

ON THE SUITABILITY OF THE CONVENTIONAL INJECTION MOULDING PROCESS FOR MICRO FEATURED PARTS REPLICATION - A DOE APPROACH.

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Abstract

Injection moulding has proven to be a technology of utmost importance for micro manufacturing because of its highly process automation and low cost. This study investigates the influence of three processing parameters on the replication quality of micro features with high aspect ratio. The filling performance of pin shaped micro features attached to a thin rectangular plate was studied via design of experiments (DOE) approach, considering as input factors: the barrel temperature, mould temperature and injection speed. The polymer chosen for the experiments was polypropylene (PP) and the mould temperature was kept within the conventional range. Furthermore, the results were analysed and compared with the ones obtained via numerical simulation. The latter were obtained by modelling the experimental conditions and performing a 3D analysis, based on the Navier Stokes flow model. The experimental results reveal that the injection speed was the most significant factor affecting the replication of the micro features. In addition, quantitative information extracted from the numerical simulation results was in agreement with the tendency observed experimentally. However, it was found out that the flow lengths of the micro features were under predicted by the numerical simulation, a fact that has been referred in the literature and that may be related to the lack of rheological data to describe the polymer flow in micro channels.

Keywords: *Injection Moulding, Micro Features, Numerical Simulation, DOE*

1. Introduction

The current trend for product miniaturisation dictates the continuous research toward improvement in the existent micro-engineering technologies. In the case of polymeric materials, injection moulding has been widely adopted for micro and micro featured parts fabrication, due to the cyclic nature of the process and relatively low production cost. The micro parts may be divided in two categories: the first including the parts with weight in the range of a few milligrams while the parts from the second category may have overall dimensions in conventional scale, but incorporating features in the micrometer range [1].

Success of the micro featured parts replication is highly dependent on the interaction between the geometry, size, aspect ratios, processing parameters and polymer type, being therefore, object of extensive investigation by many researchers. Particular attention has been given to the study of the influence of process parameters such as injection speed, mould/melt temperature, injection and holding pressure. Moreover, it could be said that according to the literature, the most

pertinent process parameters affecting quality (i.e. aspect ratio) of the micro features replication are the injection speed and mould/melt temperature [2-4]. Several studies were also conducted toward the validation of the existing commercial numerical simulation codes for micro featured parts replication [5,6]. Nevertheless, till now, the results obtained by numerical simulation do not always agree fully with the ones obtained experimentally, implying that further insight must be given to these issues.

In this study, the Taguchi orthogonal array method [7] was employed in defining the experimental set up as an attempt to identify the most relevant combination of process parameters for the successful replication of micro pins attached to a plate, with thickness in the micrometer range. Additionally, the experimental conditions were duplicated in Moldflow Plastic Insight® MPI6.2 and a 3D analysis was performed. The results obtained experimentally and numerically were compared, aiming to obtain a deeper insight on the micro moulding process.

2. Experimental set up

2.1 Experimental equipment

The injection moulding machine used in this study was a conventional type 65ton EURO INJ (Model: D065) with a 32 mm screw diameter and a maximum injection pressure of 1777 bar. A mould insert of rectangular shape was manufactured allowing for a cavity with 0.6 mm thickness, and 45.8 mm in length and width. The mould insert also incorporates 5 micro holes of 200 µm of diameter and depths of 400, 600, 800, 1000 and 1200 µm i.e. with aspect ratios from 2 to 6. The micro holes were obtained via drilling. An optical microscope Nikon ECLIPSE LV150 was used to assess the length of the micro pins. A semi-crystalline polymer polypropylene (PP) HP500N by Basell Polyolefins Europe was used to carry out the experiments.

2.2 Experimental method

To investigate the filling behaviour of micro pins attached to a thin plate, Taguchi Method Design of Experiments (DOE) [8] was employed. The parameters selected to be studied within DOE were the barrel temperature (T_b), the mould temperature (T_m) and the injection speed (VI), varied at three levels: low - 1, intermediate - 2 and high - 3. In the case of full factorial design it would result in (3³), 27 trials being quite time consuming and costly to perform. To minimize the number of experiments, the L9 orthogonal array was selected and the number of experiments was reduced to nine.

2.3 Experimental procedure

Nine experiments have been conducted according to the routine described in table 1. Injection and packing pressures were kept constant during all the experiments, and were set up at 76 and 51 MPa, respectively.

In order to evaluate the impact of the processing conditions on the micro pins length, the latter was defined as the output from the planned experiments. So, for every set of the processing conditions, 15 parts were produced and then 10 were collected randomly and the micro pins length was measured by means of the optical microscope.

