Micro injection moulding: an experimental study on the relationship between the filling of micro parts and runner designs

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Abstract

To increase productivity and thus reduce the unit cost, often micro moulding tools incorporate multiple cavities. For this a runner design must be selected, the main function of the runner system is to facilitate the flow of molten material from the injection nozzle into the mould cavity. Therefore, the micro injection filling process depends on the optimum design of runner systems. In this context, the paper reports an experimental study that investigates the flow behaviour of the polymer melts in micro cavities with a particular focus on the relationship between the filling of micro parts and the size of the runner system. In particular, the runner size effects on the micro injection moulding process were investigated. The filling performance of spiral-like micro cavities was studied as a function of runner size in combination with melt temperature, mould temperature, injection speed and holding pressure time employing the design of experiment approach. In addition, the results were analysed further to identify the effects of the runner size together with flow properties of polymers, PP and ABS, on the behaviour of the micro injection moulding process.

Keywords: micro fabrication, injection moulding, runner system, polymer processing

1. Introduction

Micro Injection Moulding (IM) of polymer materials is one of the key technologies for manufacturing micro devices as it provides reliable and cost effective means of producing micro components in large quantities.

Consistent replication is a key issue for serial manufacture and in the last 30-40 years, a rich repository of polymer processing knowledge was created in macro moulding. Unfortunately, such know-how cannot be employed directly in micro IM due to scale effects [1]. For example, for any given geometric shape, smaller objects have a higher surface to volume ratio (SV_R) than larger ones with the same shape. Such high SV_R increases the heat dissipation which affects the moulding performance of polymers. Thus, existing tool and part designs and polymer processing methods should be applied cautiously in micro IM and most likely some proven designs and processing strategies at macro scale should be re-considered taking into account these scale effects [2].

This observation also applies when considering existing methodologies for designing runner systems [3]. In particular, the runner system is one of the most important basic elements of thermoplastic injection moulds [4]. Its main function is to facilitate the flow of molten material from the injection nozzle into the mould cavity. To increase productivity, often moulding tools incorporate multiple cavities and runner systems that are designed for producing many components from a single shot volume.

One of the most important conditions for consistent replication is the runner system to deliver a polymer melt to all cavities at same time and with as small as possible variations of pressure and temperature [5]. Therefore, for micro components the increased heat dissipation due to high SV_R should be a dominant factor in selecting the most appropriate runner system design. In addition, during the filling stage, a frozen layer is formed along the walls of the mould that affects the flow behaviour. In particular, a thicker frozen layer results in a lower flow of polymer melt, and as the flow reduces, the heat loss increases and thus the frozen volume, too. The resulting flow resistance can then lead to excessive pressure in order to fill the multiple cavities [6]. To avoid this, it is necessary to analyse the effects of different runner designs on the thickness of the formed frozen layer and employ monitoring techniques such as the measurement of maximum cavity pressure (P_{max}) during the filling stage [7].

Thus, the optimum design of runner systems is an important pre-requisite for the production of quality parts with the micro injection filling process. Therefore, this paper investigates the flow behaviour of the polymer melt in micro cavities with a particular focus on the relationship between the filling of micro parts and runner designs. The paper is organised as follows. The next section discusses the important factors in designing runner systems. Then, the experimental set-up and the test tool used to investigate the effects of runner sizes on the flow behaviour are described. Next, the design of experiments is discussed together with the approach adopted for analysing the results. Finally, the experimental results are presented and the relationship between runner sizes and the melt fill of multiple micro cavities is analysed.

2. Runner System

2.1. Design considerations

Several issues should be taken into account when designing runner systems. These include:

• *Polymer material*. Heat loss during the melt fill can prevent flow, so for high and low viscosity polymers an appropriate runner size is necessary. The heat loss in the material occurs firstly at the runner walls, where a vitrified layer of polymer acts as an insulation for the higher melt temperature (T_b) at the core of the flow. The selected T_b must be maintained long enough for the cavity to be filled completely. Once filled with the volume required, the temperature in the core should be high enough to apply the holding pressure. During the holding pressure time (t_h), the material is packed out in

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the cavities long enough for it to solidify and counteracts any contraction during cooling.

• *Injection moulding machine*. The pressure, temperature the runner size, notably its cross section, results in T_b that is less affected by wall temperature. However, there are two economic implications that are associated with large runners and speed capabilities together with its minimum and maximum shot weights should be considered. The ratio of runner to part weights is important because micro part volumes with large or small runner systems can be outside the machine shot weight range.

