

Simulation. Expansion injection molding facilitates the production of very thin-walled parts by the explosive relaxation of compressed melt. A research group has now developed a software that simulates the process based on a physical model. The program's practical capability is demonstrated by a comparison between the virtual and actual process in the production of check cards.

Virtual Process Design in Expansion Injection Molding

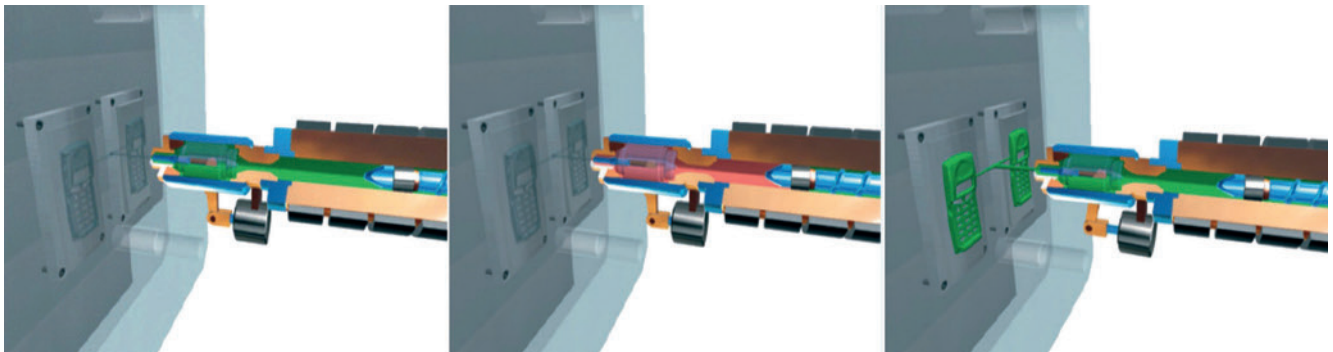


Fig. 1. Process steps in expansion injection molding: After plastication and melt metering in the injection unit, the process can be subdivided into a compression phase and an expansion phase (figures: Engel)

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Engel Austria GmbH, Schwertberg, Austria, developed expansion injection molding for the production of parts with very low wall thicknesses (less than 1 mm and flow path/wall thickness ratios up to 400:1) [1]. The main characteristic of the process is the separation of melt compression and the injection phase. First the melt in front of the screw is compressed to a maximum pre-compression pressure of 1,800 to 2,500bar while the needle valve nozzle is closed. When the needle valve is opened, the melt expands and fills the mold cavity at a high volume flow rate within fractions of a second. After plastication and melt metering in the injection unit, the process can thus be subdivided into a compression phase and expansion phase (Fig. 1).

Translated from *Kunststoffe* 10/2010, pp. 204–208
Article as PDF-File at www.kunststoffe-international.com; Document Number: PE110507

The process sequence of expansion injection molding can be readily represented in the pV-T diagram: With the mold closed and the nozzle sealed – either the injection unit or hot-runner system in the mold is equipped for this – the melt is pre-loaded by a forwards movement of the screw plunger to maximum compression. The compression heats the melt and the specific volume increases slightly because of the higher temperature. When the nozzle opens, the pressure in front of the screw drops from compression pressure to a final pressure as a function of the expansion time. This pressure difference effects the volume flow rate for cavity filling (Fig. 2).

Physical Model for Expansion Injection Molding

The melt compression and melt expansion phases can be described by the thermodynamic material behavior and the process parameters of end pressure (p_E), compression pressure (p_C) and compressed melt quantity (m_C). The relationship between the shot weight (m_F), com-

pressed melt quantity (m_C) and the end pressure (p_E) can be obtained if the specific volume $v(p, T_M)$ of the plastic melt is known as a function of the pressure and melt temperature (T_M) from equation 1:

$$m_F = \frac{m_C}{v(p_E, T_M)} \int_{p_E}^{p_C} \kappa(p, T) v(p, T) dp$$

This isothermal compressibility (κ) of the thermoplastic melt is calculated from equation 2:

$$\kappa = - \frac{1}{v_i} \left. \frac{\partial v}{\partial p} \right|_{T_i}$$

The melt quantity or shot weight (m_F) required for mold filling is obtained via the melt expansion and the associated pressure drop from the compression pressure (p_C) to the end pressure (p_E) according to equation 3:

$$m_F = \frac{m_C}{v(p_E, T_M)} \cdot [(v(p_C) - v(p_E))]$$

Unlike the compression pressure (p_C), the end pressure (p_E) is determined by

the geometry, the flow resistance of the mold cavity and the viscosity of the plastic melt. The end pressure (p_E) established after the melt expansion must ensure complete cavity filling and also perform the holding pressure function. The calculation method presented below serves to determine the minimum compression pressure for complete cavity filling.

