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ORIGINAL ARTICLE

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Micro-injection moulding: Factors affecting the achievable aspect ratios

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Abstract Micro-injection moulding is one of the key technologies for micro-manufacture because of its mass-production capability and relatively low component cost. The aspect ratios achievable in replicating micro features are one of the most important process characteristics and constitute a major manufacturing constraint in applying injection moulding in a range of micro-engineering applications. This research studies the effects of five process and one size factors on the achievable aspect ratios, and the role they play in producing micro components in different polymer materials. In particular, the following factors are considered: barrel temperature, mould temperature, injection speed, holding pressure, the existence of air evacuation and the sizes of micro features. The study revealed that the barrel temperature and the injection speed are the key factors affecting the aspect ratios of micro features replicated in PP and ABS. In case of POM, in addition to these two factors, the mould temperature is also an important factor for improving the replication capabilities of the micro-injection moulding process. For all three materials, an increase of feature sizes improves the melt flow. However, the melt fill of micro features does not increase linearly with the increase of their sizes.

Keywords Micro channels · Micro features · Micro-injection moulding

1 Introduction

With the rapid development of micro-engineering technologies there is an increasing trend towards product miniaturisation. The development of new micro devices is highly dependent on manufacturing systems that can reliably and economically produce micro components in large quantities. In this context micro-injection moulding of polymer materials is one of the key technologies for micro manufacturing.

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Components manufactured by micro-injection moulding fall in one of the following two categories. Type A are components with overall sizes of less than 1mm while type B have larger overall dimensions but incorporate micro features typically less than 200 µm. Currently, the following main groups of components are moulded successfully: optical grating elements, micro pumps, micro fluidic devices and micro gears. In all these applications the replication of component micro-features is a key issue determining the reliability of the selected manufacturing route. It depends greatly on their size, aspect ratio and surface area [1].

The aspect ratio achievable in replicating micro features is one of the important characteristics of any micro fabrication process and determine the manufacturing constraints of a given process/material combination. Thus, it is very important to study the factors that affect the replication capabilities of the micro-injection moulding process. For instance, to mould micro features with high aspect ratios is still a challenge [2]. The main reason for this is that the high surface-to-volume ratio that is typical for micro cavities makes the melt fill freeze or solidify much faster than in conventional injection moulding and leads to an incomplete fill of micro features.

To improve the quality of injection-moulded micro-components many research groups worldwide investigated different factors affecting the replication capabilities of the process. In particular, this includes research in process optimisation, development of new tooling technologies, material rheology, and tool design and manufacture. With regard to process optimisation the melt and mould temperatures [3] and injection speed are considered as the main factors affecting the replication quality and the filling length in micro-injection moulding. However, with the increase of the mould temperature the cycle time also increases, which introduces stringent requirements in the technology for heating and cooling the tool. In addition, it reduces the process output and hence increases the cost of the moulded components.

This research investigates the effects of five process factors and one size factor on aspect ratios achievable in replicating micro features in three polymer materials. An attempt is made to identify which process parameters are the most influential during the filling stage of the micro-injection moulding process.

2 Literature review

There are many factors that could influence replication capabilities of micro-injection moulding. A sub-set of them called process factors are of significant importance and therefore have been studied by many researchers.

In general, the process factors studied are melt and mould temperature, injection speed/rate, injection and holding pressures, and cooling time. With the development of the micro-injection moulding technology, new machines were introduced that were specially designed for fabrication of miniature components incorporating micro features. In addition, new process factors were considered such as the metering size and a small forward movement of the injection plunger for controlling the holding pressure [4], in the attempt to improve the process performance.

The main factors investigated by researchers are melt and mould temperature, injection speed and pressure due to their direct effects on the melt flow property and flow status in conventional injection moulding. Many researchers have studied the importance of those factors in micro-injection moulding, including Yao and Kim [2], Mönkkönen et al. [3], Zhao et al. [4], Yoshii et al. [5], Wimberger-Friedl [6], Yu et al. [7], Arlø and Kjær [8], Shen et al. [9], Spennemann and Michaeli [10], Yu et al. [11], Shen and Wu [12], Su et al. [13], Yao and Kim. [14] and Saito et al. [15]. The main conclusions from these studies are that high melt and mould temperatures, and high injection speed have a positive effect on the melt flow in very small cavities. However, when comparing the magnitude of their influence on the melt filling quality the reported results are not consistent. For example, Wimberger-Friedl [6] and Shen et al. [9], [12] reported that a high mould temperature above the glass transition temperature of polymers or close to their melt temperature is the most important factor for improving the replication capability of micro-injection moulding. Other researchers, [3], [4] and [11], came to the conclusion that the injection speed, melt temperature or holding pressure were the most influential factors. Such discrepancy in their findings could be explained with the fact that the studies were carried out under different experimental conditions, for example different polymers and test structures were used. At the same time, it should be noted that although high settings of the considered process factors could improve the melt flow in micro cavities, this could also have a negative effect on injection moulded components. For instance, a high mould temperature may result in temperature-induced defects on micro features as reported by Madou [16] and also could increase the cycle time and the processing cost due to the need of additional heating and cooling devices [17].

