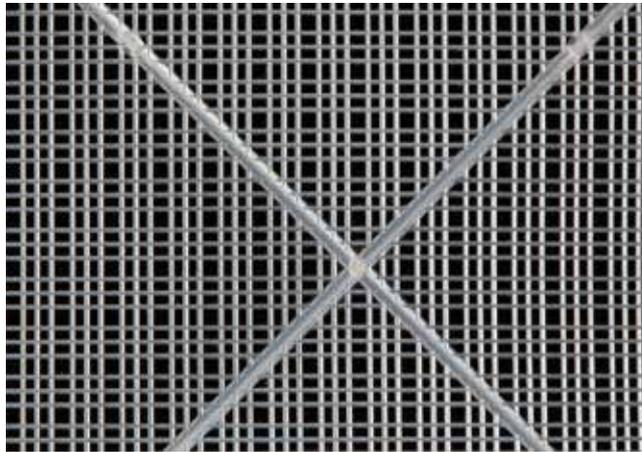
Injection molding machine manufacturers increase the available injection pressures to allow for parts with larger flow path/wall thickness ratios. What is typically not considered, however, is the fact that the pressure also substantially influences the melt flow, and that increasing the injection pressure can be counterproductive in terms of energy efficiency.

The wall thicknesses of molded parts are continuously being reduced. This achieves savings in terms of both material costs and cycle time. On top of this, many new applications – for example, filters or light-guiding elements – need the lowest possible wall thicknesses to achieve the desired functionality. The development of polymers with increasingly improved flowability also promotes this trend.

In addition to the injection speed and part geometry (flow path/wall thickness ratio), the flowability of the polymer that is used largely determines the injection pressure required to fill the cavity. Powerful servo-electrically driven injection units for thin wall injection molding accelerate the screw for the injection action to 800 mm/s in 30 ms and build up injection pressures of 2,400 bar and more (Fig. 1).

Injection molders still determine the flowability of a melt via melt index values (the measured MFR – melt or volume flow rates listed in g/10 min or cm³/10 min) based on data from the raw material supplier. These values indicate the melt's behavior at very low shear rates that tend towards zero viscosity.

In injection molding, far higher shear rates occur, especially when the melt fills thin-walled parts or flows through gates with very small diameters, so that the information provided by the listed values is only of limited relevance for flowing behavior under processing conditions. On top of this, the influence of high injection pressures – 2,400 bar and more – remains completely neglected in this method. This often leads to errors in simulating injection molding processes and



Numerous new applications – for example, in the field of filter elements – require minimal wall thicknesses to achieve the desired functionality. The figure shows part of an injection molded filter element (100 x 100 mm; thread diameter: 0.4 mm; mesh: 1 mm) (figure: Engel)

choosing the right injection molding machine.

Factors that Influence Viscosity

Fundamentally, the viscosity of a melt is determined by the polymer's structure. For example, a higher molecular weight, or long-chained branches lead to higher viscosity values. In addition to this, the flowability can be influenced by additives such as lubricants. Influencing the flowability by varying the molecular weight of the polymer used must always be viewed as finding a compromise between the properties required for the application and the processability.

During processing, the flowability of the melt is influenced by the process parameters. As a general rule, polymer melts demonstrate "shear thinning" behavior, in other words, the viscosity drops as the shear rate increases (Fig. 2). Thus especially during injection, where high shear rates of more than 5,000 s⁻¹ occur, the injection speed has a

major influence on the viscosity. At higher injection speeds and the resulting higher shear rates, the viscosity drops substantially for a given molded part geometry.

The melt temperature also affects the flow behavior: the viscosity drops as the melt temperature increases (Fig. 2). The viscosity's dependency on the temperature can be explained on the one hand by the flexibility of the polymer chains, and on the other by the free volume (the volume that is not occupied by polymer chains). As the melt temperature increases, the molecular chains become more flexible, and heat expansion also enlarges the free spaces or free volume. This reduces the interactions between the polymer chains and thus also the viscosity. During the injection process, the melt temperature is determined by the temperature of the material in the screw antechamber, the mold wall temperature and the heat caused by dissipative energy (friction).

Another parameter that has a major influence on the polymer melt's viscosity is the local pressure that is required »

Fig. 1. Machine manufacturers have geared themselves for the thin wall trend. Servo-electrically driven high-performance injection units accelerate the screw for the injection action to 800 mm/s in 30 ms and build up injection pressures of more than 2,400 bar (figure: Engel)



for transporting the melt under the given process conditions. Increasing the pressure acting on the polymer melt reduces the free volume on the one hand, and intensifies the interactions between the molecular chains on the other, thus increasing the viscosity.

The reason that the influence of pressure remains largely ignored is because pressure-dependent viscosity data is not readily available. While the temperature dependence of flowability is well-documented for many polymers in the form of measurement graphs, very little measurement data is available for pressure-dependent viscosity due to the complexity of the measuring procedure. Even simulation packages that feature the ability to include pressure-dependent viscosity in the calculations for the injection process can only rarely find pressure-dependent viscosity data to rely on despite their oftentimes very extensive material databases.

