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Characterization of the Microinjection Molding Process

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The commonly used plunger injection system in the microinjection molding (μ IM) process has separate screw melting, metering, and injection units. As a result, extra operating parameters and complexity are introduced, in comparison with conventional injection molding. In this study, a μ IM machine was used to obtain micromoldings of polyoxymethylene, high-density polyethylene, and polycarbonate. A data acquisition system was developed to record traces of data regarding the evolution of process variables with time. Cavity filling was followed, at the millisecond time scale, using short-shot experiments and traces of injection pressure, runner pressure, and plunger position. Six characteristic process parameters (CPPs) were defined to characterize both the cavity filling and packing stages. The method of design of experiments was used to investigate the effects of machine settings on the CPPs. Metering size, which was optimized for each set of machine variables, was also used as a CPP. Injection speed was the most significant factor affecting plunger velocity and injection pressure during cavity filling, while the effects of mold and melt temperature varied with the material and machine settings. POLYM. ENG. SCI., 50:1214–1225, 2010. © 2010 Society of Plastics Engineers

INTRODUCTION

The use of micromolding to produce very small plastics parts is growing, because of demands by the electronics, biomedical, and other industries for such parts and for the production of components for complex microelectromechanical systems. The polymer microinjection molding (μ IM) process is a key enabling technology for microsystems, because it has the potential to produce repetitively and consistently large numbers of microcomponents with complex shape and high surface quality at low cost [1]. The production of microparts using conventional injection molding (CIM) machines leads to large amounts of waste

and material degradation during different processing steps [2]. Thus, special μ IM machines have been developed to minimize waste and to limit degradation of the polymer. The plunger injection system, which has been adopted by many machine manufacturers, uses separate screw melting, metering, and injection units and introduces extra parameters. The main reasons for choosing this system configuration are to control metering accuracy and homogeneity of the very small quantities of melt in the μ IM process and to limit material degradation. The screw, typically 14 mm in diameter, to allow the use of regular polymer granules, provides heating based on both thermal and mechanical energy. It produces efficient and homogeneous plasticization. The melted material is then introduced into a 5-mm diameter metering barrel to a preset volume. The accuracy of this volume is critical for consistent processing, in view of both flow and heat transfer considerations. The metered melt is then delivered into the injection unit, where a 5-mm diameter plunger pushes the material into the cavity. The injection plunger, combined with the electrically driven cam mechanism, provides high injection speed, high injection pressure, and low switchover volume, which are necessary to avoid premature freezing and achieve accurate feature replication. However, it is difficult to study the different process variables, because of the very short filling time and the limited space available for installation of sensors. Also, the extra parameters associated with control of plunger movement and melt storage make the process setup and optimization more difficult, in comparison with the CIM process.

The μ IM process, based on the above three separate units, has received considerable interest. However, most of reported research [1, 3, 4] has been devoted to empirical studies of the effects of machine variables on the quality of the molded product. Thus, conclusions made in these studies depend on the selected machine variables and the quality parameters of the different end products. Zhao et al. [1] investigated the effects of machine variables on the micromolding process and part quality by

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molding a series of microgears using the design of experiments (DOEs) method. They considered the following five factors: mold temperature, melt temperature, injection speed, metering size, and hold pressure time. They found that holding pressure time and metering size and their interaction were the machine variables that had the most significant effects on part quality. However, the results do not provide insight into the flow and thermal behavior of the melt during the process, because neither the holding pressure time nor the metering size could be related directly to variables in the governing equations. In addition, the metering size could be eliminated from the machine variables by setting it at an optimum level. Pirskanen et al. [3] used a special mold insert to conduct a full factorial design comprising 32 test runs to study the effects of the following five factors on product quality: injection speed, metering size, vacuum, holding pressure, and diameter of the plunger. It was found that the diameter of the plunger, shot size, and injection speed had the greatest effects on replication of the submicrometer features. Yet, it is still difficult to understand the fundamental physics that contributed to these effects.

Whiteside et al. [5–7] monitored the dynamics of both the injection pressure and cavity pressure and studied the flow behavior by visualizing the polymer flow through a transparent cavity and using sol–gel film ultrasonic sensors. It has been reported that cavity pressure measurements offer the most sensitive indicators of process variation. Both flow visualization and ultrasonic measurements have been useful in detecting the flow front position and measuring shrinkage development. However, the cavity filling and packing stages have not been described clearly and quantitatively. Thus, the relationship between process conditions and polymer melt behavior during the micro-molding process remains unexplored.

