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Prediction of micro-sized flash using micro-injection moulding process simulations

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Abstract
In micro-manufacturing, the accurate prediction of defects affecting the part quality by means of process simulations is of paramount importance. With this purpose, micro-injection moulding process simulations can be fundamental with the aim of strongly reducing experimental and quality assurance efforts. In this study, the usage of process simulations for the prediction of the size of the flash affecting an ultra-small three-dimensional polyoxymethylene (POM) micro component is discussed. A three-dimensional multi-scale mesh was used to discretize a geometry comprising the part and the feed system of the one-cavity micro mould. The venting channel was included into the model in order to simulate the flash formation as a virtual short-shot. Simulation were run with Autodesk Moldflow Insight 2017® and results validated by comparing numerical results with experimental observation of the flash size. A state-of-the-art 3D focus variation measurement instrument was used for characterizing the flash on moulded parts. Four injection moulding process parameters were tested using a Design of Experiment (DoE) approach in both real experiments and simulations in order to validate the numerical outputs with respect to process variations. The results showed that flash size was generally overestimated by simulations. However, both real parts measurements and numerical results agreed on the signs and magnitudes of the effects of the investigated process parameters, demonstrating that simulations are an useful tool for process/product optimization.

Micro injection moulding, POM, Flash, Process simulation

1. Introduction

Micro-injection moulding (µIM) is the miniaturized counterpart of conventional injection moulding (IM) and a process enabling the mass production of polymer micro components with unique repeatability and productivity [1]. Being µIM a downscaled process, its optimization becomes more difficult than in its macro version and new solutions have to be adopted. In this context, process simulations can be a powerful tool for the optimization of mold design, parts and process. Different commercial packages for simulating moulding processes exist on the market. However, they are specifically designed for IM. Being the flow of a polymer melt in micro channels characterized by peculiar phenomena that are not implemented in these packages such as wall-slip, high shear rates and surface tension [2], the results may lack of quantitative accuracy when applying them to µIM. A proper modelling strategy can anyhow lead to better results: adopting a 3D mesh and setting profiled boundary conditions [3], [4] were proved to be decisive steps in carrying out a succesfull validation of numerical results.

This paper aimed at applying µIM process simulations as a tool for prediciting the size of the flash affecting an ultra-small micro polymer part. The simulation results were validated by comparison with real moulded parts manufactured over a range of the main µIM process parameters.

2. Materials and methods

2.1. Experimental setup

The micro moulded part was a component used in medical applications, having a volume of 0.07 mm^3 and a mass of 0.1 mg. It had a three-dimensional shape and a 2° tapered hole having smallest diameter of 100 µm. Moulding experiments were carried out with a state-of-the-art Wittmann-Battenfeld MicroPower 15 µIM machine having a 14 mm plasticisation screw and a separated 5 mm injection plunger. The selected polymer was a polyoxymethylene (POM) with high flowability (Hostaform® C 27021). A one-cavity insert machined by micro-electro-discharge-machining (µEDM) was mounted on a three-plate mould and used as master for replication. Such a mould architecture allowed to carry out an automatic detachment of the gate from the part, eliminating the influence of any manual operation on the final part quality. Preliminary moulding trials revealed that complete filling was not possible to achieve because of entrapped air in the cavity. This issue was tackled by machining a circular 4 µm deep venting channel on the ejection plate. If, one hand, this modification allowed to achieve a consistent filling of the cavity, on the other, it generated a micro-sized flash on the part largest diameter caused by the flow of the material inside the venting channel. The effects of four process parameters on the flash size were investigated using a full-factorial two-level DoE (see Table 1). The selected parameters are known to have the biggest effect on the outcome of the µIM process [1]. 5 parts were collected and measured for each of the 16 experimental runs. The flash size was measured by means of a 3D focus variation microscope (Alicona InfiniteFocus) having 10× magnification (0.44 µm lateral digital resolution). In particular, the flash area A_{flash} was selected as flash size indicator.

Table 1 Experimental moulding process parameters.

Process parameter	Low level	High level
Melt temperature [°C], T_{melt}	200	220
Mould temperature [°C], T_{mould}	100	110
Holding pressure [bar], p_{hold}	250	500
Injection speed [mm/s], v_{inj}	150	350

2.2. Simulation setup

Injection moulding simulations were run with Autodesk Moldflow Insight 2017®. The model comprised the part and the feed system (see Figure 1). The venting channel was modelled as a continuation of the part geometry: the flash was then visualized as a short-shot in the software. A multi-scale 3D mesh was used for discretization: element size ranged from 300 µm to 20 µm, generating circa 1 milion elements. To reproduce the experimental campaign, 16 simulations were run and the flash size measured inside the software. The velocity and pressure profiles were recorded and then implemented as boundary conditions of the numerical model. The material properties were modelled according to Autodesk Moldflow database.

