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MICRO INJECTION MOLDING: CHARACTERIZATION OF CAVITY FILLING PROCESS

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Abstract

Based on reciprocating micro injection molding machine, this paper characterizes the influence of machine process parameters and its transition response from velocity control to pressure control (V-P transition) on the micro cavity filling process. The method of Design of Experiment was employed to systematically and statistically investigate the effect of machine parameters on actual cavity filling process, which was described by the defined process characteristic values (PCVs). The statistical analysis of the experiments indicated that injection speed was dominated factor affecting all PCVs in cavity filling process. It was also found that the machine V-P transition have significant effects on cavity filling.

1. Introduction

Micro injection molding (μIM) is not simply a scale down of conventional injection molding (CIM). It presents some particular features and requirements, such as higher surface volume ratios, earlier freezing off, higher injection pressures and temperatures, and precise metering capability [1]. However, since there is limited space available to install sensors into a micro cavity, especially for a micro part, it is difficult to investigate the influence of machine settings on μIM process [2]. In addition, the configuration and dynamic response of the injection unit and metering capability of the injection molding machine influence melt cushion, metering accuracy and process repeatability and mold design etc, which would directly affect the filling of a micro cavity, part quality and its microstructure. Whiteside et al., [3, 4] monitored the injection pressure and cavity pressure using a Battenfeld Microsystem50. The melt flow visualization and morphology, mechanical properties were also analyzed at different process conditions. However, the cavity filling behavior and relationship between process condition, cavity filling and microstructure have still not been investigated. Chu et al., [2] also used Battenfeld Microsystem50 to systematically and quantitatively investigate the relationship between process conditions and cavity filling and packing behavior. However, due to space limitation of the cavity, cavity pressure sensors were not installed in the study.

In the present study, two P-T sensors were installed in the cavity along flow direction. Five process characteristic values for machine and cavity during cavity filling process were defined based on the recorded process data: metering size, average injection pressure, average screw velocity, average cavity filling velocity and average cavity pressure. The influence of machine parameters and V-P transition responses on micro cavity filling process was characterized, based on a reciprocating micro injection molding machine.

2. Experiment

Figure1 displays the detailed dimensions of a molded tensile sample. The thickness of the part can be varied from 0.1mm to 0.6mm. However, only part with thickness of 0.5mm was used in the present study. The volume of sample is around 25.34mm^3.

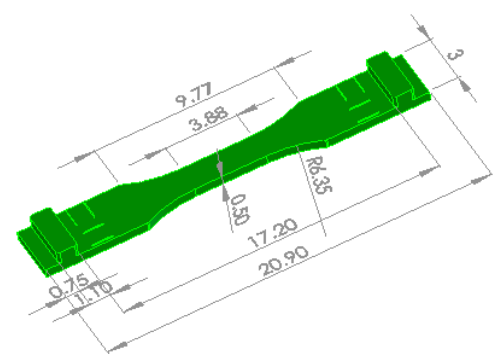


Figure1. 3D dimensions of molded tensile sample (units: mm).

Kistler COMO injection process monitoring system 2869B was used for process monitoring and data acquisition. The maximum sampling rate of the system was 1200 Hz. Two Kistler 6189A combined pressure and temperature sensors were installed outside the gauge length of the tensile sample, as shown in Fig 2, so that the temperature and pressure were measured at the same time and at the same location. We assigned the sensor next to the gate as sensor1 and the one further from the gate as sensor2. The injection pressure and screw position signals were also inputted into the COMO. The injection signal from the Fanuc ROBO Shot 2000i 15B micro injection molding machine was used to trigger the COMO in order to receive all these signals synchronously.