Besides process parameters, the geometric configuration of test parts is also a factor affecting melt filling results in micro-injection moulding. For example, Yu et al. [11] investigated the effect of the distance between micro features and the gate of the mould tool on the melt filling depth. The result showed that micro channels near the end of the flow path would be better filled. Also, the study of Mönkkönen et al. [3] showed that the angle of micro features and the direction of the melt flow could result in different filling depth, although the effect of these factors depends strongly on polymers used to replicate the features. These studies provide very useful information for the design of tools and components that incorporate micro features.

As stated in this section, high settings of some process parameters could increase the melt fill in micro cavities. Conversely, materials and geometric configurations of components show different responses to changes of these process factors in micro-injection moulding. Thus, it is very important to study systematically the combined effects of relevant factors. In this research an attempt is made to conduct such experimental study with a focus on identifying the significant factors affecting the achievable aspect ratios at the filling stage.

3 Experimental set-up

Polymer micro components have a wide variety of designs. As stated in section 2, these different designs can affect the melt flow filling behaviour. In particular, the distance of the micro features from the gate could result in different filling lengths of features [11]. Also, it is necessary to fill micro features in different positions in micro-cavities. Thus, to make sure that the experimental results are applicable to real micro structures and representative of the melt flow behaviour during the micro moulding, a test part with micro features in the form of legs was designed as shown in Fig. 1. By varying the width (W), 250 or 500 μm, and the depth (D), 70 (D_1) or 100 μm (D_2) of the leg features in the cavity form, the replication of micro features having different aspect ratios was investigated. The features having the same depth, D_1 or D_2, were grouped on one side of the part. The average aspect ratios of micro legs with the same width and depth were used to study the process replication capabilities in this research.

Two tooling inserts were manufactured in tooling steel and AISI 01 on a micro-machining centre, KERN HSPC. The injection-moulding machine used in this study was Battenfeld Microsystem 50. To measure the length of micro legs and capture images of the produced micro-features, a Mitutoyo Quick Vision system, Accel Pro 404, was employed.

4 Experiment design

Semi-crystalline polymers, polypropylene (PP Sabic-56M10) and polyoxymethylene (POM C-9021), and an

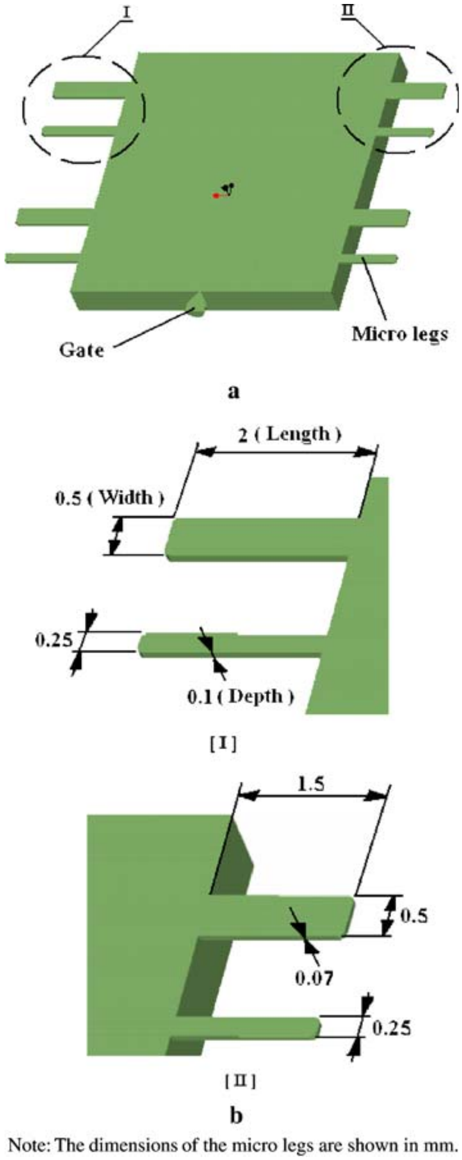


Fig. 1 The test part

amorphous polymer, acrylonitrile-butadiene-styrene (ABS Cycolac-X17), were used to conduct the experiments. To study the filling behaviour of these three materials, five process and one size control parameters were used. The parameters investigated in this research were barrel temperature (T_b), mould temperature (T_m), injection speed (V_i), holding pressure (P_h), the existence of air evacuation (V_a) and the width (W) of micro-legs. In addition, the effect of the feature height, the two depth levels D_1 and D_2 of the legs was observed at different process settings. All control parameters together with their interactions were factors affecting the replication capabilities of the process. To assess their effects on the aspect ratios achievable in micro-injection moulding, the design of experiment (DoE) approach was applied [18]. In particular, a two-level six-factor randomised full factorial design would have required 64 experiments. To reduce the number of experiments to 16 (2^4), a two-level six-factor randomised fractional factorial design (2^{6-2}) was applied in this research.

The experiments were conducted in a randomised sequence. This 2^{6-2} fractional factorial experimental design provided sufficient information about single-factor and two-factor interaction effects. However, it is usually required that the results from the first set of experiments be verified through further tests [18]. Therefore, in this research the first set of experiments was used to identify the factors that were active and significant to study the filling of micro channels. Then, those factors were employed as control parameters for the second set of experiments. In particular, the first set of experiments revealed that T_b, V_i and W of the micro channels were the most important factors affecting the aspect ratios achievable when using PP and ABS. Regarding POM, the initial tests indicated that in addition to these three factors T_m should also be investigated.