One of the objectives of this work has been to identify a set of characteristic process parameters (CPPs) reflecting the actual conditions experienced by the material during the cavity filling and packing stages of the μ IM process, and to conduct a statistical investigation of the effects of machine variables on these CPPs. The cavity filling stage was studied, using short-shot trials and analysis of data tracing the evolution of injection pressure, runner pressure, and plunger position, at the millisecond time scale. The CPPs for the cavity filling stage include peak injection pressure, average injection pressure, and average plunger velocity, all during filling. For the packing stage, the CPPs are plunger stroke at 0.2 s packing, total plunger stroke during packing, and average injection pressure during 0.2 s packing. These parameters were extracted from the dynamic data recorded for plunger position and injection pressure. The metering size, optimized for each set of machine variables, to have a uniform switchover position (start of packing stage) for each process condition, was also used as a characteristic parameter. The DOEs method was used to investigate the effects and coupling effects of machine variables on the CPPs.

The proposed methodology is useful for analyzing and understanding the actual conditions experienced by the material during the μ IM process. Although the proposed methodology is used here in conjunction with the operation of a specific type of μ IM machine, it should be applicable for understanding the behavior of other types of machines. The application of the methodology to evaluate the responses of three different polymeric resins to machine settings provides a deeper understanding of the material–machine interactions. Obviously, no two machines operate in an identical fashion, and machine settings do not reflect the exact conditions to which the material is exposed. Thus, studies following the methodology used in this work represent a significant step toward understanding the real processing conditions experienced by the material and the responses of the material, irrespective of machine type. Such understanding is critical for developing process and product quality optimization and control strategies and for achieving realistic computer simulation models of the μ IM process.

EXPERIMENTAL

Materials

The following materials were selected for this study: (i) polyoxymethylene (POM) homopolymer (Delrin 900P; MFR: 11 g/min, Dupont), (ii) high-density polyethylene (HDPE) (Sclair 2714; MI: 51 g/10 min; Nova Chemical), and (iii) polycarbonate (PC) (CALIBRE 1080 DVD; MFR: 80 g/10 min; Dow).

POM has been widely used in μ IM studies because of its processing characteristics, such as low viscosity, fast molding, and good processing stability for deposit-free molding. POM is also noted for its high mechanical strength and rigidity, excellent dimensional stability, natural lubricity, fatigue endurance, high resistance to repeated impacts, toughness at low temperature, and excellent resistance to moisture, gasoline, and many other neutral chemicals. POM Delrin 900P was dried at 80°C (176°F) for 2 h before use.

HDPE is also a semicrystalline material. The main advantages of this material include its wide processing window, excellent processability for applications requiring good stiffness and toughness, and good cold temperature impact properties. The extensive knowledge available regarding the process-structure-property relationships for the material helps in understanding the thermomechanical history experienced by the material and its effect on the development of microstructure and property of the molded product. HDPE Sclair 2714 was dried at 65°C (149°F) for 2 h before use.

Polycarbonate is an amorphous material with excellent and very consistent flow properties, very low level of impurities, and state-of-the-art demolding performance. It is the material of choice for manufacture of CD and DVD

products. PC disk properties include low birefringence over the whole play length, low disk staining, and excellent pit reproducibility. The PC CALIBRE 1080 DVD resin was dried at 120°C for 4 h before processing.

Machine and Data Acquisition System

The plunger injection system, with separate screw melting, metering, and injection units, was adopted widely by machine manufacturers, to achieve the metering accuracy and homogeneity required for the very small quantities of melt used in the micromolding process. The Battenfeld Microsystem 50 has been used by various researchers for μ IM research [1, 3–5, 8, 9]. The machine maximum clamping force, injection speed, and injection volume were 50 kN, 760 mm/s, and 1100 mm³, respectively. As shown in Fig. 1, a 14-mm diameter extrusion screw, mounted at an angle of 45° to the injection axis, feeds into the metering unit for accurately preparing a dose of material against the preset volume. The metering plunger delivers the shot volume to the injection barrel, after the set volume has been achieved. The injection plunger pushes the melt into the mold, and a holding pressure may be applied by a slight forward movement of the injection plunger.

The diameters of small injection plungers range from 4.89, 4.94, to 4.96 mm. According to Pirskanen et al. [3], the diameter of the injection plunger has an effect on the replication quality. However, a consistent diameter of 4.89 mm was used for all experiments in this study.