• *Mould design*. This includes part size, number of cavities and the selected layout. The choice of the runner type must be based on the available tool space and include adequate distance between the part cavities. Available technologies/methods for machining the cavities can also influence the runner design, especially the runner size in order to minimise the tool manufacture cost.

• *Part design*. The cooling time of the runner and the part depends on their dimensions. In particular, an increase in. The first is that the runner cooling time can exceed that of the parts, and thus lead to an increase of the cycle time. Secondly, as the runner is not part of the final product this represents an extra material cost. An optimum runner should provide flow control within a reduced working area, and ideally should be as small as possible with a cooling time equal to that of the parts.

2.2. Runner cross section

The cross section has an impact on the thermal losses in the runner system, and thus on ensuring that an optimum viscosity is maintained for each specific material. Three main types of runner cross sections are typically used: round, trapezoidal and parabolic. Trapezoid and parabolic, in this investigation only the runner type with a circular geometry is studied as it is considered optimum in regard to temperature losses [8].

In addition, in micro IM it is difficult to estimate the optimum size of the runner, e.g. its diameter (D), based on the empirical knowledge that exists at the macro scale [3]. Therefore, the effects of the runner diameter on the behaviour of the micro IM process is investigated by taking into account material and process related factors.

3. Experimental setup

3.1. Part design and tool manufacture

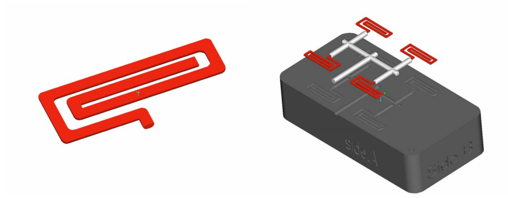
The part used to analyse the runner size influence in the filling of micro cavities is a spiral (see Fig. 1(a)) that incorporates eight unequal sections with a total length of 29 mm and a cross-section of 500 x 250 µm (Table 1).

Table 1. Spiral lengths

Section	1	2	3	4	5	6	7	8
Length [mm]	1	3.5	2.5	7.5	1.5	6.5	0.75	5.75
Total [mm]		4.5	7	14.5	16	22.5	23.25	29

Three tools were manufactured with four identical and symmetrically positioned micro cavities for replicating the spiral (Fig. 1(b)). Due to the symmetrical design, the branches of the runner to each part are balanced and its cross section is round with an overflow for the melt front. The diameter D of the runner cross section varies in the range from 1 to 3 mm for these three tools.

All three tools were made from brass and the cavities were machined using micro milling with surface finishes of 0.12Ra, 0.1Ra and 0.27Ra for the1mm, 2mm and 3mm runners respectively.



(a) (b)

Fig.1. (a) The spiral (b) Tool configuration.

3.2. Condition monitoring

In this study, pressure and temperature variations in the runner area were investigated using a piezoelectric force transducer and thermocouples, respectively. Each of the three tools had been modified to accommodate the condition monitoring sensors as it is shown in Fig. 2(a).

In order to measure the pressure, a 1mm measuring pin (MP) and a force transducer were positioned in the centre of the runner system in the moving half of the tool as it is shown in Fig. 2(b).

Temperature readings were taken directly from the runner area of each tool. Two holes were drilled in the fixed half of the tool to accommodate 500µm diameter K type thermocouples as shown in Fig. 2(a). In particular, temperature readings were taken at the entry and at the end of the runners, and the difference between them was used as an indication of the thermal efficiency of the runner.

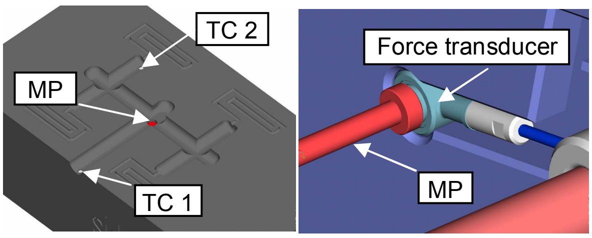


Fig.2. (a) The positions of thermocouples, TC1 & TC2, and measuring pin (MP) (b) The force transducer behind MP.