The results obtained from the first set of experiments allowed the number of processing combinations for the second set of experiments to be reduced significantly by excluding the less significant factors. Thus, for PP and ABS, the second experiment design was a two-level three-factor full factorial design (2^3). In regards to POM, a two-level four-factor full factorial design (2^4) was applied. In addition, it was possible to reduce the number of experiment runs to four for PP and ABS, and to eight for POM, because micro legs with different widths were incorporated in each test part. Table 1 presents the process settings used for PP, POM and ABS during the both sets of experiments.

5 Experimental results

Table 2 presents the results obtained within the first set of experiments. Twelve moulded parts were measured for each processing combination. The aspect ratios achievable in the replication process, the ratios between the length of the melt fills and the depth of the channels, D_1 or D_2, are

Table 1 Processing parameters

Polymers	Level	T_b (°C)	T_m (°C)	V_i (mm/s)	P_h	V_a	W (μm)
(a) The first set of experiments							
PP	−	200	35	50	No	No	250
	+	225	50	100	Yes	Yes	500
POM	−	180	35	50	No	No	250
	+	200	60	100	Yes	Yes	500
ABS	−	248	60	50	No	No	250
	+	258	75	100	Yes	Yes	500
(b) The second set of experiments							
PP	−	225	50	100	No	No	250
	+	255		200			500
POM	−	200	60	100	No	No	250
	+	220	120	200			500
ABS	−	258	75	100	No	No	250
	+	268		150			500

Table 2 Achieved aspect ratios in the 1st set of experiments

	Levels						PP		POM		ABS	
	T_b	T_m	V_i	P_h	V_a	W	D_2	D_1	D_2	D_1	D_2	D_1
1	−	−	−	−	−	−	9	4	4	2	8	0.5
2	+	−	−	−	+	−	13	6	5	4	7	4
3	−	+	−	−	+	+	15	7	6	4	17	5
4	+	+	−	−	−	+	20	8	12	6	19	6
5	−	−	+	−	+	+	20	11	5	4	20	6
6	+	−	+	−	−	+	18	17	12	6	20	7
7	−	+	+	−	−	−	18	10	6	3	19	6
8	+	+	+	−	+	−	20	15	14	6	20	7
9	−	−	−	+	−	+	11	7	4	3	18	3.5
10	+	−	−	+	+	+	19	7	5	4	20	5
11	−	+	−	+	+	−	10	5	5	3	8	0.8
12	+	+	−	+	−	−	14	7	8	5	9	1.2
13	−	−	+	+	+	−	16	9	6	4	18	6
14	+	−	+	+	−	−	20	12	11	5	20	7.5
15	−	+	+	+	−	+	20	11	11	5	20	7
16	+	+	+	+	+	+	20	17	16	8	19	7.5

given in the table. They are the average values of 24 measured legs with the same W and D (two per part) applying the process setting in Table 1.

When the processing parameters were set to their high levels, the resulting melt fill length of the legs differed depending on their depth D. The aspect ratios achieved for D_2 micro legs were higher than those for D_1 ones as it is shown in Table 2.

Tables 3 and 4 presents the experimental results from the second set of experiments. Again, 12 moulded parts were measured for each processing combination. The importance of the control parameters selected after the first set of experiments was confirmed for all three materials. The aspect ratios that could be achieved at the high settings of these factors are around 20 for the micro features incorporated in the test part. Also, the second set of experiments shows that the size factors, in this case W and D of micro legs, at the higher settings have less impact on the melt fill of micro features. In addition, based on both sets of experiments, it could be concluded that PP exhibits the best flow property among the three investigated materials.

6 Analysis of the experimental results

DoE is the formal tool used to analyse the results obtained from the experiments. In this respect, the normal probability plot, one of the analytical methods of DoE, is employed as a graphical means for displaying the factor effects. The influence of each factor is measured by the magnitude of its effects and plotted against a theoretical normal distribution on the X-axis. Using the mean and standard deviation which are calculated from the measured response values, the data is transformed to the standard normal values, i.e. where the mean is zero and the standard deviation is one. Then the data points are plotted along the fitted normal line on the Y-axis. The data when plotted against the theoretical normal distribution should form an approximate straight line and any deviation from this straight line indicates departure from normality, i.e. a significant effect. The magnitude of the effect is calculated by analysis of variance (ANOVA) [18]. There is no need for normalising the different parameters used in ANOVA because they are considered independent when this type of analysis is applied.

In this research the Minitab 14 software was used to carry out the statistical analysis of the experimental results. Significant effects were studied depending on the average aspect ratios achievable for each combination of control parameters. The influence of investigated factors were estimated using the normal probability plots of these effects. In particular, these are the plots of the single-factor and two-factor interaction effects.

It should be noted that in some cases the micro channels were fully filled by the melt. Thus, because the flow of material was constrained by the channel length, such test results provided limited information for this study. For example, the PP and ABS melts filled the D_2 micro channels completely for some combinations of control parameter settings. In these cases only the D_1 micro legs that were not completely filled were analysed to study the effects of the control parameter.