The cam mechanism, which drives the injection plunger during filling and packing, has not received sufficient attention in the literature, despite its importance in calculating the metering size and creating a viable process. The eccentric plate cam installed on the Battenfeld machine is used to translate circular movement to a smooth reciprocating (back and forth) motion of the plunger. A displacement diagram, which relates angular position of the cam to the linear displacement of the plunger, is displayed in Fig. 2. Two regions in the cam

FIG. 1. Sensor installation positions on the injection unit of the Battenfeld Microsystem 50.

FIG. 2. Plunger displacement versus cam rotation angle.

profile, the injection ascent and the holding ascent, define the two linear relationships between cam rotation angle and the plunger displacement, corresponding to the filling and holding stages of the process. The melt volume for this mechanical switchover, during which the plunger decelerates from injection velocity to packing velocity, amounts to only 2 mm³. The packing stage is achieved within the relatively smooth section of the cam profile, under the control of the packing velocity profile.

A data acquisition system was designed for process monitoring and data recording. Figure 1 displays the suite of sensors installed on the machine. The thermocouples installed on the melt heater and in the mold plate were HASCO (Ludenscheid, Germany) Z1295 type 1 and type 3, respectively. Three thermocouples were installed on heaters distributed on the extruder, distributor, and barrel, for controlling the melt temperature. In this study, the temperature setting at the injection barrel was regarded as the melt temperature, and the melt temperature was assumed to be uniform. The thermocouples in the mold were installed at the interface between the mold insert and the die, and the mold temperature was found to be constant at the setpoints. The injection pressure sensor and pressure sensor in the runner system were KISTLER 9204B and KISTLER 6183, respectively. The voltage signals representing the cam rotation angle were converted into plunger displacement according to two equations provided by Battenfeld, corresponding to injection ascent and holding ascent, as shown in Fig. 2. The dynamic process data of injection pressure, runner pressure, and plunger position at different processing conditions were recorded and studied. In view of the restrictions of available space, no sensors were placed inside the cavity in this study. National Instruments DAQ card PCI-6052E and LabVIEW 7.0 software were used as the hardware and

software, respectively. The CPU of the computer was 2.53 GHz and memory was 1 GB. The true data sampling rate was found to be restricted by the execution time of the LabVIEW program. The maximum achievable sampling rate was at 5 ms, even when the sampling rate was set at any value below 5 ms.

Mold Insert and Part Geometry

The Battenfeld “master mold” concept and a square plate insert of simple geometry were used in the study, as shown in Fig. 3a. Figure 3b displays a three-dimensional view of the final molding, modeled with a CAD software. The final molding consisted of two parts at each end and a runner system, including a remaining sprue, a gap ring, two blind runners, and two branch runners connected with two gates. Figure 3c displays a side view of the whole molding.

The thickness of the remaining sprue after molding depends on the plunger stroke during the packing stage, ranging from 0.1 mm, the minimum allowed to protect the mold insert, to 0.7 mm, when both injection speed and packing velocity were set to low levels. The volume of the whole molding with 0.99 mm thickness of the remaining sprue and 0.11 mm thickness of the gap ring is 148 mm^3 , according to the modeling software. Figure 3d displays detailed dimensions of a molded part, which has a volume and surface area of around 18 mm^3 and 112 mm^2 , respectively. Thus, the ratio of surface area to volume and the ratio of part weight to the whole shot weight (including runner system) were around 6 and 24%, respectively.

FIG. 3. (a) Image of the mold insert and a final molding; (b) 3D view of the whole molding; (c) side view of the whole molding; and (d) 3D dimensions of a molded part.

FIG. 4. Filling pattern images of short-shot trials.

Process Characterization

Short-shot trials were performed to study the filling pattern for various process conditions, including both high and low levels of mold temperature, melt temperature, and injection speed. Filling patterns similar to those shown in Fig. 4 were observed. The features of the filling pattern could be summarized as follows. The runner system was first filled. Flow hesitation occurred at the $110\text{-}\mu\text{m}$ thickness gap between the nozzle end surface and the movable mold plate. During the early stage of the cavity filling, the flow was radial and the melt front circular, where a biaxial orientation would be expected. As the melt front advanced away from the gate, the front shape became almost flat in the middle and curved at the edge. This pattern was similar to that reported for polymer flow in CIM process [10, 11]. Melt flow was well balanced in both the runner system and the two cavities. The gap ring proceeded at the same time as cavity filling.