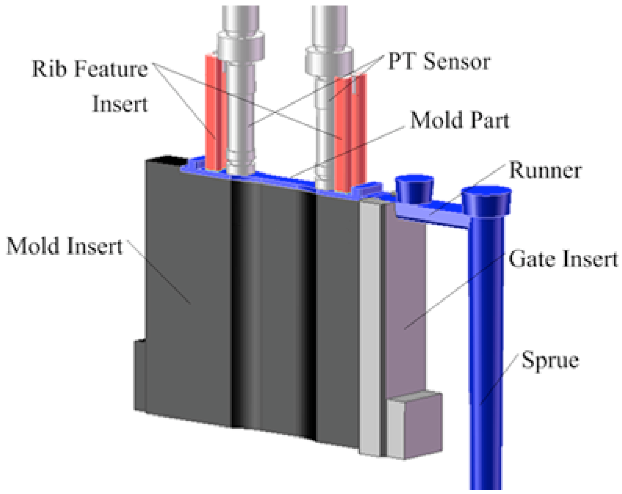


Figure 2. Location of PT sensors in dog-bone mold cavity.

High density polyethylene (HDPE HMA016 grade, ExxonMobil) was selected as a molding material for the present study, due to its excellent processability, good impact strength and dimensional stability. The material was used directly without drying. The DOE method was used to analyze the effect of machine parameters on process conditions. The following machine parameters were selected: injection velocity (V_i), holding pressure (P_h), holding time (t_h), barrel temperature (T_b) and mold temperature (T_m). The levels of machine parameter are shown in Table 1. Minitab software was used for statistical analysis. In light of the experimental cost, a two level, half factorial (2^{5-1}), resolution V design was constructed, as displayed in Table 2. All process conditions were randomly repeated 3 times according to the built in random function of Minitab.

Table 1. Levels of selected machine parameters.

Level	V_i (mm/s)	P_h (MPa)	t_h (s)	T_b (°C)	T_m (°C)
+	450	120	0.6	160	70
-	100	70	0.2	150	40

Table 2. Experimental design matrix.

Process condition	V_i(mm/s)	P_h(MPa)	t_h(s)	T_b(°C)	T_m(°C)
1	-	-	-	-	+
2	+	-	-	-	-
3	-	+	-	-	-
4	+	+	-	-	+
5	-	-	+	-	-
6	+	-	+	-	+
7	-	+	+	-	+
8	+	+	+	-	-
9	-	-	-	+	-
10	+	-	-	+	+
11	-	+	-	+	+
12	+	+	-	+	-
13	-	-	+	+	+
14	+	-	+	+	-
15	-	+	+	+	-
16	+	+	+	+	+

3. Results and Discussion

Cavity Filling

Figure 3 shows the typical trace curves of monitored screw position, injection pressure, cavity pressure and material contact temperature in the cavity for case 10 within 0.8s after injection.

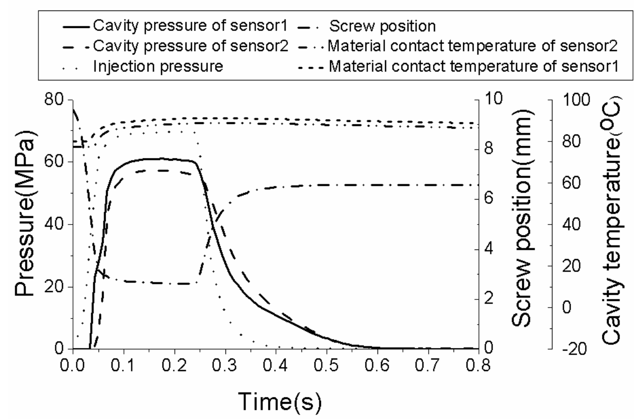


Figure 3. Trace curves of screw position, injection pressure, cavity pressure and material contact temperature.

Figure 4 shows the trace curves of injection pressure, screw position, cavity pressure and material contact temperature within 0.07s. At the beginning, the screw moved forward with no significant pressure rise during the first 5ms. This is probably due to that the small flow resistance after decompression in the plasticising stage.

Both the little jump of injection pressure and screw position at 17ms might indicate that the melt front starts to fill the runner. The volume filling the sprue is around 190mm^3, which corresponds to 1.47mm of screw forward displacement. The corresponding metering volume is 226mm^3, which is almost 19% higher than the volume of sprue as calculated by 3D geometrical model. This larger difference is probably because the P-v-T behavior of the polymer melt and also material being lost due to leakage from the backflow of nozzle. A similar phenomenon can be seen when filling the runner, gate and cavity. The screw reaches the mechanical switchover position (around 5mm) at around 33ms, at which the machine switches from velocity control to pressure control.