The investigated factors, T_b, T_m, V_i, P_h, V_a and W are represented as parameters A, B, C, D, E and F respectively in DoE. The effects of the six factors investigated in the first set of experiments for PP, ABS and POM are shown in Figs. 2, 3 and 4, respectively. The results show that in case of PP and ABS, V_i was a very important factor in improving the melt fill of micro features. In addition, by increasing T_b and W, higher aspect ratios were achieved. However, the responses were not consistent throughout the experiments as it is shown in Table 2. For example, for PP, the interaction of V_i and T_b shows a significant effect on the achievable aspect ratios. In case of ABS, the interaction of T_m and P_h had a negative effect on the melt fill. Due to the negligible effect of T_m, P_h and V_a on the length of the micro legs, these control parameters were ignored in the second

Table 3 Achieved aspect ratios in the 2nd set of experiments for PP and ABS

	Levels							PP		ABS	
	T_b	V_i	W	P_h	V_a	T_m(°C)		D_2	D_1	D_2	D_1
						PP	ABS				
1	−	−	−	No	No	50	75	20	15	20	16
2	+	−	−					20	21	20	18
3	−	+	−					20	20	20	19
4	+	+	−					20	21	20	21
5	−	−	+					20	18	20	19
6	+	−	+					20	21	20	20
7	−	+	+					20	20	20	21
8	+	+	+					20	21	20	21

Table 4 Achieved aspect ratios in the 2^{nd} set of experiments for POM

	Levels						POM	
	T_b	T_m	V_i	W	P_h	V_a	D_2	D_1
1	−	−	−	−	No	No	12	5
2	+	−	−	−			16	8
3	−	+	−	−			20	17
4	+	+	−	−			20	17
5	−	−	+	−			16	8
6	+	−	+	−			20	11
7	−	+	+	−			20	19
8	+	+	+	−			20	20
9	−	−	−	+			14	7
10	+	−	−	+			19	9
11	−	+	−	+			20	13
12	+	+	−	+			20	17
13	−	−	+	+			19	10
14	+	−	+	+			20	13
15	−	+	+	+			20	15
16	+	+	+	+			20	18

set of experiments for PP and ABS. Thus, only the other three factors, V_i, T_b and W, were analysed further.

With regard to POM, in addition to the three factors that were identified for PP and ABS, T_m was also investigated as an important control parameter for improving the filling of the micro legs. The other two factors, P_h and V_a, were ignored in the second set of experiments for POM due to their apparent minor affects on the melt fill of the legs.

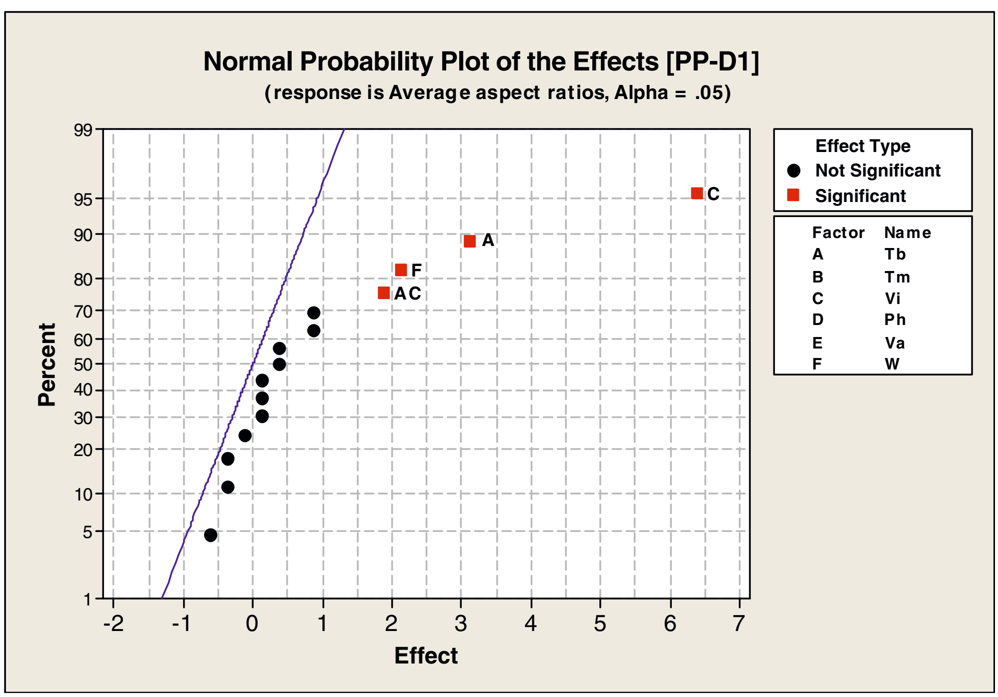
Tables 3 and 4 show the average aspect ratios achieved in the second set of experiments. They confirmed that the processing factors selected during the first set of experiments were really the most influential ones for improving the melt fill of micro features in all three investigated materials. The micro channels were completely filled in most combinations of control parameters except those with depth of 70 µm replicated in POM. Except for ABS, W did not consistently show throughout the experiments that it was an important size factor in replicating micro features with high aspect ratios. Figure 5 shows that in contrast to PP and ABS, POM exhibited more sensitivity to T_m under the conventional processing condition. It should be noted that in Fig. 5, D represents W and not P_h as in the first set of experiments due to the reduction of investigated factors in the second set of experiments. In addition, the interaction of T_m and W has a noticeable negative effect on the melt fill. Figure 6 indicates that the reason for this could be the trapped air at the end of the flow path for the legs with 70 µm depth and 0.5 mm width. The results in Tables 2, 3 and 4 also show that generally D had a larger effect on the melt fill than W; however this relationship is not linear.