Figure 5a displays trace curves of injection pressure, runner pressure, and plunger position, recorded for a single molding cycle for Case 1 of POM experiments, in which the injection speed, packing velocity, and mold temperature were set at 150 mm/s, 1 mm/s, and 70°C , respectively. The injection plunger traveled with almost

FIG. 5. (a) Process data of one molding cycle (POM Case 1); (b) process data of cavity filling including five substages (1: first filling, 2: first static, 3: second filling, 4: second static, and 5: third filling).

constant speed at around 150 mm/s, equal to the set injection speed. The lower injection pressure before melt entrance into the cavity represented the injection pressure required for pushing the melt to reach the set injection speed. The injection pressure and runner pressure reached their highest values almost simultaneously. Then, the runner pressure decreased, monotonically with variable slope, while the injection pressure reached its second peak during the packing stage. To reveal the patterns of cavity filling and packing in detail, the time scale was expanded to exhibit changes at the millisecond scale level, as shown in Fig. 5b. As indicated earlier, Fig. 5 was obtained at the highest sampling rate obtainable with the LABVIEW data acquisition system used. The rapid rise in both injection pressure and runner pressure probably reflected arrival of the melt at the blind runner and its entry into the cavity, respectively. This explained the small time difference between the first peak of injection pressure and the peak of the runner pressure.

It would be reasonable to correlate the plunger displacement and velocity with cavity filling progress and flow rate. The sudden change in the slope of the injection pressure and the jump in injection pressure at around 8-mm plunger position, as shown in Fig. 5b, indicated that the melt starts to enter the runner system, when the plunger position reached slightly more than 8 mm. How-

ever, filling progress could not be calculated simply based on the melt volume left in the barrel, after the melt entered the mold insert. This was manifested by the observation that the metering size required to fill the mold insert was 176 mm³, which was 19% higher than the combined volumes of the molding with a 0.99 mm thickness of the remaining sprue, which was around 148 mm³ as shown in Fig. 3c. Obviously, this was due to the variation of specific volume with pressure and temperature.

It was found that a stable switchover position of plunger could only be obtained at around 0.8 mm, which was slightly after the mechanical switchover position according to cam structure, 1.0 mm. A stable switchover position was an important indicator that the machine was under control. Therefore, the whole mold insert could be regarded as filled when the plunger has moved from 9 to 0.8 mm in the barrel. Then, it was necessary to establish the plunger position when the melt starts to fill the two cavities. As shown in Fig. 3, there are totally four runners, two "flow runners" lead to two cavities and two "blind runners" that have closed ends. Each flow runner was around twice as long as the blind runner. As shown in Fig. 5b, the runner pressure sensor started to register pressure of 26.5 MPa at 0.495 s, when the plunger position was at 4.7 mm, indicating that the cavity filling did not start yet, considering the volume left in the barrel and the low pressure in the runner system. The injection pressure reached its first peak, due to the sudden decrease in flow cross section, as the two blind runners were completely filled with melt. The next runner pressure and plunger position data acquired 5 ms later at 0.500 s are 82.5 MPa and 2.1 mm, respectively. Both the jump in the runner pressure and the plunger position indicated that the cavity filling started when the plunger was between 2.1 and 4.7 mm, during which the melt passes through the narrowest cross section at the gate. However, the exact position remains unclear because of the limitation of data sampling rate. Further efforts were made to estimate the plunger position at the start of cavity filling from the last filled volume of two cavities and the gap ring. This volume was calculated at around 45 mm³ using a 3D modeling software. Thus, it was assumed that the melt volume in the injection barrel in front of the switchover position (0.8 mm) was equal to the melt volume required to fill the two cavities and the gap ring, that is, 45 mm³. Moreover, it was estimated that the plunger position to start cavity filling was at 3.1 mm. Considering the effects of pressure in the barrel and runner system during cavity filling, the errors of the above estimated values should be within 19%.

The plunger movement from 3.1 to the 0.8 mm in 0.035 s was divided into five substages, which consisted of three filling substages and two static stages, as shown in Fig. 5b. The pattern of plunger movement indicates that the flow rate during filling of the two cavities and the rest of the mold insert was not constant, as shown in Fig. 6.

FIG. 6. Estimated percent flow rate versus percent shot volume during the filling stage of the whole molding.

The cavity pressure was not measured in this study, because of the restricted space available for such measurement. However, both Whiteside et al. [5] and Kuek and Angstadt [12] found that, for similar gate dimensions at lower mold temperature, the cavity pressure increased for ~ 100 ms before starting to decrease due to gate freezing. In this study, the CPPs for the packing stage are defined at 0.2 s, when packing was still in effect.