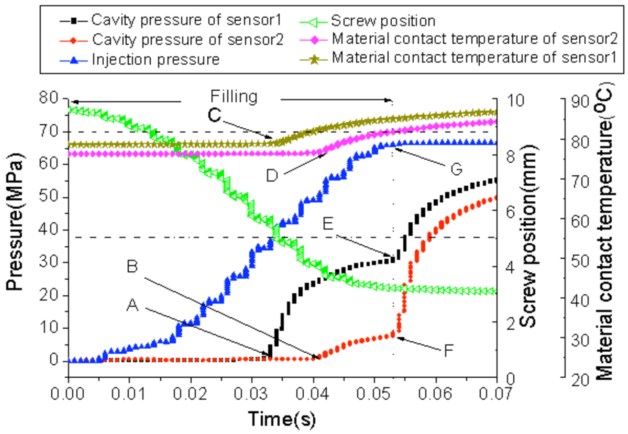


Figure 4. Trace curves of injection pressure, screw position, cavity pressure and material contact temperature within 70ms.

Figure 5 displays the actual switchover position (V-P transition position) of 100 cycles of the same process conditions. The average switchover position is 4.97mm with a standard deviation of 0.063. The coefficient of variation is 1.26%. This proves that the machine is under control. The fluctuation of V-P position might be caused by factors such as non-homogenous material properties and machine control mechanism, metering size, back flow of Fanuc machine used in study. In fact, the set injection velocity did not actually build up within around 33ms from the start of injection to switchover position. The actual peak injection speed is around 220mm/s for case 10, when the calculated slope of screw displacement is against time from beginning of injection to switchover position. The building up of velocity depends on the dynamics of driven motors and selected dynamic response style, control unit etc.

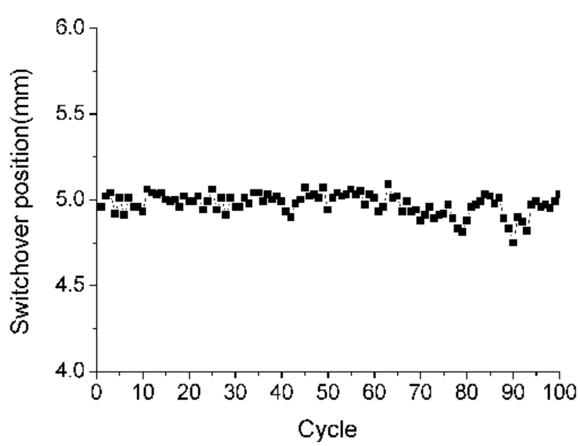


Figure 5. Actual switchover positions of 100 cycles.

The screw, runner and part of the cavity were filled before sensor1 registers any signals. The material contact temperature of the sensor1 is higher than that of sensor2. This is probably due to the heat loss from the material to the cold mold wall. Sensor 1 registered pressure and temperature at the same time around 34ms after injection. However, the material temperature at the position of sensor 1 is significantly lowers than an expected temperature, which is normal for advancing fountain flow. This could be attributed to possible jetting problems as was reported for HDPE [5]. The temperature at sensor1 was the material temperature at skin layer of jetting flow and it increased with time while heat transfers from the core region to the mold wall. Around 8ms later, sensor2 registered pressure and temperature signals at the same time, as indicated at point B and D in Fig 4. Both the jump of cavity pressure sensed by sensor1, sensor2 and injection pressure at 53ms indicate the cavity is fully filled, at which the screw position is 3.21mm. The entire corresponding displacement of screw during the filling stage is approximately 6.29mm and the corresponding volume is 969mm^3, which is 32% bigger than the volume of the whole molded part. The difference could be attributed to the P-v-T behavior of the material.