Pressure-Dependence of Viscosity

The influence that pressure has on viscosity is expressed as the pressure coefficient β . With this coefficient, the pressure-dependent viscosity can be computed on the basis of a known reference pressure, p_0 :

$$\eta(p) = \eta(p_0) e^{\beta(p-p_0)} \quad (1)$$

The pressure coefficient can be described in different ways:

$$\beta_o = \left(\frac{\partial \eta_o}{\partial p} \right)_{\tau, T} \quad (2)$$

$$\beta^r = \left(\frac{\partial \eta}{\partial p} \right)_{\tau, T} \quad (3)$$

$$\beta^s = \left(\frac{\partial \eta}{\partial p} \right)_{\tau, T} \quad (4)$$

Equation 2 describes a pressure coefficient for zero viscosity at a constant tempera-

ture. Although the equation is easy to use if data for zero viscosity is available, its relevance for practical applications is limited by the fact that zero viscosity virtually never occurs in injection molding. **Equations 3 and 4** are more useful. **Equation 3** describes the pressure coefficient for a constant shear rate and a constant temperature, while **equation 4** provides a description for constant shear stress and temperature.

In the following sections, **equation 3** is used because the viscosity's pressure-dependency is measured using a high-pressure capillary rheometer at a constant shear rate, and conditions that come somewhat close to constant shear rates and temperatures prevail at least in segments during the injection process.

The high-pressure capillary rheometer (type: Rheograph25; manufacturer: Göttfert Werkstoff-Prüfmaschinen GmbH, Buchen, Germany) uses a counter-pressure chamber, a kind of throttle valve which is used to achieve various counter-pressures with different valve settings. The result is the pressure coefficient β as a function of the shear rate (**Fig. 3**), which shows how the flow curve is dependent on pressure.

To demonstrate the influence of pressure on viscosity, the data of two polymers are compared: an HDPE with an MFR of 11 g/10 min (2.16 g, 190 °C) and a PP with an MFR of 30 g/10 min (2.16 g, 230 °C). If the pressure is increased from 50 to 1,000 bar, the viscosity η of the HDPE increases by approx. 92% at a shear rate of 50 s⁻¹. The influence of the pressure on the melt's viscosity decreases as the shear rate increases, but the viscosity is still increased by 27% at a shear rate of 5,000 s⁻¹.

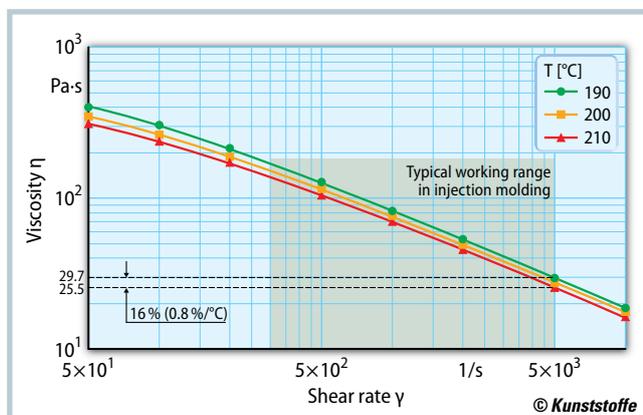


Fig. 2. Dependency of the viscosity on the shear rate and melt temperature for a polypropylene. If the melt temperature is increased by 20 °C (from 190 to 210 °C) at a shear rate of 5,000 s⁻¹, the viscosity is reduced by 16% (0.8%/°C)

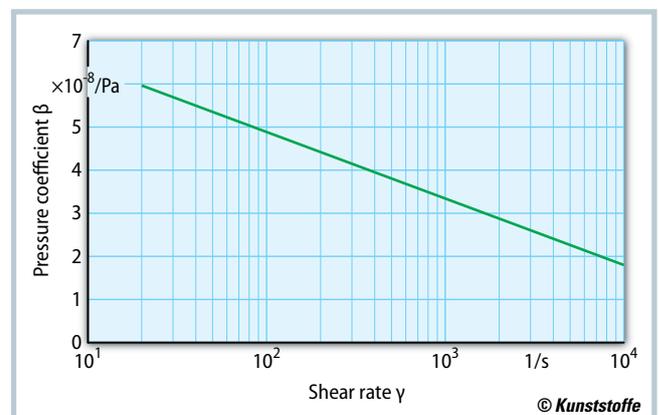


Fig. 3. The pressure coefficient of the polypropylene under investigation as a function of the shear rate (figures 2 to 4:JKU)

The results for polypropylene are even more pronounced. At a shear rate of 50 s^{-1} , an increase in pressure from 50 to 1,000 bar actually increases the viscosity by 122%; even at a high shear rate of $5,000 \text{ s}^{-1}$, the increase in viscosity is still 86% (Fig. 4). In comparison, a melt temperature increase of 20°C reduces the viscosity by only 16% at the same shear rate (Fig. 2).