Calculation Program for Complete Cavity Filling

The flow diagram of the computer program starts with the computation of the approximated filling time for a thin-walled part (Fig. 3). In the method, the minimum filling pressure is calculated by segmenting the longest flow path into multiple individual segments connected in series. In series connection, the volume flow rate stays constant – however, the pressure drop can be different in each individual segment. The required overall filling pressure is thus composed of the sum of all the pressure drops in the individual segments.

To increase the computational accuracy, the influences of the frozen outer layer are taken into account according to a

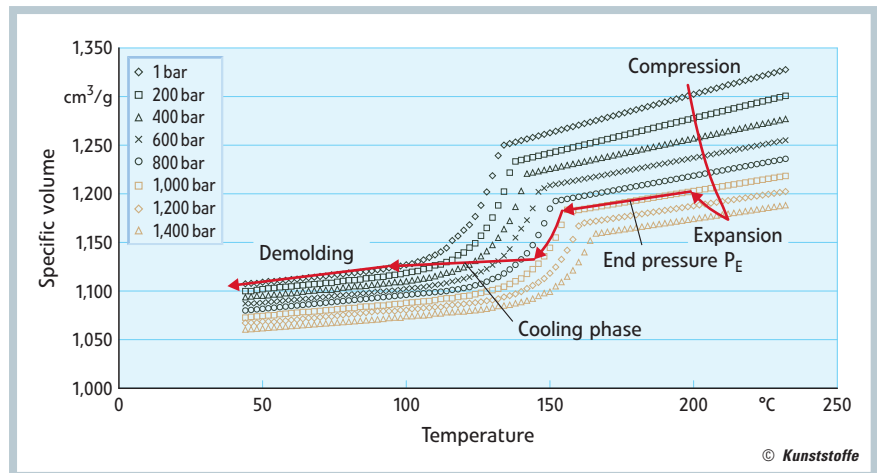


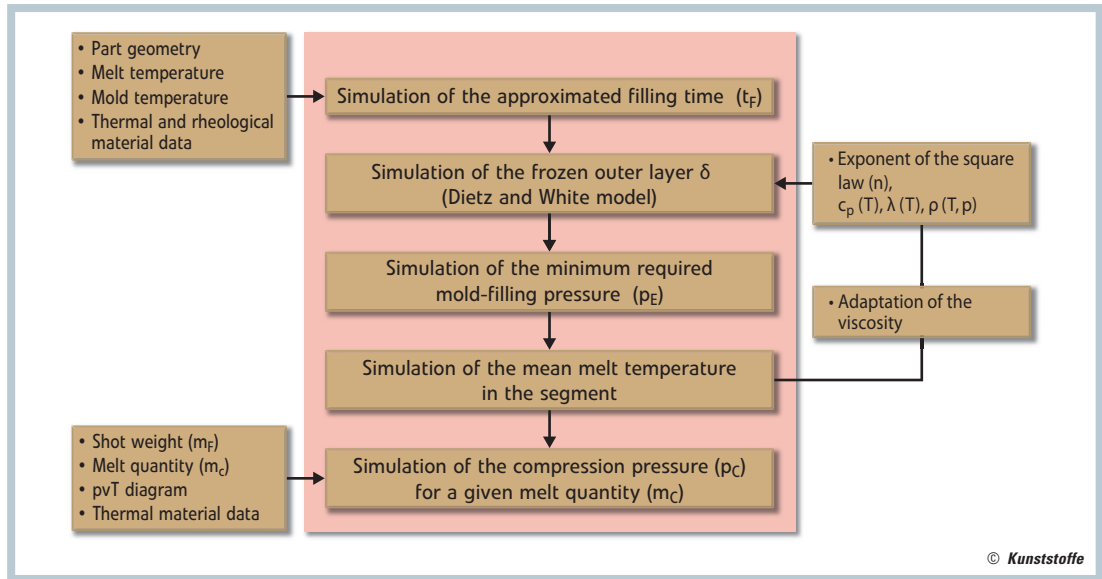
Fig. 2. pvT diagram for expansion injection molding of PP: When the nozzle is sealed the melt is pre-compressed to maximum compression pressure. When the nozzle opens, the pressure in front of the screw drops as a function of the expansion time

method determined by Dietz et al. [2]. From the calculated distribution of the outer layer thicknesses, the residual channel height is obtained in each segment. This is used for calculating the pressure gradient in the respective segment and the change of the melt temperature as a result of dissipation and cooling.