The symmetry of the sample was used to estimate the corresponding screw position at the beginning of cavity filling. It can be seen that the tensile sample is axially symmetric along the dashdot line at the middle of the sample. As displayed in Fig 6, the volume of the sample from the gate to sensor1 is equal to that of the sample from sensor2 to the sample end. The corresponding screw displacement of filling the volume from sensor2 to the sample end is about 0.75mm. Assuming that the volume from the gate to sensor1 equals that from sensor2 to the sample end, the corresponding screw displacement for filling the volume from sensor2 to the sample end is approximately equal that from the gate to sensor1. Therefore, the corresponding screw position at the start of cavity filling approximately equals 5.8mm. The corresponding estimated cavity filling beginning time is around 29ms. Based on the P-v-T data from paper [6] and considering the influence of pressure inside the cavity during cavity filling, the error of the above estimated screw position is around 4%.

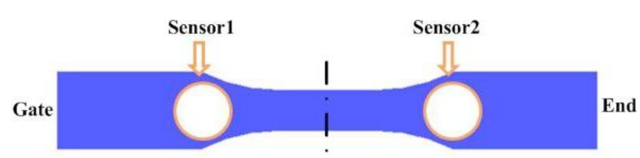


Figure 6. Schematic of symmetry of tensile sample.

In summary, mold filling is triggered by injection start signal. The sprue is filled at around 17ms. After that, the melt keeps moving forward to fill runner and gate. The estimated time at which cavity filling start was 29ms. The cavity filling time is around 24ms.

Characterization of V-P Switchover of Machine

One of the most important mechanisms in the injection molding process is the transition from velocity control to pressure control. The improper switchover can lead to overpacking and underpacking. Overpacking forces more material into the cavity and makes demolding more difficult. Underpacking leads to underweight and sink marks [7]. Typically, there are several transition methods: injection time switchover, screw position switchover, hydraulic pressure switchover, nozzle pressure switchover, cavity pressure switchover.

In the present study, metering size was considered as a variable and optimized by short shot trials for each process condition in order to obtain a uniform switchover position. The typical position switchover method was adopted with the set mechanical switchover position being 5mm in all the experiments. The experiments of case 10 with and without packing pressure were implemented to investigate transition from velocity control to pressure control. Figure 7 displays the profiles of cavity pressure, injection pressure, screw position and screw injection velocity for case 10 with and without packing pressure. The set switchover position is 5mm, as shown by the dashdotted line at position B. The corresponding injection pressure is around 53MPa. The corresponding injection velocity approximately reaches the maximum point and decreases quickly after this point. This indicates that the machine starts the V-P transition from its switchover position. When screw reaches position D, i.e., at 3.5mm, both the injection pressure, screw position and screw velocity of case 10 with and without packing diverge from each other, which indicates that the transition from velocity control to pressure control has completed and the pressure control starts taking effect. The period of time during which the screw travels from position B to position D was defined as V-P transition time, which is around 10ms. The corresponding screw displacement is around 1.5mm, which is so-called deceleration stroke. The corresponding deceleration volume is 231mm^3. The V-P transition is an inherent characteristic of the injection molding machine. The transition time is assumed to be constant for all process conditions in the present study.

It is worth noticing that the cavity is not fully filled before the V-P transition when the screw stays at position B. The corresponding cavity pressure is around 12 MPa, as shown at point C. The actual cavity filling continues with the transition from velocity control to pressure control.