Another important observation is that in most cases the micro legs along the melt flow are filled better at the higher settings of T_b, V_i and W as the data in Tables 3 and 4 indicates. In case of PP and ABS, all micro features were completely filled while for POM only those at the start of the flow path or the legs with D_2 thickness were completely filled, as is shown in Fig. 6. The improvement of the POM melt fill of 70 µm micro legs at the end of the flow path could be explained by the trapped air in the channels.

In particular, the following observations could be made about the infl1uence of the seven studied factors on aspect ratios achievable in micro injection moulding.

– *Barrel temperature*. By controlling T_b it was possible to control the melt temperature directly. The robustness of this control improves with the increase of the temperature. In particular, with the increase of the

Fig. 2 Analysis of the results for PP



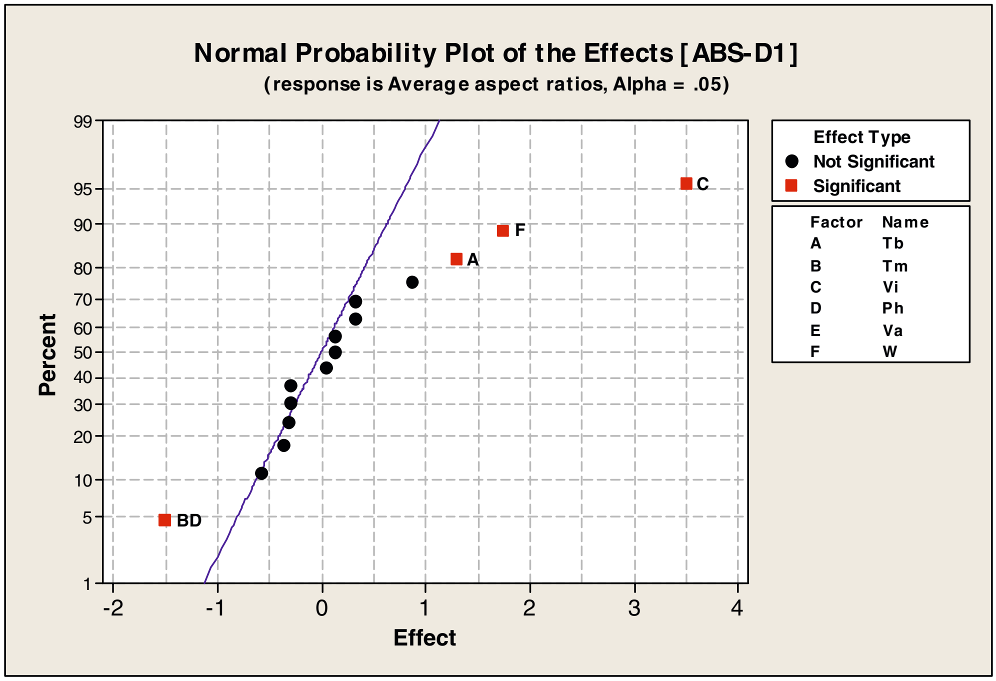
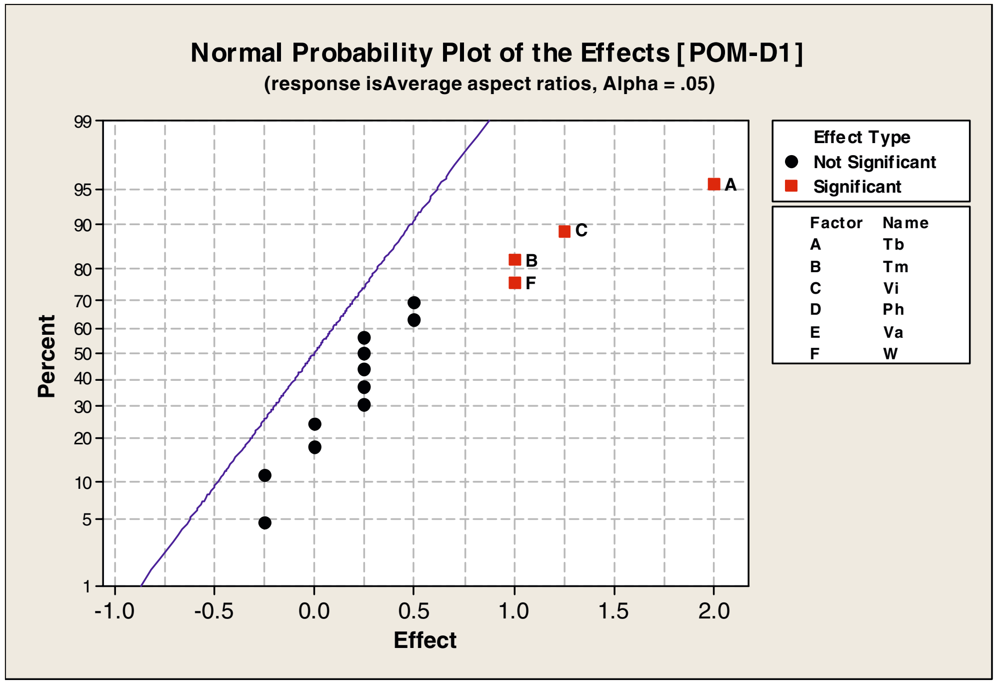