The calculated required minimum pressure for filling the cavity is chosen as the end pressure (p_E). The calculation of

the maximum compression pressure (p_C) for filling the cavity during the expansion phase is based on the input values of end pressure (p_E), shot weight (m_F), compressed melt quantity (m_C), melt temperature and melt incompressibility and the specific volume from the pvT diagram. Based on the aforementioned calculation, the “Xmeltsoft V.1.0” simulation program was developed as an Excel add-in using VBA. →

Fig. 3. Flow diagram of the calculation program: The method serves to determine the minimum compression pressure for complete cavity filling



Simulation with a Check Card

As a practical example and experimental check of the simulation quality, a check card format with a constant wall thickness of 0.5 mm and dimensions of 84 × 54 mm was chosen. The melt volume flow rate (MVR) of the polystyrene used (type: PS 495F; manufacturer: BASF SE, Ludwigshafen, Germany) is 9.5 g/10 min (200°C/5 kg). The simulation used the following process parameters:

- Melt temperature: 230°C
- Mold wall temperature: 40°C
- No-flow temperature: 140°C
- Compressed melt volume: 120.56 cm³
- Part volume: 2.295 cm³
- Part weight: 2.38 g

The overall length of the flow channel, which was subdivided into seven segments, is 73 mm. The maximum thickness of the calculated frozen outer layer along the flow path is 0.057 mm (Fig. 4, left). The comparison of the pressure losses along the flow length shows that when

the outer layer is taken into account, the filling pressure is significantly higher than the calculated pressure value for neglecting the frozen outer layer (Fig. 4, right). With the calculated filling pressure as end pressure, the necessary compression pressure for the melt accumulator is calculated. The simulation result can be summarized in three lines –

- approximate filling time: 0.044 s,
- calculated end pressure: 1,120 bar,
- calculated precompression pressure: 1,590 bar.

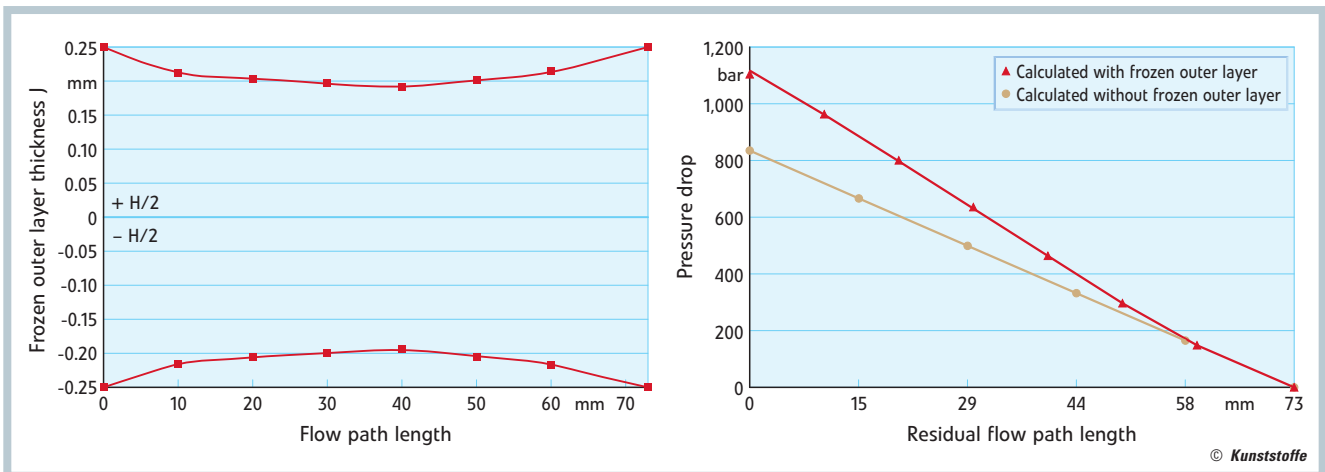


Fig. 4. The maximum thickness of the frozen outer layer for PS 495F (left) and the calculated pressure losses along the flow path (right)