Based on the above observations, the main features of the μ IM process considered in this work can be described as follows. Initially, the plunger travels at the set injection speed, until the start of cavity filling, when the plunger position reaches 3.1 mm. The plunger speed varies with the progression of cavity filling. The cavity filling is completed and the packing stage starts when the plunger reaches the switchover position. In the system under consideration, the plunger movement during the cavity filling stage consists of a series of filling and quasi-static substages. The number of filling substages was repeatable for a specific material under the same machine setpoints, whereas the number of static substages varied randomly in a narrow range. The cavity pressure rise during packing could be maintained for only 100 ms, because of the fast freezing of the gate.

Experimental Design

The DOE method was used to investigate the effects of machine variables on the CPPs. The machine variables selected were injection speed (V_i), packing velocity (V_p), mold temperature (T_m), and melt temperature (T_b), which are the key molding machine settings for the μ IM process [2]. HDPE exhibited good processability, thus, a two-level four-factor half fractional design with eight experiments was selected. Three additional cases were included for verifying statistical analysis results and also for evaluating the mechanical behavior of HDPE at very high injection speeds. The melt temperature was not considered for POM to avoid thermal degradation. Therefore, a two-level

three-factor full factorial design was chosen. PC exhibited an even narrower processing window. Therefore, a two-level two-factor full factorial design was used. Table 1 displays the DOE experimental matrix for the three materials. The statistical analysis was performed using the Design-Expert 6.0 analysis software. The injection speed high limit was only tried in additional runs for HDPE and POM due to leakage through the back of the plunger. Every process condition was repeated twice to confirm the repeatability of process conditions. The repeatability of the process was found to be good. The experiments were conducted in a randomized sequence.

The CPPs of the filling and packing stages were defined to describe the process conditions and flow behavior during these stages. The CPPs for the cavity filling stage included peak injection pressure, average injection pressure, and average plunger velocity, all during filling. For the packing stage, plunger stroke at 0.2 s packing, total plunger stroke during packing, and average injection pressure during 0.2 s packing were the CPPs extracted from the process data recorded for plunger position and injection pressure. The metering size, a process parameter in other studies [1, 3], was normally optimized for each set of machine variables, to have a uniform switchover position for each process condition. In this study, it was also treated as a CPP.

In this study, the holding pressure option was selected as “Start Inj. Press.–Specific.” Thus, the process would be switched over to the packing stage, when runner

TABLE 1. Experimental matrix for POM, HDPE, and PC.

DOE	Cases	V_i (mm/s)	V_p (mm/s)	T_m (°C)	T_b (°C)
		A	B	C	D
POM	Case 1	150	1	70	205
	Case 2	150	6	70	205
	Case 3	380	6	70	205
	Case 4	380	1	70	205
	Case 5	380	1	100	205
	Case 6	380	6	100	205
	Case 7	150	6	100	205
	Case 8	150	1	100	205
	Case 9	265	3.5	85	205
	Case 10	650	6	100	205
HDPE	Case 1	380	6	70	230
	Case 2	150	1	70	230
	Case 3	380	1	35	230
	Case 4	150	6	35	230
	Case 5	380	6	35	190
	Case 6	150	1	35	190
	Case 7	380	1	70	190
	Case 8	150	6	70	190
	Case 9	265	3.5	52	210
	Case 10	650	6	35	230
PC	Case 11	650	6	70	190
	Case 1	700	N/A	75	N/A
	Case 2	350	N/A	75	N/A
	Case 3	700	N/A	110	N/A
	Case 4	350	N/A	110	N/A

FIG. 7. Typical injection pressure traces of eight process conditions.

pressure reaches a specified pressure. The metering size was obtained by trial-and-error starting from 148.1 mm^3 , which was the total volume of the molding including the remaining sprue and a gap ring, as shown in Fig. 3b. At this dosage, the final moldings were found to be short shots and the switchover to the packing stage could not occur. The metering size was then increased at an increment of 3 mm^3 to obtain full parts first and then to have a switchover position within 1.1 mm , but the switchover position could only stabilize at around 0.8 mm . Fine tuning of metering size was sometimes required to stabilize the switchover position. The accuracy of metering size was very important to obtain high repeatability and reproducibility of the molding process.