Table 1. Combination of the controlled parameters for L9 orthogonal array

Experiment N° and factor combinations	Barrel temperature, °C	Mould temperature, °C	Injection speed, % max inj. speed
1_111	220	20	20
2_122	220	35	50
3_133	220	50	80
4_212	235	20	50
5_223	235	35	80
6_231	235	50	20
7_313	250	20	80
8_321	250	35	20
9_332	250	50	50

3. Numerical simulation

In this study, numerical simulation of the polymer flow in micro cavities was performed with the commercial software program MPI6.2. The CAD model with the attached runner system was imported and meshed with 3D tetrahedral meshing. The 3D analysis algorithm, based on a Navier Stokes flow model was used. Cross-Williams-Landel-Ferry (WLF) viscosity model with pressure and temperature dependent factors was chosen in this study to represent the rheology of the polymer melt.

Taking into account the significant differences between the micro pin's and the other model dimensions, the mesh size for the micro features was refined. That is, the average edge length of a tetrahedral element was defined as 100 µm for the micro pins and 1mm for the plate base and runner system. The mesh size differentiation was done aiming to minimize the number of the model's elements and speed up the computational time. The resultant mesh consists of 282476 tetrahedral elements. The model of the plate with micro pins is shown on Figure 1, where the mesh size difference can be seen.

Nine simulation runs of the mould filling were carried out, duplicating the L9 orthogonal array arrangement performed earlier, experimentally. The output of numerical simulation runs were chosen to be two response factors i.e. flow front temperature drop at the micro pins extremity and its flow lengths.

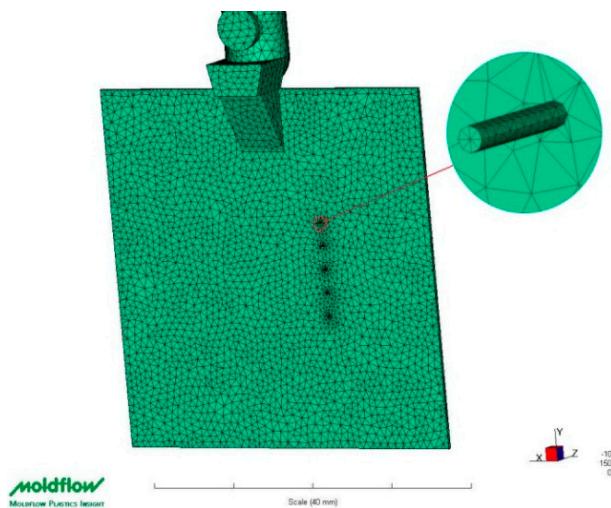


Fig.1 Finite element model with mesh refinement at micro pins

4. Results and discussion

In Fig. 2 it is shown the average fill lengths for the pins with the aspect ratios 3, 4, 5 and 6. The data for the aspect ratio 2 was omitted, since all the pins were completely filled with any combination of the process parameters. Moreover, the pins with aspect ratio 3 also filled with all process parameter combinations, with the exception of experiment number 1, being also excluded from further analysis.

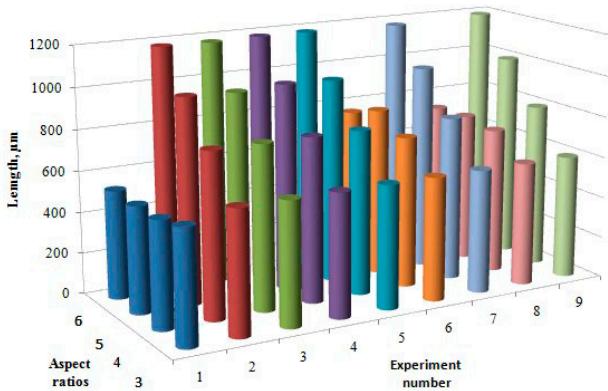


Fig.2 The average pins length (aspect ratios 3, 4, 5, 6).

In this study, the analysis of the orthogonal array was performed by the Taguchi method, designated a signal to noise (SN) ratio [7]. This method is used to determine the deviation of the quality characteristics from the desired value. In this particular case, the desired value is the maximum achievable fill length of the micro pins, for that reason the SN ratio for larger-the-better characteristics is considered. The equation for the SN ratio (larger-the-better) in the i^{th} experiment can be expressed as:

$$SN_L = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (1)$$

where i is a number of experiment, y is the data and n is a number of the trials in each experiment. The computational routine for the average SN levels has explicitly been described in [8]. The results of the calculations are summarized in Figs. 3, 4 and 5 for the pins with aspect ratios 6, 5 and 4, respectively.

