Figure 1. Micro spiral (left) and 3D model geometry (right)

Because of the symmetry, only one half of the spiral needs to be modelled (Figure 1, right). In fact, the program considers the symmetry surface as a usual mould wall and applied the no-slip condition. However, because of the large region surrounding the symmetry surface compared to the thickness of the cavity in the spiral region, this simplification is acceptable. Likewise, the conical sprue was not included in the model. This way, the calculated injection pressure can be related to the cavity pressure measured at the end of the sprue (Figure 2).

The material used in the study is polypropylene H600TF supplied by Borealis Polyolefine GmbH (Linz, Austria). Since this material is not included in the standard database of the program, extensive material testing had to be done. Particularly, the temperature dependence of the thermal properties and the pressure dependence of the viscosity are relevant for the filling simulation of a micro cavity. The pvT-diagram and the heat conductivity were conducted by the Lehrstuhl für Kunststofftechnik at the Friedrich-Alexander University Erlangen-Nuernberg (Erlangen, Germany), while the specific heat, the transition temperature and the viscosity data were measured by MOLDFLOW (Framingham, USA). Detailed information about the material data may be found in [10].

In order to consider the compressibility of the melt in the injection barrel, information about the plunger diameter, its starting position and velocity should be available. During the filling simulation, the actual melt temperature and the actual flow rate are calculated at each time step based on the actual flow resistance in the cavity given by the pressure calculated at the injection location. The appropriate heat transfer coefficient was identified in the following way. For each processing condition, simulations with different heat transfer coefficients were carried out providing various relationships between the injection pressure and the filling degree, which have to be compared with the corresponding experimental data. Accordingly, an appropriate heat transfer coefficient can be determined.

Figure 2. Position of the pressure sensor

Experimental. Experiments were carried out using a plunger injection moulding machine with a plunger pre-plastification (formi-calPlast), which was developed by the Kunststoff-Zentrum in Leipzig (Germany) [11]. The diameter of the injection plunger is 3 mm, ensuring a high-precision control of the injection speed and the plunger position. The cavity of a micro spiral (Figure 1) is 0.2 mm and 0.5 mm thick. Four different plunger speeds (20 mm/s, 50 mm/s, 100 mm/s and 200 mm/s) were applied. The nominal melt temperature was 280 °C and the mould temperature was kept constant at 30 °C for the nozzle side and 20 °C for the rest of the mould. Short shots of the micro spiral of different filling degrees were produced by limiting the end position of the plunger. The cavity pressure was measured using a miniaturized quartz sensor (KISTLER 6183AE). As an example, Figure 3 shows 50 profiles of the cavity pressure measured for 50 shots (five profiles for each plunger end position). Of these five shots, average value was obtained for the maximum pressure and the filling degree, whereby the maximum pressure can be considered as injection pressure since the pressure loss in the sprue is minimal and therefore negligible.

Figure 3. Cavity pressure for 10 filling steps with 5 shots at each step

Results. Figure 4 shows the relationship between the injection pressure and the filling degree for the spiral thickness of 0.2 mm. In general, the experimental data can be “fitted” properly except for the lowest injection speed of 20 mm/s, where no heat transfer coefficient
can be determined so that the experimental data can be fitted over the whole range. As can be seen in Figure 5, with a heat transfer coefficient of 14000 W/m²K, the maximum filling degree would be predicted correctly, but the calculated injection pressure is too low at other filling degrees compared to the experimental data. Even with higher values for the heat transfer coefficient, the pressure level cannot be shifted much towards the experimental values.

In other cases, it can be seen that the heat transfer coefficient decreases with increasing injection speed (Figure 4), which may be related to the decreasing pressure level in the cavity. The same tendency can also be observed for the thicker spirals (Figure 6), where the heat transfer coefficients are lower than those in the case of the thinner spirals. Again, it may be concluded that the heat transfer coefficient is dependent on the pressure level in the cavity, since the injection pressure is lower for a thicker cavity.

Moreover, it should be mentioned that a low injection speed leads to an extremely non-uniform temperature distribution not only in the thickness but also in the width direction (Figure 7), which narrows the cavity in a significant manner so that a viscoelastic model may not be capable of representing the resulting complex thermal behaviour.

The exceptional case with the plunger speed of 20 mm/s, which can be seen for both cavity thicknesses, may be a further indication for the dependency of the heat transfer coefficient on the pressure in the cavity. In fact, a lower injection speed means a higher injection time and subsequently a stronger variation of the cavity pressure at the mould wall during the filling of the cavity. At the beginning, high pressure in the cavity still leads to a better thermal contact at the mould wall. In the course of time, the frozen-in layer is increasing and the viscosity of the melt is getting higher so that the pressure in the middle of the cavity no longer compensates the shrinkage at the outer surface. Consequently, a uniform heat transfer coefficient is not capable of representing the resulting complex thermal behaviour.

Figure 4. Injection pressure vs. filling degree (spiral thickness 0.2 mm)

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Conclusions. It can be shown that the heat transfer coefficient between the polymer and the mould wall, which cannot be assumed as a constant for all process conditions, has a significant influence on the simulation results. In combination with precise material data and by calculating correctly the reduced volume rate and the increased temperature of the melt at the entrance of the cavity due to the melt compression in the barrel, the heat transfer coefficient may be quantified by means of reverse engineering. In general, the heat transfer coefficient decreases when either the cavity thickness or the injection speed increases. It is believed that a pressure dependent model for the heat transfer coefficient would be more suitable to describe the thermal contact behaviour in micro injection moulding.

References: