Implementation strategies for the optimization of micro injection moulding simulations

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Abstract

In polymer micro manufacturing technology, software simulation tools adapted from conventional injection moulding can provide useful assistance for the optimization of moulding tools, mould inserts, micro component design, and process parameters. Conventional implementation methods of simulation are not suitable for micro injection (µIM) application and are limiting the possibility to extend the use of existing packages for the modelling and the simulation of polymer micro parts. Different strategies optimized for the set-up the simulation of a miniaturized part with micro features are presented. Model design and mesh issues are discussed, as well as dynamic implementation of the flow constrains for the creation of an effective interface between the machine and the polymer flow in the simulation software. The results of the different methods are evaluated by means of a quantitative study which compares the simulated results and the actual micro injection moulding experiments.

Keywords: micro injection moulding, simulation, cavity injection pressure, cavity injection time

1. Introduction

Simulation programs in polymer micro technology are applied with same purposes as in conventional injection moulding. To avoid the risks of costly re-engineering, the functions of the final products as well as the manufacturing steps are simulated extensively before starting the actual manufacturing process: important economic factors are the optimization of the moulding process and of the tool using different simulation techniques.

Simulation tools can work adequately from a qualitative point of view but numerical values cannot be calculated as precisely as necessary [1]. In addition to that, most programs have difficulties in simulating exactly the filling of microstructures with high aspect ratio. The reason is that commercial software tools developed for macroscopic applications do not consider microscopic aspects properly.

However, a proper implementation strategy employed during the set-up of the simulation can greatly improve the quality (i.e. the accuracy) of the simulated results. During this research work, an extensive experimental data base (based on actual micro injection moulding experiments) has been set in order to carry out a comparative study with simulations results. Simulations were carried out using a commercially available code and their implementation was performed applying different approaches. Results were compared in a quantitative study to indicate the method which is leading to the most accurate results. In particular, performance indicators such as cavity injection pressure, injection cavity time and flow front position have been selected for the analysis.

2. Experimental validation of simulation of µIM

Validation of simulation software is an essential step in order to assess the capability of the implemented mathematical model to predict what is actually taking place during the process under investigation. In order to validate the polymer flow (i.e. filling) simulation in µIM, different approaches can be employed: a micro cavity partially filled in subsequent steps (the so-called short shots method) [2,3,4], flow-melt visualization method using a in-cavity high speed camera [5], the use of flow marker positions to trace the evolution of the flow front [6,7], the comparison of process parameters levels (i.e. injection pressure) sampled during the process. Eventually a comparison can be performed between the simulation and experimental results.

3. Experimental micro injection moulding

In order to establish a consistent database to be used for the simulation software validation, experimental micro injection mouldings were produced on a Battenfeld Microsystem50 injection moulding machine. In-cavity injection pressure samplings were executed using a piezoelectric pressure sensor applied at the injection location (where the melt is pushed into the cavity by the injection piston) of a two-cavity micro structured mould (see Fig. 1). Pressure samplings over time allowed the determination of the cavity injection speed and the punctual value of the cavity pressure during the filling of the cavity.

Fig. 1. Two-cavity micro mold (A) equipped with in-cavity pressure sensor at injection location (B).
The moulded component was a tensile bar test part with the shape of a thin plate (15x3x0.3 mm³) including three micro features having semi-circular section (150 µm radius) and lengths from 1500 µm up to 2000 µm (see Fig. 2, 4E, 4F). The part was moulded using a commercially available polystyrene (PS)/polymer grade. PS is a relevant material in the field of micro injection moulding for its high flowability and optical properties (i.e. high transparency).

4. Micro injection moulding simulation

The commercial software program Moldflow Plastics Insight® MPI 6.1 was employed for simulation. The main material functions implemented were Cross-WLF (William Landel Ferry) for viscosity and two-domain Tait for pvT. Details on the mathematical-physical models of the simulation including the finite element formulation are given in [8]. Three dimensional filling simulations were performed setting the melt temperature equal to the barrel temperature and the mould temperature equal to the temperature acquired by the sensor in the mould. Mould temperature was monitored with a closed-loop control system by the µIM machine.

Boundary conditions related to the part (i.e. modelling and meshing) as well as the dynamic management of the interface machine/polymer flow/cavity were investigated and are described in the following sections.

4.1. Part modelling and meshing

When simulating conventional macro-moulded parts, even though the part cavity is modelled and meshed with a three dimensional mesh, the sprue-runner system is usually meshed using simplified one-dimensional elements in order to save computational time. This is due to the fact that the volume of the sprue-runner system is very low when compared to the part volume, i.e. to 1 to 5%, and it is safely assumed it is not going to affect the results of the simulation sensibly.

On micro injection moulding simulation, as mentioned in the previous section, the runner system can easily account for more than 50% of the injection volume. The thermo-mechanical history of the melt flow is heavily influenced by the dynamic evolution through the whole runner, gate and finally the cavity. Therefore, a full three-dimensional meshing of the whole system composed by the runner (see Fig. 4A), the two gates (see Fig. 4B) and the two parts considered as a one complete moulded part was carried out. Furthermore, actual volume left on the surface by the ejectors and the pressure sensor were solid-modelled as part of the moulded product (see Fig. 4C, 4D). Mesh tolerances were also analysed and optimized to fit the need for accuracy of the µIM application. In particular, an average length of the side of a single element (i.e. tetrahedron) of 90 µm was adopted. Moreover, a tolerance between the meshed model and the CAD solid model of 30 µm was used. These settings were chosen as trade-off between the accuracy of the part modelling (especially needed for the micro features modelling, see Fig. 4E, 4F) and the resulting number of elements (i.e. the computational time). The model had a volume of 107 mm³ and was modelled using 1215156 tetrahedrons 3D solid elements.