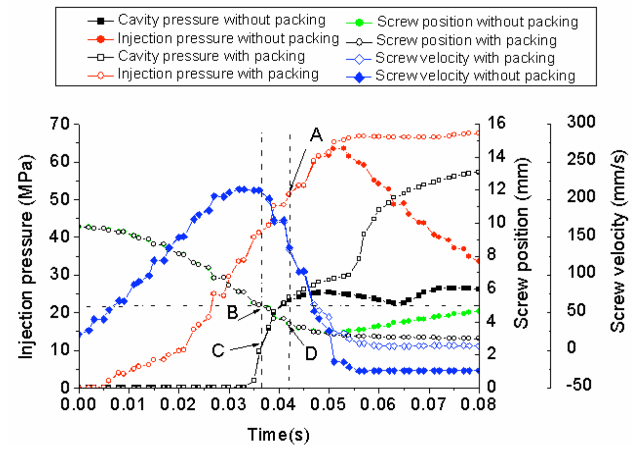
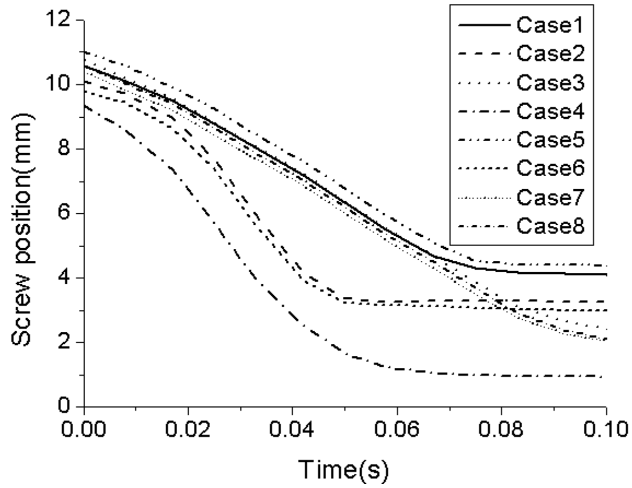


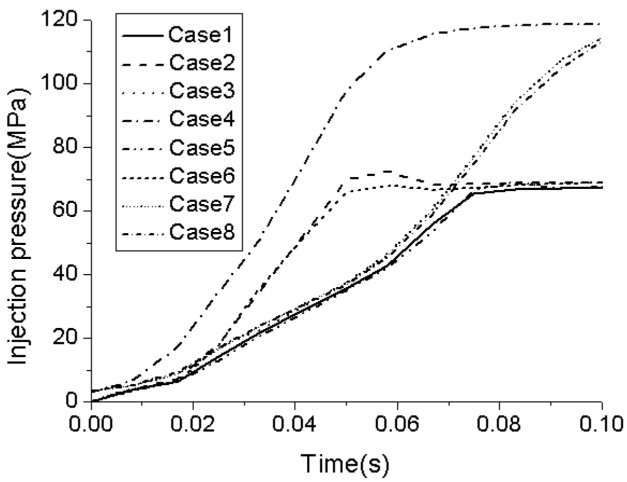
Figure 7. Profiles of cavity pressure, injection pressure, screw position and screw velocity for case 10 with and without packing pressure.

Process Characterization in Cavity Filling Stage

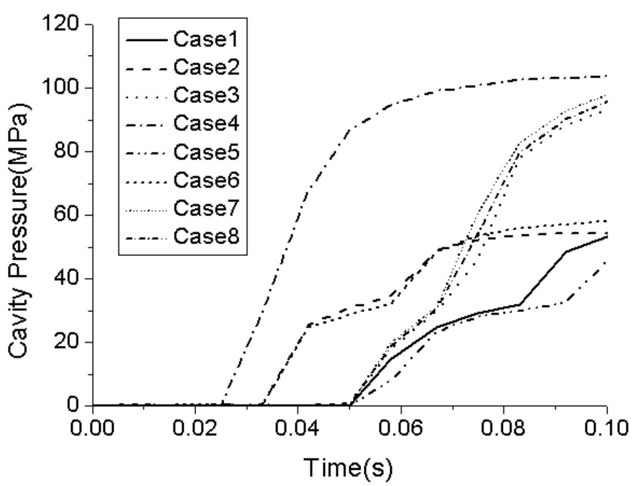
Figure 8 (a), (b) and (c) show the evolution of screw position, injection pressure and cavity pressure for sensor1 of eight process conditions within 0.1s. It can be seen that the slope and shape of the screw position, and injection pressure vary at different process conditions. Therefore, average injection velocity and average injection pressure during the cavity filling stage are used as process characteristic values. In addition, it can be seen that the shape of the cavity pressure changes at different process conditions, as shown in Fig 8. As cavity pressure is sensitive to changes injection pressure, injection rate, screw speed, back pressure and cushion [8], average cavity pressure is adopted as a process characteristic value. By using the method that was adopted to estimate the corresponding screw position at the beginning of cavity filling, the start time for cavity filling was determined. Based on the length of the tensile sample, the average filling velocity was calculated as another process characteristic value. This work also used the predetermined metering size as a process characteristic value. The average screw velocity and average injection pressure describe machine dynamic responses during the cavity filling process. The average cavity pressure and average filling velocity illuminate the actual cavity filling process. The metering size determines the amount of material injected into the mold.