3.3. Design of experiments

The filling performance of micro cavities relies heavily on the speed and the temperature control during injection. Therefore, in addition to the runner diameter (D), the effects of T_b, mould temperature (T_m), injection speed (V_i) and t_h were investigated in this study.Taguchi orthogonal arrays (OA) were employed to ensure that the experimental results were representative of a broad processing window. In addition, by employing OAs the experimental results could be used further to optimise the process by identifying the best combination of processing parameters, and also the most significant of them in regard to the runner performance.

Two commonly used materials in IM, PP and ABS, were selected to conduct the planned experiments. For each combination of runner size and material used, given that four factors at three levels were considered, a Taguchi L9 OA was selected. The three levels of control for V_i and t_h were the same for all materials, while the levels for T_b and T_m were different (Table 2).

Table 2. L9 orthogonal array for PP and ABS

	t_h (s)		T_b (ºC)		T_m (ºC)		V_i (mm/s)	
	PP	ABS	PP	ABS	PP	ABS	PP	ABS
1	0		220	220	20	40	200	
2			250	250	40	60	500	
3			270	280	60	80	800	
4	2		220	220	40	60	800	
5			250	250	60	80	200	
6			270	280	20	40	500	
7	4		220	220	60	80	500	
8			250	250	20	40	800	
9			270	280	40	60	200	

The output of each experiment was assessed by measuring the flow length of the mouldings, the temperature and P_{max} in the runner cavity. Given that three runner sizes and two different materials are considered, six L9 OAs were defined. In addition, ten trials were performed for each combination of controlled parameters in these six OAs. Thus, in total 10 x 9 x 6 = 540 experimental trials were carried out.

3.4 Simulation

When a plastic is sheared, heat is generated. The amount of the released heat is determined by the product of viscosity η and shear rate γ. In particular, the higher the η and higher the γ the higher the heat generation. To determine the runner effects on τ and γ a finite element analysis (FEA) simulation using Moldflow software and a dual domain flow model was conducted. The simulation used experiments 1-3 from table 2, the t_h factor was omitted and a injection time factor (t_i) was used to replace the V_i factor. A total of three simulations are conducted for each runner and material.

4. Analysis of the results

4.1. Flow length

Fig. 3 presents a summary of the flow length results obtained from all 540 trials. Given that there are four cavities, the maximum and minimum average flow lengths achieved during the experiments are provided.

For the 3mm runner, the maximum average flow length show that both PP and ABS only achieved 90% filling of the cavities. Both materials had unequal filling for the four cavities while a higher variation between the maximum and minimum lengths was observed in the case of ABS.

For the 2mm runner, PP filled completely the cavities in all 9 experiments. This shows that this runner size was more efficient than the 3mm one. For ABS, the maximum filling achieved was 90%, which was similar to that observed with the 3mm diameter runner while the minimum length was higher, 77%. Thus, for both materials the 2mm runner can be considered more efficient.

For the 1mm runner, PP filled completely the cavities in all 9 experiments. Thus, it is difficult to judge whether this runner size is more or less efficient than the 2mm one. However, it is evident that it is more efficient than the 3mm diameter runner. The maximum filling achieved in the ABS experiments was 79.5% while the minimum length was 72.4%. Although, the difference between high and low flow lengths is relatively small compared to the 2 and 3 mm runners, by looking at the maximum flow length results achieved with the three different runner sizes it is considered that for ABS the 1mm runner is the least efficient one.

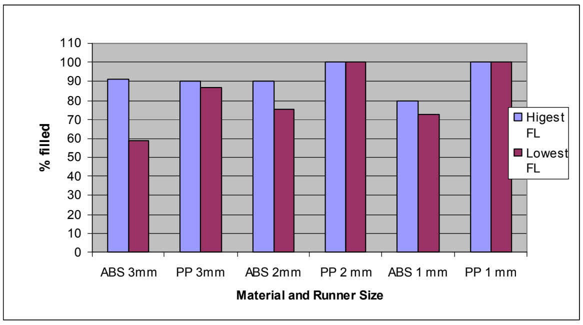


Fig.3. Maximum and minimum average flow lengths.

4.2. Temperature

For each trial, the temperature changes between TC1 and TC2 in the runner cavities was measured to judge about the size effects. Fig. 4 presents the average temperature variations for each combination of runner diameter and material.

For the 2mm and 3mm runners, a temperature increase between the beginning and the end of the runner system was observed for both materials, with a higher increase for PP in both cases.

For the 1mm runner, PP exhibited a marginal temperature increase while a decrease was observed in case of ABS. These results show clearly that the 1mm runner causes the lowest deviation from the set T_b of the three sizes investigated in this study.