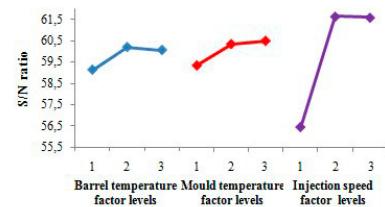


Fig.3 SN response for the pins with aspect ratio 6: barrel temperature, mould temperature and injection speed

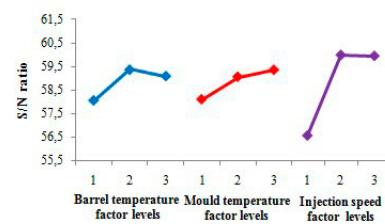


Fig.4 SN response for the pins with aspect ratio 5: barrel temperature, mould temperature and injection speed

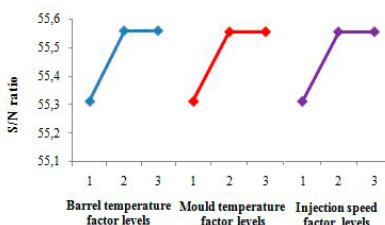


Fig.5 SN response for the pins with aspect ratio 4: barrel temperature, mould temperature and injection speed

As it can be observed from Fig. 2, with none of the set process conditions it was possible to fill completely the micro pins with the higher aspect ratio (6). In addition, the response from the experiments 2, 6 and 8 demonstrates significant short shot. As it can be easily detected from table 1, the above mentioned experiments have one common condition, namely, low injection speed. The latter, leads to an increase in the melt viscosity and originates early freeze of the polymer. By selecting the level with highest value for each factor, the SN response data allowing for the selection of the best combination of parameters for the highest quality criteria

(max fill length). Furthermore, the difference between the maximum and minimum levels shows the influence of each factor on the fill length. The levels difference highlights the injection speed as the most significant factor affecting the filling of the micro pins. The latter can easily be depicted from Figs. 3, 4 and 5. With an increase of the injection speed, filling performance improves drastically, corroborating the data shown in Fig. 2. Barrel temperature and mould temperature were factors of secondary importance, in what concerns the improvement of the micro pins filling.

From the results extracted from the numerical simulation it was verified that all the micro pins were filled completely with any combination of the process parameters, even with the one at the lowest levels. This diverges significantly from the data obtained experimentally and may suggest a deficiency of the used rheological model for representing the filling of micro cavities.

Nevertheless, it was possible to identify the data predicted numerically which follows the same trend observed experimentally, namely a temperature drop at the extremity of pins (Fig.6). As it can be observed from the plot, the maximum temperature drop occurs during the experiments 2, 6 and 8 being detected for the micro pins with all aspect ratios. This result is in agreement with the data obtained experimentally, where the above said trials resulted in significant flow shortening due to the premature polymer freeze during injection.

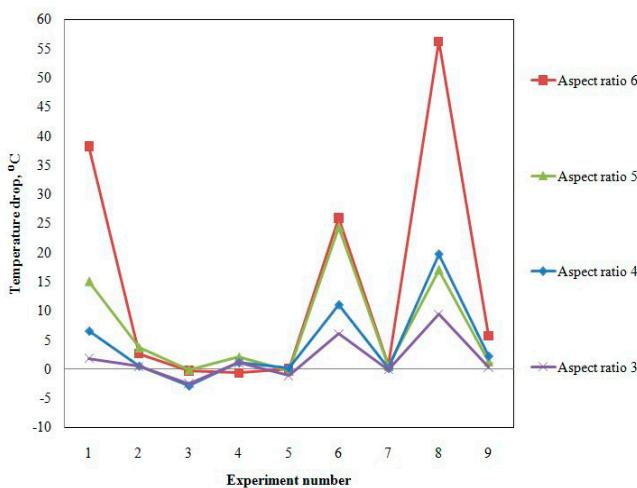


Fig.6 Temperature drop at flow front at the pins extremity.
 *positive values indicate temperature drop, negative values indicate temperature rise due to the shear heating

5. Conclusions

In this study the filling of the micro cavities was investigated experimentally via DOE approach and

numerically by the commercial simulation program. From the analysis of the results some conclusions can be stated as follows:

- For the investigated combination of the plastic material, microcavity design and set of processing parameters, the filling length of the micro pins was primarily affected by injection speed, whereas barrel and mould temperature were parameters of less importance
- With none of the set process conditions it was possible to fill completely the micro pins with the higher aspect ratio (6). The latter may probably establish the limit of the filling performance to the used micro feature geometry and process parameters under analysis.
- Fill length of the micro pins was under predicted by the numerical simulation results, appointing to the lack of precision in the rheological model used. Nevertheless, this issue must be addressed carefully, since further knowledge is required to fully assess the problem.

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