a) Screw position trace curves



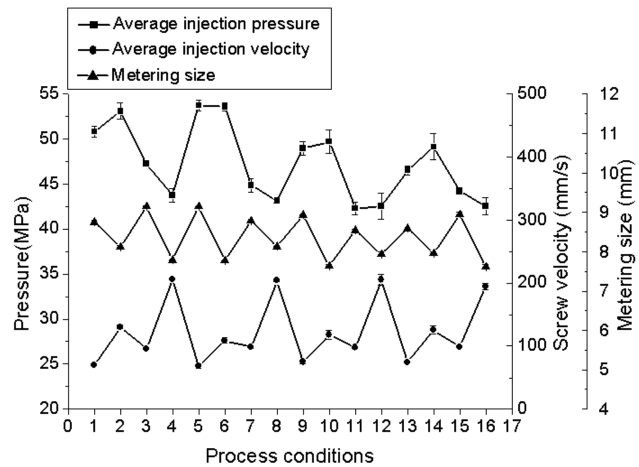
b) Injection pressure traces curves



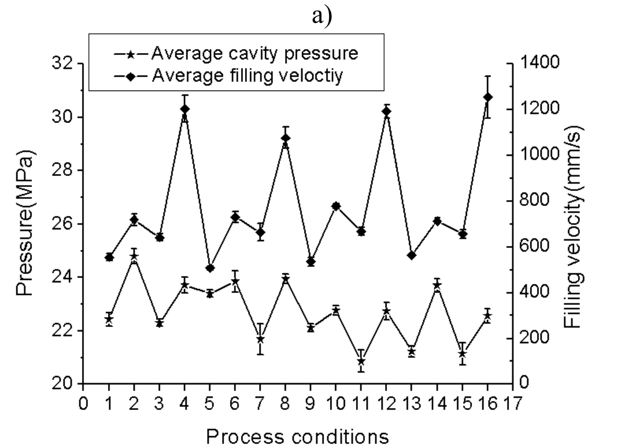
c) Cavity pressure traces curves

Figure 8. Evolution of process parameters for eight process conditions within 0.1s.

Five consecutive cycles of each process condition were selected to obtain the process characteristic values. Figure 9 (a) and (b) display the mean and standard deviation of the defined process characteristic values during the cavity filling process for each process conditions.



a)



b)

Figure 9. Process characteristic values of filling process at each standard order.

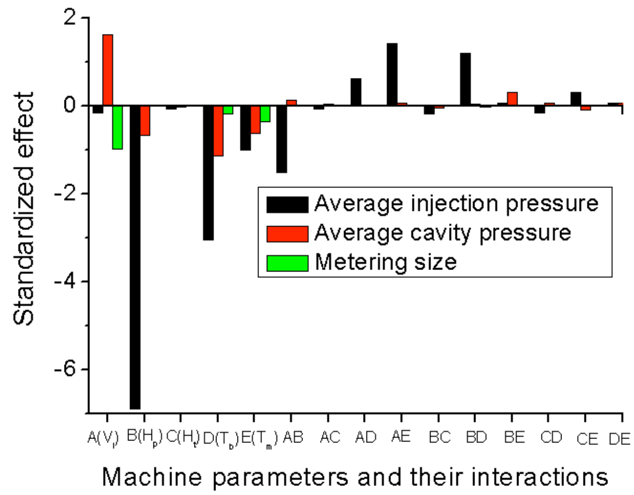
It is obvious that the process characteristic values vary significantly with process conditions. The average injection velocity ranges from its lowest value of around 70mm/s at process conditions 1, 5, 9, 13 to its highest value of around 205 mm/s at process conditions 4, 8, 12, and 16, as shown in Fig 9 (a). Compared with cases of lower injection velocity settings (100mm/s), the average injection velocity of the cases with high injection velocity setting (450mm/s) are far from the set injection velocity value. This indicates that the screw speed does not fully build up at the high injection velocity setting cases, which might be due to the dynamic response of injection server motor [9]. The metering size displays the exact opposite trend to the average screw velocity, as shown in Fig 9. This means that the metering size increases with a decrease of injection velocity. Meanwhile, at the same setting of injection velocity, the metering sizes are higher at cases with lower mold temperature and melt temperature. The variations of metering size indicate that metering size is primarily dominated by injection velocity and mold and melt temperature. This can be explained by viscous dissipation caused by high shear rates, and P-v-T behavior of the material.