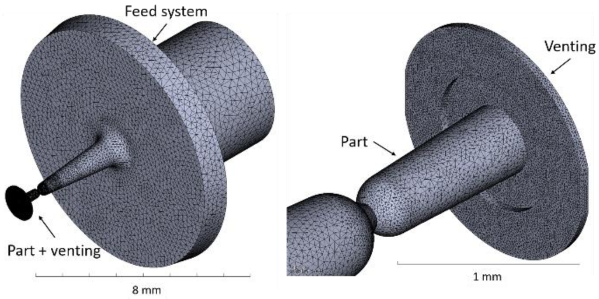

Figure 1. Whole meshed model (left) and close-up of the part (right).

3. Results

Figure 2 shows an example of real flash and the correspondent simulated one: the flash affecting the real part was smaller than the one predicted with the numerical model. This means that, in the simulations results, the polymer flow was able to proceed further inside the venting channel before freezing. This discrepancy could be due to various reasons, most of them related to the underlying simplifications introduced by the numerical model, as for example the neglection of the cavity surface roughness that, in particular for polymer melts flowing in micro channels, can be decisive in determining the filling history. Other reasons could be unrealistic heat transfer coefficient, due to the impossibility of modelling the real surface texture of the cavity, and venting boundary conditions.

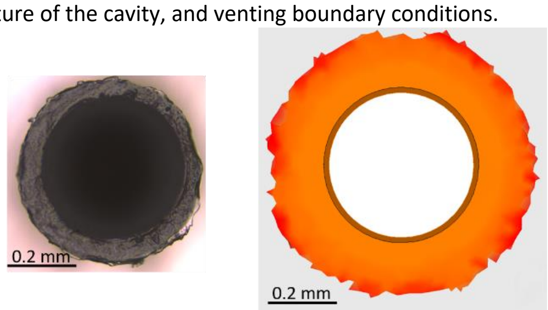

Figure 2. Real flash on the part (left) and simulated flash (right).

Figure 3 shows the main effects plot for flash area measurements. By looking at the scales of the two sets of results, it can be concluded that the simulations provided a flash area equal to circa twice the real one ($A_{flash\text{-}meas}$ and $A_{flash\text{-}sim}$ were on average 0.064 mm^2 and 0.137 mm^2 respectively). However, the slope signs of the two plots are equivalent for all the experimented process parameter ranges. In particular, the increase of the four variables led to an increase of both the measured and simulated flash area. The reasons for this lies in polymer rheology: an increase of T_{melt} and T_{mould} led to a decrease of the melt viscosity, therefore allowing the flow to proceed more inside the venting channel. Increasing v_{inj} had an analougous effect, since the viscosity of shear thinning fluids, such as POM, diminishes when increasing the imposed shear rate. Finally, an augmented p_{hold} allowed more material inside the cavity, thus increasing the flash size. Both experiments and simulations agreed on the sign of the four effects. The magnitude of the effects, which is identified by the value of the slopes, was very similar for the two sets of results. This was particularly true for T_{mould} and v_{inj}, for which experiments and simulations provided an almost identical influence on variation of flash size. As for p_{hold}, the numerical model overestimated the real effect, being the variation introduced by this process parametes bigger than the real one. On the other hand, the effect of the T_{melt} was larger for experimental results and therefore underestimated by the numerical analysis.

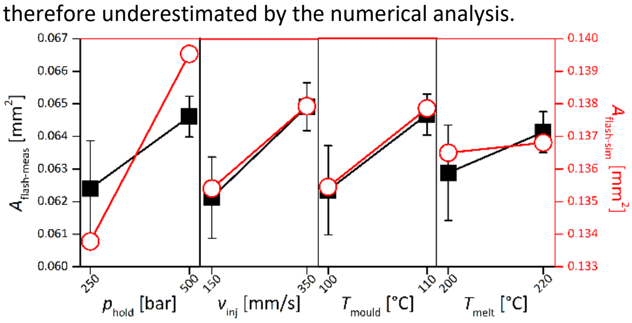

Figure 3. Main effects plot of flash area for experiments $A_{flash\text{-}meas}$ (in black) and simulations $A_{flash\text{-}sim}$ (in red). Note that the scales for the two sets of results are different but the shown ranges are equal. Interval bars represent the standard errors of experimental data.

4. Conclusions

An investigation on the applicability of process simulations for the prediction of flash size of a µIM plastic part was carried out. Flash size on moulded parts was characterized by the flash area measured using a focus variation microscope. Injection moulding simulations were run and the flash was visualized as a virtual short shot. Experimental and numerical results were compared over a range of process parameters. Results showed that simulations overestimated the flash size affecting the part. However, the effects of the process parameters was well predicted by the numerical model, being the slope signs of the main effects plot analogous. The magnitude of the effects was also similar, particularly for mould temperature and injection speed. This proved that injection moulding simulations can be a valuable tool for product/process optimization when flash minimization is the objective. Future research will be dedicated to a more comprehensive modelling of the machine/feed system interface in order to minimize the flash size overestimation.

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