The volume average plunger velocity was defined using the plunger velocity versus shot volume fraction profile as the sum of products of velocity of each filling substage and the corresponding fraction of the shot volume, relative to the total melt volume of the two cavities and gap ring, as shown in Eq. 1. The calculation was started from the last filling substage. The shot volume of the last filling substage was calculated from the difference between switchover position and start position of the last filling substage.

$$\begin{aligned} \text{VAPV} &= V_3 \times P_3 + V_2 \times P_2 + V_1 \times P_1; \\ P_1 &= 1 - P_2 - P_3, \end{aligned} \quad (1)$$

where V_1 , P_1 , V_2 , P_2 , V_3 , and P_3 are the velocities (V_i) and shot volume fractions (P_i) of the series of filling substages. The velocities in each filling substages were assumed to be constant. The static substages were excluded from the calculation of average plunger velocity during filling. Minor modifications may be needed to adapt Eq. 1 to the cases with more or less filling substages. At least two filling substages were found for all process conditions in this study. The main limitation related to the estimation of plunger velocity arose from the estimation of the velocity of the first filling substage,

which was only a part of the sampling period as shown in Fig. 5b.

Process data for five molding cycles were recorded after the machine reached steady state, which usually took about 5–10 min for each process condition. Process stabilization was identified by monitoring the switchover position, peak runner pressure, and peak injection pressure on the machine screen. An unstable process condition was often caused by unexpected accumulation of leaked material behind the plunger at high injection speed. Regular checking and clean-up were needed, when the injection speed was set to a high level.

RESULTS AND DISCUSSION

Polyoxymethylene

Typical injection pressure trace data of a whole molding cycle, for each process condition of POM experiments, are presented in Fig. 7. These curves exhibited different characteristics corresponding to the machine settings. Higher peak injection pressure during the filling stage was observed, when higher injection speeds were used, that is, Cases 3, 4, 5, and 6. Higher injection pressure in packing stage was observed, when higher packing velocity was used, that is, Cases 2, 3, 6, and 7.

Figure 8 displays the mean values and standard deviations of peak injection pressure, average injection pressure, average plunger velocity of the filling stage, and metering size for each process condition of the POM experiments. According to the sampling rates used, it is seen that the plunger undergoes sequences of moving and static steps. We refer to these as moving or static substages. The estimated average plunger velocities during filling ranged from 374 to 697 mm/s, which were approximately twice as high as the injection speed settings, due to the exclusion of the static substages. The average plunger velocities were generally higher for high injection speed settings than for low injection speed settings. At the same injection speed setting, the average plunger

FIG. 8. Characteristics process parameters of filling stages for each process condition of POM experiments.

velocities at high mold temperature were higher than those for low mold temperature. This was probably due to the low viscosity of the material at high mold temperature.

The peak injection pressure and average injection pressure during filling followed approximately a similar pattern, in which the high values were associated with high injection speed and low mold temperature. The injection pressure was controlled to permit reaching the injection speed setting, so it was directly related to the flow resistance or the viscosity of the material.

The metering size decreased with increasing mold temperature and injection speed, and the highest metering size was required for the case with low injection speed and low mold temperature. This suggested that the metering size was mainly determined by the average material temperature, which was attributed to both shear rate and heat transfer between mold surfaces and melt. Higher metering size indicated that more materials were injected into the cavity during the filling stage.

Figure 9 displays the standardized effects of the machine variables and their interactions on the CPPs of filling stage. Injection speed was the major positive factor in affecting average plunger velocity, peak injection pressure, and average injection pressure, while it was the major negative factor in affecting metering size. An increase in injection speed resulted in an increase in all CPPs of filling stage, except the metering size which decreased. The mold temperature was another factor that had considerable effects on the CPPs. An increase in mold temperature resulted in an increase in average plunger velocity, but decreases in the other three parameters. Injection speed/mold temperature interaction had noticeable effects, which were similar to that of the mold temperature but to a smaller extent. The other interactions of injection speed/packing velocity and packing velocity/mold temperature were not discussed because of process data variability.

FIG. 9. Standardized effects on the CPPs of filling stage for POM experiments.

FIG. 10. Characteristics process parameters of packing stage for each process condition of POM experiments.

Figure 10 displays plunger stroke at 0.2 s packing, total plunger stroke, and average injection pressure during 0.2 s packing for each process condition of POM. The plunger stroke at 0.2 s of packing, representing the effective compensation for material shrinkage before gate freezing, was generally higher at high injection speed than for low injection speed. The total plunger stroke during packing, calculated from the difference between switch-over position and last position of the plunger, varied in a narrow range, for the process conditions of high injection speed or high packing velocity. The minimum total plunger strokes during packing were found at low injection speed and low packing velocity, that is, Cases 1 and 8. The average injection pressure during 0.2 s of packing could be regarded as an extension of the injection pressure during filling, as they approximately followed a similar pattern.