As shown in Fig 9 (b), the average filling velocity and average cavity pressure present a similar pattern. The actual average cavity pressure ranges from 20.8 MPa to 24.8 MPa. The maximum and minimum average cavity filling velocity is around 1200mm/s and 500mm/s respectively. Based on Newtonian flow, the corresponding shear rate ranges from $2500s^{-1}$to $6000s^{-1}$, which is directly associated with the skin-core micro structure. This will be studied later.

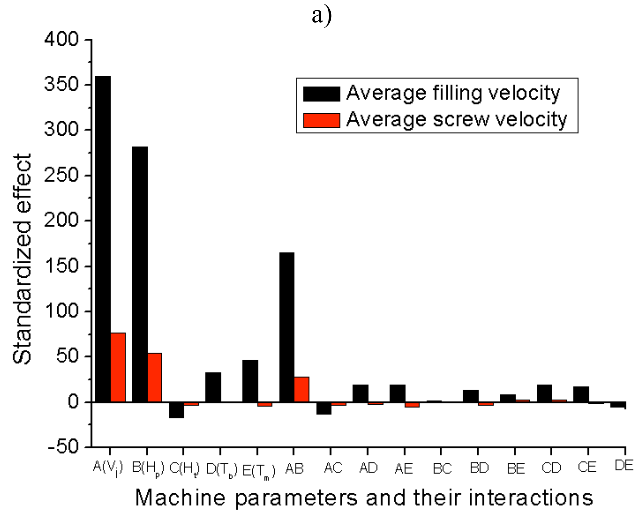
Compared with the process characteristic values for the machine and cavity from both (a) and (b) in Fig 9, it can be seen that the average filling velocity has a similar distribution to that of the average screw velocity. It also presents a similar pattern with average cavity pressure, which indicates that an increasing screw velocity can lead to a rise of cavity pressure.

Figure 10 shows the standardised effects of the machine parameters and their interactions on process characteristic values. Injection velocity is the main positive factor to influence average cavity pressure. Melt temperature and mold temperature both have a negative effect on the average cavity pressure, which is closely associated with the shear thinning behavior of HDPE and flow resistance of the cavity. Both the injection velocity melt temperature, and mold temperatures have a negative effect on the metering size. The holding pressure, melt temperature and mold temperature exert a negative effect on the average injection pressure. It is for this reason that the average injection pressure presents a complex pattern in Fig 9 (a). As shown in Fig 10, injection velocity, holding pressure, melt temperature and mold temperature all show positive effects on average filling velocity. Similarly, both the injection velocity and holding pressure have positive effects on average screw velocity. The interactions of injection speed, holding pressure and mold temperature are not considered, due to process data variability.

The statistical analysis also indicates that the filling stage is also affected by holding pressure. Trace curves of process variables of both cases 10 and 16 are displayed in Fig 11. These two cases have the same machine parameters except for holding pressure and holding time. The holding time was not considered due to its small effect on the filling stage. The holding pressure was set as 70MPa and 120MPa for cases 10 and 16, respectively.



a)



b)

Figure 10. Standardised effects of machine parameters on the process characteristic values of filling stage.