Fig. 3 Analysis of the results for ABS

temperature the melt viscosity decreases and as a consequence of this the polymer flow properties improve. In addition, by increasing the melt temperature the thickness of the solidified layer along the surface of the cavity decreases and thus the melt fill of micro features is facilitated. The general conclusion is that the replication capability of the micro-injection moulding process improves with the increase of T_b.

– Injection speed. Vi is a control parameter only for the filling stage of the injection moulding process. However, it is an important factor for improving the melt fill of micro cavities. In micro-injection moulding, with the increase of V_i the shear rate increases significantly, which leads to a temperature increase [19]. Because of this, the polymer viscosity decreases resulting in a better filling of micro features. Also, with the increase of Vi the material flow rates in micro cavities increase leading to a higher amount of material reaching the micro features before the melt solidifies.
– *Mould temperature*. In micro-injection moulding the polymer flow has a high surface-to-volume ratio, which leads to a high cooling speed. Thus, by increasing Tm the melt flow could be improved. At the same time, with the increase of Tm the thickness of the solidified layer along the surface of the cavity decreases, which has a positive effect on the melt flow into micro features. However, it is worth noting that polymers respond differently to the changes of T_m. The results in this research show that an increase of T_m leads to significant improvements of the melt flow and achievable aspect ratios only for POM. The reason for this is that POM, PP and ABS have different thermal properties so that they demonstrate different sensitivity to T_m changes. Hence, this process parameter should be applied selectively for improving the melt fill of micro cavities.
– *The width and depth of the micro channels*. In general terms, deeper and wider micro channels are more easily filled by the melt because of the reduction of the surface-to-volume ratio. However, the melt filling length does not increase linearly with the increase of W and D according to the experimental results. In particular, at the higher settings of T_b, T_m and V_i, an increase of W did not lead to obvious improvements of the melt fill in the micro channels and at the same time a decrease of D resulted in less melt filling. The nonlinear response of the melt fill to changes of W and D are most likely due to factors related to processing parameters and polymer properties.
– *Holding pressure*. During the holding stage, the flow speed of the melt is very low. The role of P_h is to prevent the melt from flowing back and also to compensate for any reduction of the volume due to the shrinkage of moulded parts. P_h could slightly improve the aspect ratios of micro features however its main effect is to maintain what is achieved during the filling stage. For POM, this is demonstrated in Fig. 7. This figure also shows that the filling length could decrease in spite of the increase of P_h in the case of PP and ABS. To explain this phenomenon further research is required.
– *The existence of air evacuation*. A vacuum pump was employed to evacuate the air from the micro cavities. This control parameter could improve the melt fill and the surface quality of the injection moulded components. However, it should be noted that air evacuation could lead to a decrease of the surface temperature in micro channels as a result of taking away warm air from the cavity. Hence, with the increase of the surface-to-volume ratio in micro cavities air evacuation



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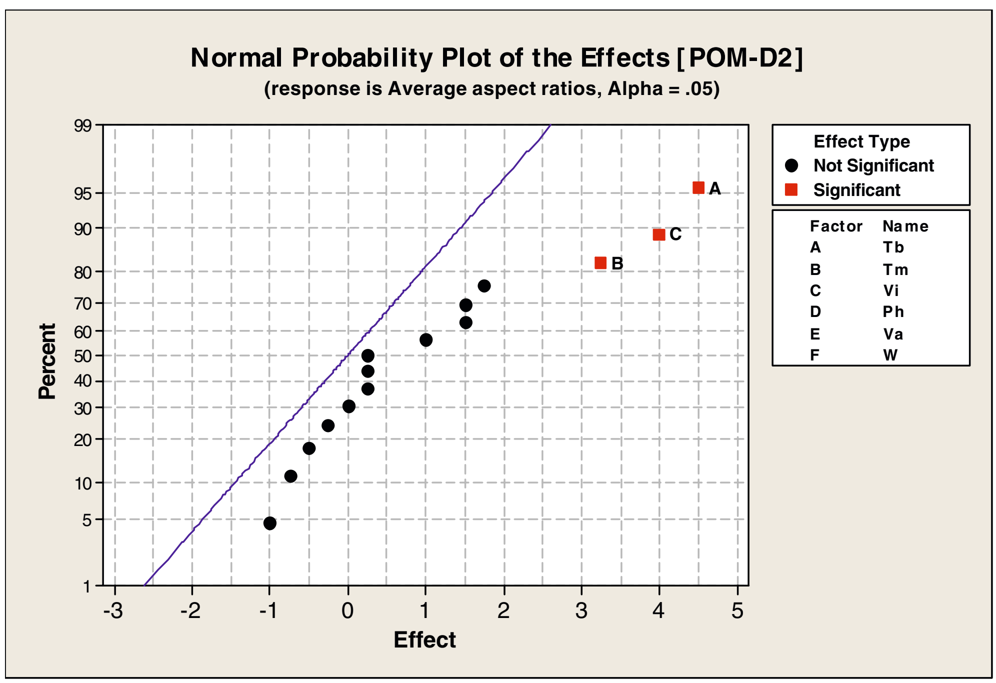

b

Fig. 4 Analysis of the results for POM

could have a detrimental effect on the melt fill for polymers that are sensitive to changes of T_m. For example, Fig. 7 shows that in case of POM, a polymer sensitive to changes of T_m, the melt fill decreases when air evacuation is applied.

7 Conclusions

This work investigates the effects of process and size factors on the replication capability of the micro-injection moulding process within the conventional mould temperature scope. The following conclusions could be drawn from this study.

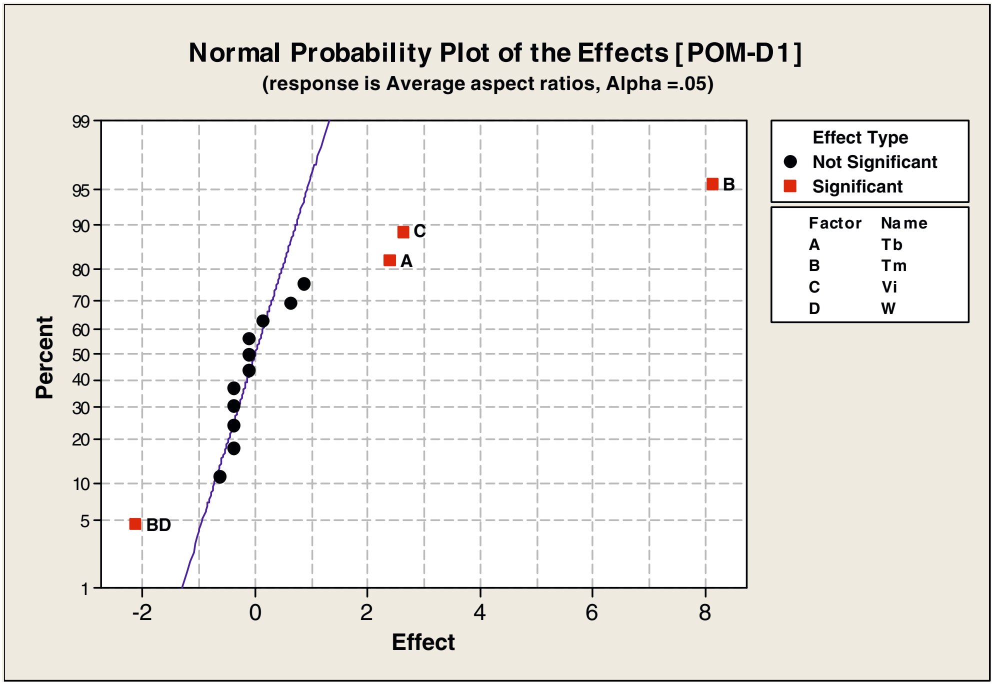

Fig. 5 Analysis of the results for POM (the 2nd set of experiments)

– T_b and V_i were the key factors affecting the aspect ratios achievable in replicating micro features in PP and ABS.
– In the case of POM, T_m, T_b and V_i were the most important factors for improving the replication capabilities of the micro-injection moulding process.
– If polymers that are not so sensitive to changes of T_m are used, for example PP and ABS, an increase of T_m does not have a significant effect on the filling of micro features.
– The use of air evacuation could substitute the traditional vent grooves and thus increase the replication quality of the micro-injection moulding process. However, the existence of air evacuation could also reduce the surface temperature in micro channels, which could have a detrimental effect on the melt flow, especially for materials sensitive to changes in T_m such as POM.
– An increase of W and D of micro-channels improves the melt flow because it leads to reduction of the surface-to-volume ratio in micro cavities. However, the melt fill of micro features does not increase linearly with the increase of channel dimensions.

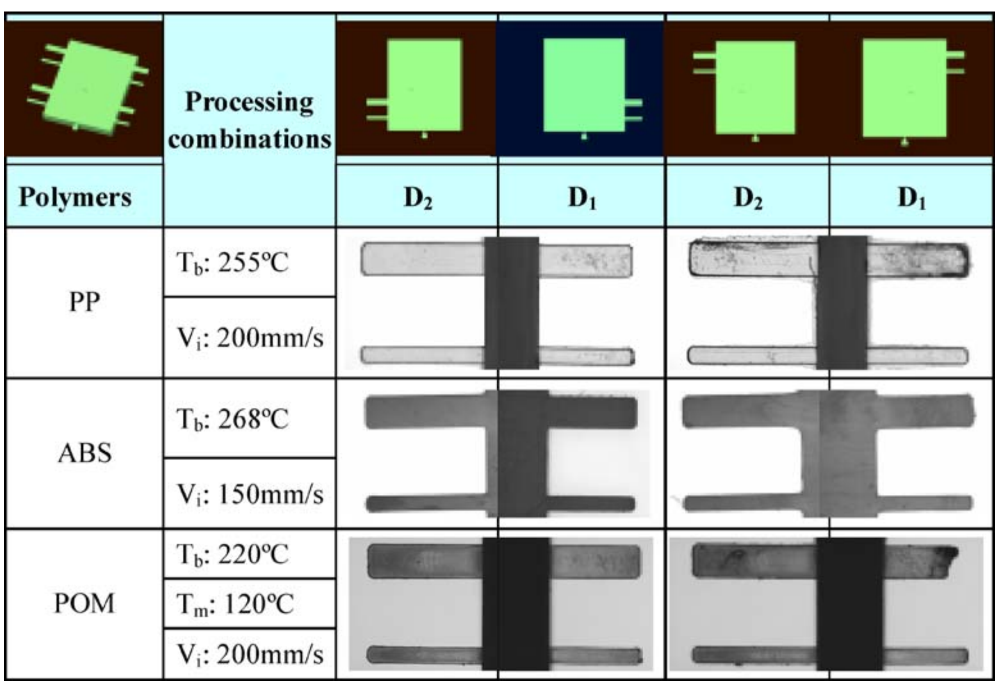

Fig. 6 QV photos of micro legs at the high settings of significant processing parameters in the second sets of experiments

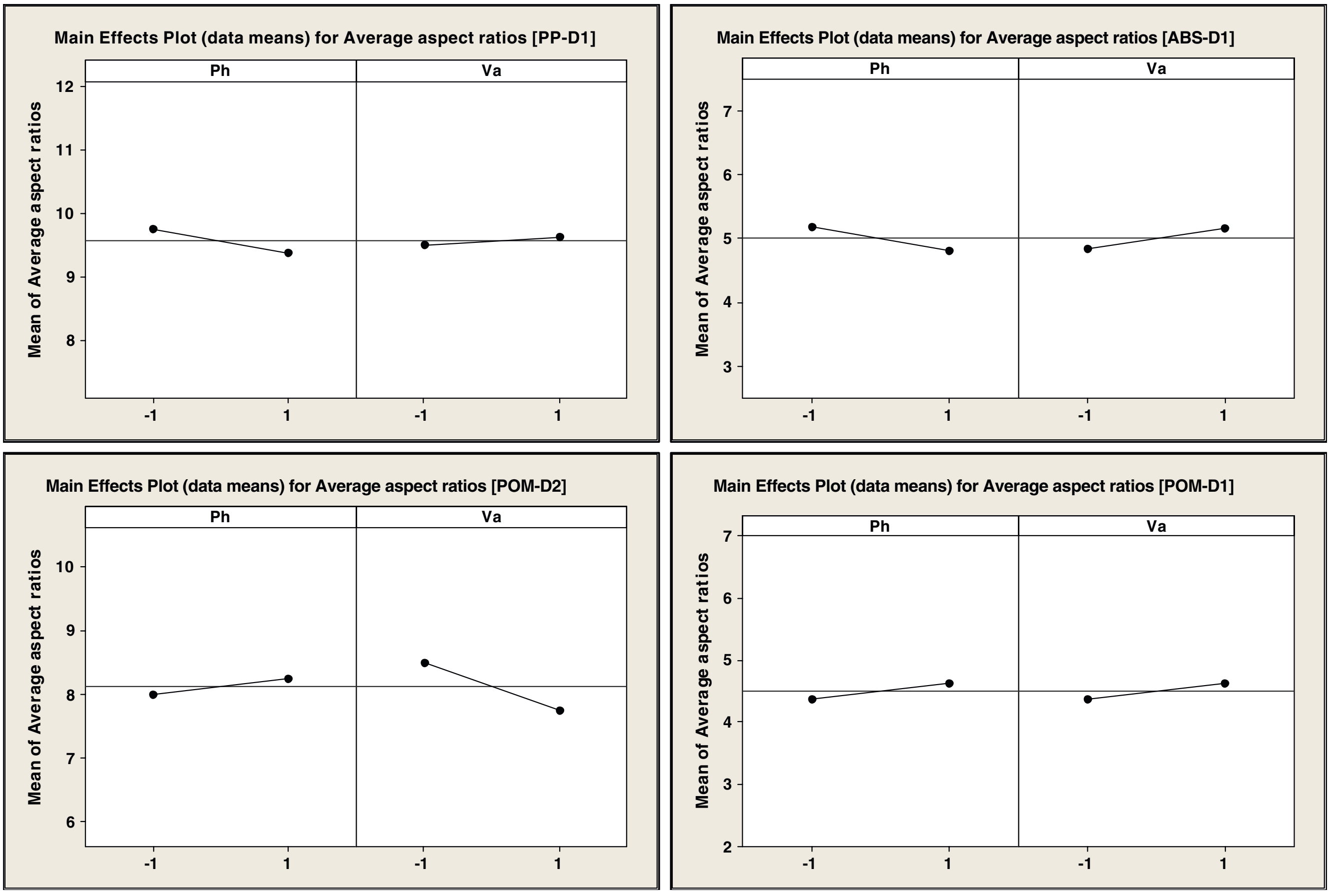

Fig. 7 The main effect plots of P_h and V_a

– An increase of P_h could slightly improve the aspect ratios of micro features or could just help to preserve what is achieved during the filling stage. Furthermore, in the case of PP and ABS, a decrease of the filling length of the micro channels was observed. To explain this phenomenon further research is required.

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