If a temperature increase within the runner system is required in order to improve the filling, the 2mm runner can be regarded the best choice of the three sizes considered in this research.

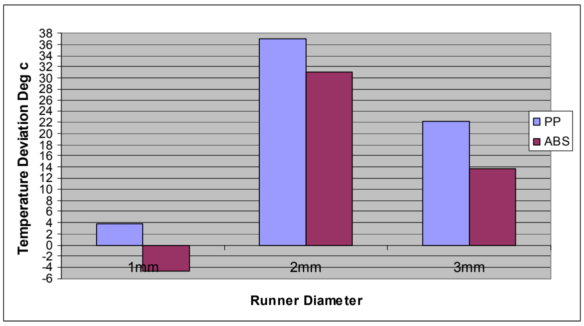


Fig.4. Temperature changes in the runner system.

4.3. Pressure

The runner size effects on P_{max} in the runner cavities were also analysed. Fig. 5 presents the average P_{max} for each combination of runner size and material.

Both materials were subjected to a higher P_{max} with the decrease of the runner diameter. In particular, in case of PP the average P_{max} is doubled with the decrease of the runner size from 3 to 2 mm.

From the carried out experiments, it can be concluded that to extend the tool life it will be desirable to use a bigger size runner because of the P_{max} reduction with the increase of the runner diameter.

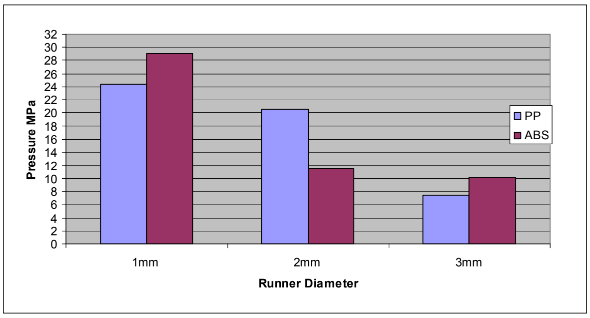


Fig.5. Runner cavity pressures.

4.4 Simulation

High shear rates tend to occur in the feed system due to the high volumetric flow, the average shear results taken from the three simulations for each runner and material identify that the runner size decrease resulted in an increase in both τ and γ (Table 3). The associated heat generation from such an increase could account for the temperature results for the 2mm runner (fig 3), though the heat generation appears to be counteracted by the SV_R for the 1mm runner.

Table 3. Simulation shear results

Runner	3mm	2mm	1mm
PP τ[MPa]	.035	.061	.094
PP γ [1/s]	144.9	318.0	590.6
ABS τ[MPa]	.090	.143	.273
ABS γ [1/s]	90.3	107	195.3

5. Conclusions

The paper reports an experimental study that investigates the flow behaviour of the polymer melts in micro cavities with a particular focus on the relationship between the filling of micro parts and the size of the runner system. The following conclusions can be made based on the reported research:

1. The flow length results for both PP and ABS showed that the 2mm size runner had the optimum surface to volume ratio and shear heating balance in regard to the filling performance. It is important to note that an increase of the runner dimensions did not have a positive effect because both materials failed to fill the micro cavities with the larger 3mm runner.

2. A temperature increase from the set T_b was measured for both materials and all three runner sizes, except for ABS with the 1mm runner system. The use of the 2mm runner resulted in the highest increase of the average temperature while the 1mm runner was the least subjected to temperature variations. For PP, the temperature variations in the runner system do not seem to affect the filling performance. In particular, the micro cavities were completely filled when using the 1mm and 2mm runners while not with the 3mm. This suggests that PP is not sensitive to temperature losses. On the contrary, the results for ABS suggest that the flow temperature affects the filling performance. In particular, the highest flow length was obtained when the highest temperature increase was recorded using the 2mm runner system. In contrast, for the 1mm runner the decrease in temperature led to the lowest flow length.

3. For both materials, an increase in pressure with the reduction of the runner size was observed. The use of the 1mm runner resulted in the highest pressure, with P_{max} doubled and trebled in comparison to the results obtained with the 3mm runner system for PP and ABS, respectively.

Finally, from the simulation shear results it is important to stress that in micro IM the polymer properties become an even more important factor in selecting the runner design. Experimental studies and simulations of runner melt flow behaviour should precede the tool manufacture.

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