Here we divided the cavity filling stage into two sub-stages: cavity filling before and after the V-P transition was complete. We defined 'sub-stage1' to be cavity filling before the V-P transition was complete and 'sub-stage2' to be cavity filling after the V-P transition was complete. The estimated cavity starting filling time is shown by dashed line A in Fig11 for both cases10 and 16. The corresponding screw position is around 5.7mm. Assuming the V-P transition time is a constant of 10ms, the estimated V-P transition finishes at 46ms for case 10, as shown by dashed line C. This is the end of sub-stage1. However, the cavity was not fully filled at this point and sub-stage2 continued to fill the rest of cavity until 57ms for case 10, as shown by dashed line D. As a result, the filling behavior is actually controlled by the holding pressure during sub-stage2. Similarly, the estimated V-P transition and sub-stage1 finishes at 43ms for case 16, as shown by dashed line B. Sub-stage2finishes at 46ms, as displayed by dashed line C. It appears that case 16 is also affected by the holding pressure. Sub-stage2 lasts for only 3ms for case 16, which is around 11ms for case10. This is because the set holding pressure for case 16 is higher than that for case 10. The bigger holding pressure requires that the injection screw moves faster to achieve its set value. The corresponding average screw velocity is 350mm/s for case 16, which is bigger than 49mm/s for case 10 during sub-stage2. The corresponding screw displacement of this stage is 0.7mm (in a volume of 108mm^3) and 0.5mm (in a volume of 78mm^3) for cases 16 and 10, respectively. Obviously, the average screw velocity and filled volume of case 16 in sub-stage2 is significantly higher than that of the lower holding pressure for case 10. The corresponding filling time of case 16 is significantly shorter than that of case 10.

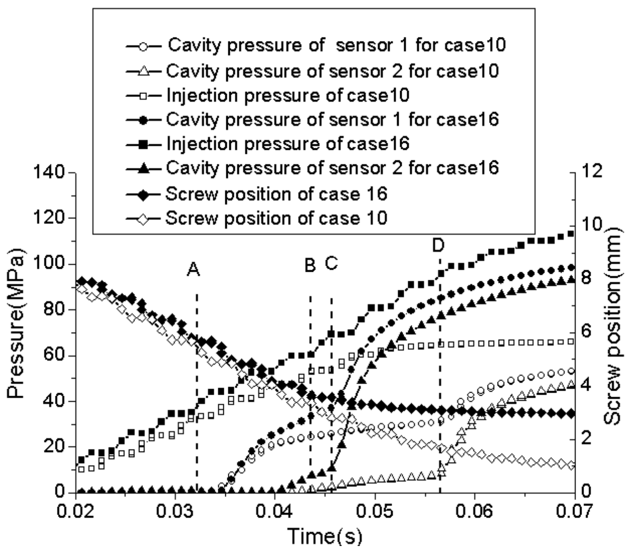


Figure 11. Comparison of trace curves of process parameters for case 10 and 16.

4. Conclusions

This study characterized the cavity filling stage for manufacturing a micro tensile specimen. The micro cavity filling process was analysed based on the recorded process data. The cavity starting filling time was estimated from symmetry of the sample. Analysis of case 10 with and without packing pressure indicates that the V-P transition time is around 10ms, and the corresponding transition volume is around 231mm^3. Statistical analysis indicates that the injection velocity dominates the cavity filling process and has significant effects on all the defined process characteristic values. Holding pressure also presents negative effects on the process characteristic values, due to an earlier transition from velocity control to pressure control. Melt temperature and mold temperature present significant negative effects on average injection pressure, average cavity pressure, and metering size and has positive effects on average filling velocity.

The set injection velocity was not achieved for the high level setting of injection velocity. The cavity filling stage was also affected significantly by the V-P transition. Holding pressure also affected the cavity filling time and the mass of material injected into the cavity by influencing the screw velocity which was required to reach its setting pressure. Further work will be done on optimisation on metering size, cushion size, machine dynamic response style to remove the influence of holding pressure on cavity filling.

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Key Words: Micro injection molding, Process characterization, V-P transition, Micro cavity filling.