4.2. Flow-time dependence implementation

When performing the micro injection moulding process, the injection speed (implemented as piston speed) is usually set as parameters to define the
evolution over time of the melt to fill the cavity. Different approaches can be employed to increase the accuracy. Two methods have been selected and are presented in the following.

A. Injection time – From the injection cavity pressure plot (see Fig. 5) given by the pressure sensor the actual cavity injection time is determined and implemented into the simulation. The software will calculate the flow in order to fit the given time constrain. In particular, an initial transition time will be allowed to the flow rate to reach a stable value of the flow rate, simulating the delay due to the acceleration of the piston. On the other hand, when such value is reached, it is kept constant during the remaining injection time until the complete filling (condition not verify in reality). An experimental cavity injection time of 83±1 ms was determined and implemented.

B. Cavity injection pressure Vs time – From the injection cavity pressure plot (see Fig. 5) given by the pressure sensor the actual cavity injection pressure over time is determined and implemented into the simulation. To obtain the experimental time-constrained pressure condition at the injection location, a definite flow rate (i.e. piston injection speed) is necessary and is calculate by the software. Therefore the delay due to the actual piston acceleration is taken into account in the simulation, as well as the actual flow rate during the filling of the whole cavity. Also, the physical condition of the polymer (through a punctual value of the injection pressure) is determined. In the experiment, the pressure repeatability was calculated for each sampled value through the all cavity injection time for three randomly chosen mouldings. A standard deviation of 1.7 MPa was calculated.

The method (A) is carried out using a filling simulation performed in speed control. On the other hand, to implement the method (B) a packing simulation is carried out (i.e. in pressure control).

5. Results and discussion

The cavity pressure profile is a fundamental factor directly correlated to the quality of the part and of the process and it is the critical process parameter for the precision moulding of high accuracy thermoplastics as micro moulded components. It is therefore of great importance that the injection pressure profile is simulated accurately in order to obtain reliable results.

First of all, it is important to observe that the maximum experimental cavity injection pressure (46 MPa) was reached at the cavity injection time of 83 ms, which corresponded to the complete part (injected volume of 130 mm$^3$). On the other hand, the experimental short shots corresponding to 125 mm$^3$ (injection time of 51 ms) shows that, despite the fact that the main flow front reached the end of the cavity, one micro feature in the middle of the moulded was not filled yet (see detail in Fig. 3). The complete µ-feature filling was obtained during the last 32 ms of the cavity filling time when the polymer could still flow, the piston was applying the needed pressure and the flow rate was very low (160 mm$^3$/s instead of 2500-3500 mm$^3$/s calculated during the cavity filling) determining an intermediate flowing condition between a filling and a packing phase.

The comparison of the experimental and simulated pressure plot shows that (see Fig. 5):

- Simulation A (i.e. implementation of the cavity injection time) appeared inaccurate in terms of pressure Vs time prediction and flow front position. The cavity injection pressure was much lower than the experimental for most of the cavity injection time. On the other hand the maximum cavity injection pressure at the very end of filling was of 55 MPa, i.e. 20% larger than in the experiments. Moreover, simulated short-shots showed that the micro features were completely filled before the main flow front has reached the end of the cavity. Complete micro features filling happened after 75 ms and complete part filling at 88 ms.

- Simulation B (i.e. implementation of the cavity injection pressure profile) showed a pressure profile following the same trend as the experimental. On the other hand, despite the fact that the entire experimental pressure plot was implemented, the simulation stopped after 76 ms (complete filling of the cavity), the micro features were filled before the flow front reached the end of the cavity (after 50 ms) and the final filling/packing phase could not be predicted.
Approach based on the injection cavity time only. With higher accuracy when compared with a first optimized implementation strategy could be simulated. Volume/injection time domain. Pressure profile using an particular, the accuracy of the filling step could be simulation software has been demonstrated. In Import the importance of reliable experimental data in terms of injection system has been shown. Moreover, the modeling and three-dimensional meshing of the whole selected. In particular, the importance of an accurate implementation strategies of simulations can heavily influence the results and they have to be careful selected. This means that the dynamic conditions of the flow could be calculated with higher accuracy by using the more advanced approach. This would bring to the fact that the calculation of the shear rate is more accurate and therefore the viscosity values of the material during the filling are determined closer to the reality.

6. Conclusion and outlook

Optimized simulations of micro injection moulding have the potential to enable more effective design phase of polymer-based micro product. The implementation strategies of simulations can heavily influence the results and they have to be careful selected. In particular, the importance of an accurate modelling and three-dimensional meshing of the whole injection system has been shown. Moreover, the importance of reliable experimental data in terms of cavity injection pressure to be implemented in the simulation software has been demonstrated. In particular, the accuracy of the filling step could be improved of at least 50% in the injected volume/injection time domain. Pressure profile using an optimized implementation strategy could be simulated with higher accuracy when compared with a first approach based on the injection cavity time only.

Results in terms of accuracy of the flow front prediction were not satisfactory, showing dysfunctional behaviour of the predicted flow.

As final result, it can be concluded that the use of experimental data from actual moulding can greatly improved the quality of µM simulations. Data should not be limited to the actual injection time, but also dynamic characteristics of the flow (i.e. pressure) should be implemented.

Further research will address other dynamic implementation approaches (e.g. injection speed or flow rate over time, etc). Moreover, other aspects to be investigated and evaluated with a quantitative method as the one presented in this paper are: the use of rheological model suitable for micro polymer application (which can effectively take into account, for example, the wall slip effect), heat transfer coefficient value optimized for micro scale polymer flow, the influence of pressure on the polymer melt viscosity, the use of an elongation viscosity model.

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