Fig. 5. The photos of check card parts photographed at different compression pressures show that the cavity was completely filled at 1,600 bar

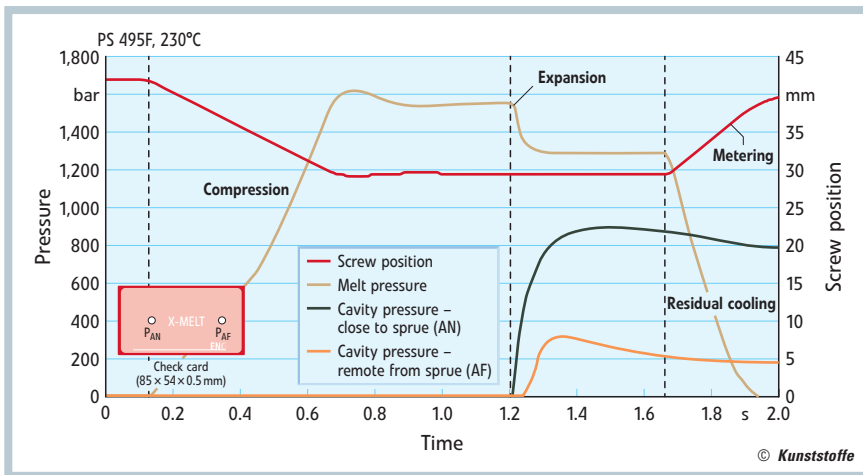


Fig. 6. Measured pressure profiles and screw displacement for PS 495F at a compression pressure of 1,600 bar. When the valve is opened, the cavity pressure reaches a maximum of 896 bar close to the sprue and 316 bar remote from the sprue

Experimental Checking

To check the simulation results, systematic tests were carried out on an injection molding machine with hybrid drive technology (type: e-Victory 940/130 with electromechanical injection unit and hydraulic clamping unit; manufacturer: Engel); the check card mold was equipped with two cavity pressure sensors (type: 6157B, max. 2,000 bar, clearance 52 mm;

manufacturer: Kistler Instrumente AG, Winterthur, Switzerland). The melt pressure in front of the screw was measured with a pressure sensor via a measurement flange.

The experiments were performed with multiple compression pressures (1,300, 1,450 and 1,600 bar) [3]. After the compression phase, the shut-off nozzle was kept open for 0.5 s for pressure equalization and for the subsequent application

of the holding pressure. The photos of the parts (**Fig. 5**) show that the cavity was completely filled at a given compression pressure of 1,600 bar. The sequence can be shown graphically using the parameters of screw displacement, melt pressure in front of the screw, and the cavity pressure profiles to and remote from the sprue (**Fig. 6**). When the valve is open, the cavity pressure reaches a maximum of 896 bar close to the sprue and 316 bar remote from the sprue.

Analysis of the Molecular Weight Degradation

The high injection and shear rates required for filling thin-walled parts (filling times < 0.05 s) lead to high thermomechanical loading of the plastic melt. For thermally sensitive materials, repeated thermomechanical loading can initiate molecular weight degradation. In this paper, the influence of shear rate, of compression pressure and of residence time on molecular weight degradation were systematically investigated; the molecular weight was determined by gel permeation chromatography (size exclusion chromatography, SEC). For this, microtome sections were taken at various points of the part. →

Using the microtome, three layers each with thicknesses of 10 µm were cut out (Fig. 7). The first sample (outer layer) corresponds to the frozen outer layer. The second sample (top layer) comes from the zone with high shear loading below the outer layer. The third sample (center layer) comes from the center of the part. The section thickness of the outer layer corre-

| | Raw material | Outer layer | Top layer | Center layer |
|---------------|--------------|-------------|-----------|--------------|
| M_n [g/mol] | 76,600 | 77,300 | 92,600 | 78,600 |
| M_w [g/mol] | 336,500 | 270,900 | 208,600 | 220,600 |
| M_z [g/mol] | 1,026,600 | 760,500 | 375,900 | 450,900 |
| PD [-] | 4.39 | 3.51 | 2.25 | 2.81 |

Table 1. Results of the SEC analysis of samples taken from the part close to the sprue. The values demonstrate the molecular weight degradation in comparison to the raw material

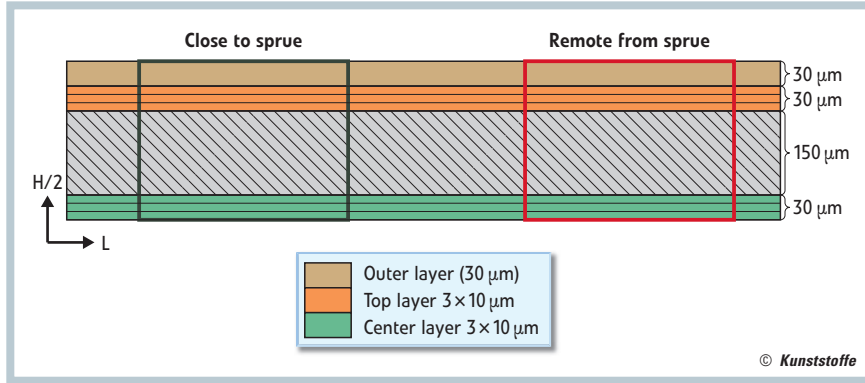


Fig. 7. Using the microtome, three layers – outer, top and center layers of the part – with thicknesses of 10 µm each were cut out

sponds to the calculated average outer layer thickness.

As the results of the SEC analysis, the distribution curve of the molecular weight (MMD) is obtained, the number average (M_n), weight average (M_w) and centrifuge-average (M_z) molecular weight, and the polydispersity ($PD = M_w/M_n$). The values of M_w and M_z represent fractions of higher molecular weights. If the polymer is degraded, the distribution curve shifts towards lower molecular weights. The weight average, centrifuge-average molecular weights and polydispersity decrease, while the number-average molecular weight increases. Because of difficult sample preparation, and a limited amount of material, the results have a measurement error of about 5 %.

To investigate the material degradation, parts of PP with compression pressures of 950 and 1,150 bar were injection molded. The results of the molecular weight analysis show that the MMD curves of the samples taken from the part close to the sprue, compared to the molding compound, are shifted in the direction of lower molecular weights (Fig. 8). The MMD curve of the upper layer (high-shear region) shows a greater fall at higher molecular weights compared to the curves of the outer and center layer. The degradation is confirmed by the rise in M_n value and the drop of M_w and M_z values of the samples from the part (Table 1).

The studies have also shown that the degradation effects are significantly low-

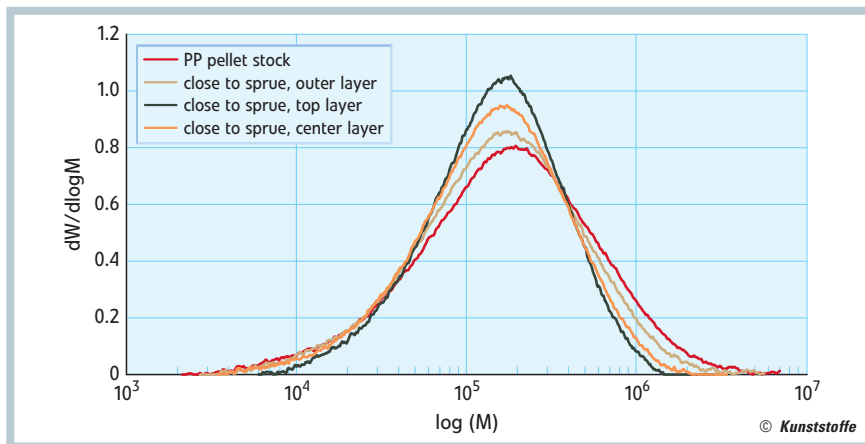


Fig. 8. The MMD curves of the outer, top and center layer samples taken close to the sprue were compared for a compression pressure of 1,150 bar are compared to the MMD curves of the pellet stock

er for PS than for PP. Further series of measurements will be made to investigate whether the ascertained molecular weight degradation has a significant effect on the mechanical properties of the part (tensile strength, impact behavior).

ACKNOWLEDGMENT

This work was performed at the Institute of Plastics Processing at the University of Leoben, Austria, in cooperation with Engel Austria GmbH, as part of a project sponsored by the Austrian Research Promotion Agency (FFG)

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