These examples show that under the conditions occurring during the injection molding process, viscosity is substantially influenced by the prevailing pressure, which therefore definitely should not be ignored.

Influence on the Injection Process

The effect that the pressure-dependency of viscosity has on the clamping force will now be examined on the example of a flat thin-walled part measuring $140 \text{ (L)} \times 70 \text{ (W)} \times 0.5 \text{ (H)} \text{ mm}$. A 4-cavity mold was assumed for the calculation, and the reference data provided for the polypropylene material were consulted.

The following approximation applies for the pressure drop in a thin cavity whose width W is far greater than the thickness H :

$$\Delta p = \frac{12\bar{v}\eta_{rep}L}{H^2} \quad (5)$$

Here \bar{v} represents the mean velocity of the melt front. The representative viscosity η_{rep} can be computed with the help of the representative shear rate

$$\dot{\gamma}_{rep} = \frac{6\bar{v}}{H} \cdot 0.772 \quad (6)$$

according to the Carreau model

$$\eta_{rep} = \frac{\eta_0}{(1 + \lambda\dot{\gamma}_{rep})^n} \quad (7)$$

with the material-dependent parameters η_0 , λ and n .

η_0 designates zero viscosity and λ designates the reciprocal value of the transitional shear velocities between Newtonian and structurally viscous flow behavior. The latter is in turn described by the parameter n .

The clamping force required in the injection phase can be estimated using

$$F = \frac{\Delta p}{2} \cdot A_p \quad (8)$$

with the projected cavity surface A_p .

The mean velocity for this example was chosen so that a representative shear rate of $5,000 \text{ s}^{-1}$ would prevail in the cavity.

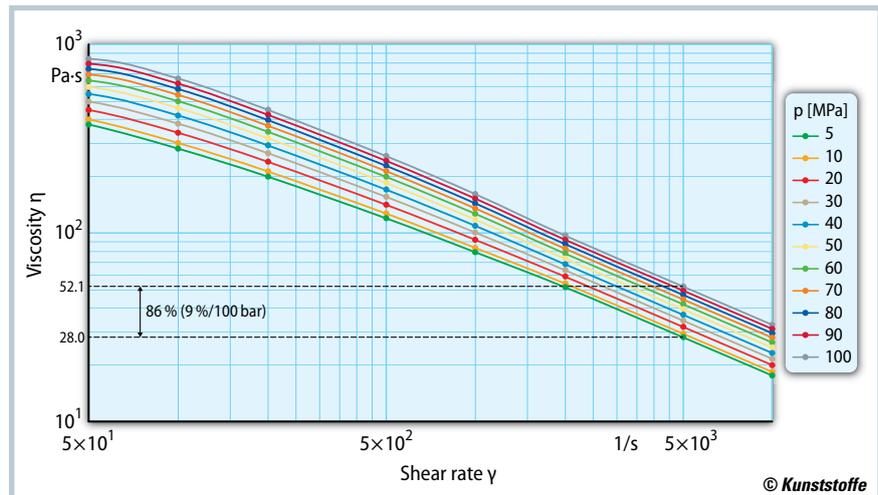


Fig. 4. Viscosity of the polypropylene under investigation as a function of the shear rate and pressure. If the pressure increases from 5 to 100 MPa (950 bar) at a shear rate of $5,000 \text{ s}^{-1}$, the viscosity increases by 24.1 Pa s (86% or 9%/100 bar)

When using a 30 mm screw, this is equivalent to an injection speed of about 115 mm/s . The filling time in this case is 0.26 s . When the viscosity's pressure dependency is ignored at first, the pressure required to fill the cavity is 806 bar (according to equation 5) and thus the clamping force required in the filling phase is 395 kN (according to equation 8).

In the next step, the pressure-dependency is taken into consideration when computing the clamping force. The mean pressure in the cavity is 403 bar ; this leads to an increase in viscosity from 22.2 to 36.9 Pa s . Due to the lower flowability of the melt, the pressure required to fill the cavity increases from 806 to $1,338 \text{ bar}$, and thus the clamping force from 395 to 656 kN . This is equivalent to an increase in the clamping force of 66% .

For the sake of completeness, it should be noted that the calculations above do not take the reduction of the flow channel thickness due to the solidified outer layer or thermodynamic effects into consideration.

Conclusion

The measurement data acquired here clearly show how high pressures affect the viscosity of polymer melts. Especially in injection molding, where high pressures occur in the cavity during the injection phase, this effect cannot be ignored. In most software packages for simulating the injection process, the vis-

cosity's pressure-dependency can at least theoretically be considered, but the key specifications for various polymers are usually missing. For the future it will be an important task to provide injection molders with process-relevant specifications. ■

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