Figure 11 displays the standardized effects of the machine variables and their interactions on the CPPs of the packing stage. Injection speed was the major positive factor in affecting plunger stroke at 0.2 s packing and

FIG. 11. Standardized effects on the CPPs of packing stage for POM experiments.

average injection pressure during 0.2 s packing, but was the minor positive factor in affecting total plunger stroke during packing. The packing velocity was the major positive factor affecting the total plunger stroke during packing. The mold temperature had a considerable negative effect on the average injection pressure during 0.2 s packing. This was probably due to the decrease of the material viscosity in the runner system and cavity with increasing mold temperature.

The coefficients of variation (COVs) of the six CPPs defined for both the filling and packing stages are presented in Fig. 12, to evaluate the process repeatability. Overall, the process conditions associated with higher injection speed exhibited better repeatability than those of low injection speed. The peak injection pressure during filling and average injection pressure during 0.2 s packing had better repeatability than other CPPs. Plunger stroke at 0.2 s packing had the highest COV at around 15%. This was probably due to the small absolute values of the plunger stroke at the 0.2 s. The COVs of other CPPs were comparable to the results reported for peak cavity pressure and cavity pressure curve integral by Whiteside et al. [5] for a 23-mg product. The COVs of the average plunger velocity, ranging from 2.43 to 11.2%, indicated the validity of both *Eq. 1* and the methodology used to describe the filling stage.

High-Density Polyethylene

Figure 13 displays average plunger velocity, peak injection pressure, and average injection pressure during the filling stage, and metering sizes for each process condition of HDPE experiments. The estimated average plunger velocities in filling ranged from 401 mm/s, at the low injection speed setting, to 965 mm/s, at the extreme high injection speed setting. In general, at the same injection speed setting and comparable mold temperature setting, the injection pressure of HDPE was lower than for POM, but the average plunger velocity was higher than

FIG. 12. Coefficients of variation of the CPPs for each process condition of POM experiments.

FIG. 13. Characteristics process parameters of filling stage for each process condition of HDPE experiments.

for POM. This was probably because the HDPE (Sclair 2704) has a much higher melt flow index. The average plunger velocity and the peak injection pressure, during filling, generally followed similar patterns, which were mainly determined by the injection speed setting. These patterns were maintained even when extreme high injection speeds were used (compare Cases 3, 4, and 10, also Cases 7, 8, and 11). However, at the same extreme high injection speed setting, when both mold and melt temperature were changed, a more complex pattern was observed. It is difficult to explain the observed differences, in the absence of more detailed experimental data. However, viscous dissipation and complex flow behavior (e.g., jetting in Case 11) should be important factors.

At higher melt temperature from Case 1 to Case 4, the average injection pressure during filling varied in a relatively narrow range with injection speed at 150 and 380 mm/s. As a result, analysis cannot be made with high confidence. The patterns of peak injection pressure and average injection pressure during filling for HDPE were not similar to those for POM experiments. The lowest metering sizes were required for Cases 1 and 3, which had high injection speed and high melt temperature. The highest metering sizes were required for Case 6, which had low settings of injection speed and mold and melt temperatures.

Figure 14 displays the standardized effects of the machine variables and their interactions on the CPPs for the filling stage. Injection speed was the major positive factor in affecting peak injection pressure and average plunger velocity and was also a minor negative factor in affecting metering size. Melt temperature was the major negative factor in affecting average injection pressure and metering size and was also a minor positive factor in affecting average plunger velocity. Mold temperature had noticeable negative effects on peak injection pressure and metering size. As the DOE design of HDPE was a resolution IV design, the interaction of two machine variables was always confounded with interaction of the other two machine variables. High-resolution design was needed to make confident conclusions with regard to the interactions between two machine variables. The above analysis

FIG. 14. Standardized effects on the CPPs of filling stage for HDPE experiments.

results were confirmed with the additional experiments of Cases 9 and 10, but large discrepancies appeared in Case 11.

Figure 15 displays the CPPs for the packing stage for each process condition of HDPE experiments. The plunger stroke at 0.2 s packing and average injection pressure during 0.2 s packing approximately followed a similar pattern, which was mainly determined by the injection speed. The lowest total plunger strokes were found for Cases 2 and 6, which had the low injection speed and low packing velocity. At the extreme high injection speed of Cases 10 and 11, the plunger reached the end of its stroke within 0.2 s of the packing stage, so the plunger stroke at 0.2 s packing was equal to total plunger stroke.

Figure 16 displays the standardized effects of machine variables and their interactions on the CPPs of the packing stage for HDPE experiments. Injection speed was the major factor in affecting plunger stroke at 0.2 s packing and average injection pressure during 0.2 s packing, and it was also a minor factor in affecting total plunger stroke. Packing velocity was the major factor in affecting the

FIG. 15. Characteristics process parameters of packing stage for each process condition of HDPE experiments.

FIG. 16. Standardized effects on the CPPs of packing stage for HDPE experiments.

total plunger stroke. The mold and melt temperature had similar effects on the three selected CPPs, with significant negative effects on average injection pressure during 0.2 s packing and minor positive effects on the plunger strokes at 0.2 s packing. The interaction injection speed/packing velocity, which was confounded with the interaction mold temperature/melt temperature, had a significant negative effect on total plunger stroke. As both the injection speed and the packing velocity had more significant effects than mold and melt temperatures, the injection speed/packing velocity interaction should also be more significant [1, 13]. It could therefore be concluded with a high confidence level that it was the injection speed/packing velocity interaction which had the significant negative effect on total plunger stroke during packing.

The COVs of the six CPPs are presented in Fig. 17 to evaluate the process repeatability. In contrast with the POM experiments, the process conditions of low injection speed setting exhibited better repeatability than those of higher injection speed. In terms of CPP repeatability, the

FIG. 17. Coefficients of variation of the CPPs for each process condition of HDPE experiments.

FIG. 18. Characteristics process parameters of filling stage for each process condition of PC experiments.

peak injection pressure during filling and average injection pressure during 0.2 s packing had the best repeatability, compared with other CPPs, as in the case of POM experiments. Again, the plunger stroke at 0.2 s packing had the highest COV at around 20%.

Polycarbonate

When the injection speed was set at 700 mm/s in the PC experiments, the switchover position could only stabilize at 0.5 or 0.6 mm, rather than 0.8 mm as in the case of lower injection speed setting. This was probably caused by the high inertia of the plunger at the extreme high injection speed. A higher metering size may be required for the later switchover position.

Figure 18 displays average plunger velocity, peak injection pressure, and average injection pressure for the filling stages, and metering size for each process condition of PC experiments. The average plunger velocities were generally higher for high injection speed settings than for low injection speed settings. However, at the

FIG. 19. Standardized effects on the CPPs of filling stage for PC experiments.

FIG. 20. Characteristics process parameters of packing stage for each process condition of PC experiments.

same injection speed setting, the average plunger velocities at high mold temperature tended to be lower than for low mold temperature. This was different from both POM and HDPE experiments, where the mold temperature was a positive factor in affecting the average plunger velocity. Both peak injection pressure and average injection pressure varied in a narrow range. The peak injection pressure tended to be higher at high mold temperature, whereas the average injection pressure tended to be lower at higher mold temperature. The trend of peak injection pressure could be responsible for the variation of average plunger velocity with mold temperature. These variations were probably related to the machine control mechanism employed in the μ IM machine used in this study.

Figure 19 displays the standardized effects of the machine variables and their interactions on the CPPs during the filling stage for PC experiments. Injection speed was the most significant factor in affecting peak injection pressure, average plunger velocity, and metering size. The mold temperature was the most significant negative factor

FIG. 21. Standardized effects on the CPPs of packing stage for PC experiments.

FIG. 22. Coefficients of variation of the CPPs for each process condition of PC experiments.

in affecting average injection pressure during filling and the minor negative factor in affecting average plunger velocity.

Figure 20 displays plunger stroke at 0.2 s packing, total plunger stroke, and average injection pressure during 0.2 s packing for each process condition for PC. The average injection pressure during 0.2 s packing mainly depended on injection speed setting. According to Fig. 21, injection speed was the dominant factor in affecting all three CPPs in the packing stage of PC experiments, most likely because of the effects of injection speed on temperature and pressure at the beginning of the packing stage.

The COVs of the six CPPs are presented in Fig. 22 to evaluate the process repeatability. PC Case 3, with high injection speed and high mold temperature, was found to have the highest repeatability. In terms of CPPs, again the peak injection pressure during filling and average injection pressure during 0.2 s packing had the best repeatability compared with other CPPs. The average plunger velocity during filling was much noisier than other CPPs, probably because of the high injection speed setting.

CONCLUSIONS

The processing conditions during the cavity filling stage, in a plunger μ IM system, were estimated by using short-shot trials and by analysis of data tracing the evolution of injection pressure, runner pressure, and plunger position, at the millisecond time scale. The cavity filling and packing stages were described by six CPPs derived from experimental data and the corresponding optimized metering size. The use of CPPs instead of machine settings provides a more viable approach to achieve process simulation or process and product optimization and control, consistent with the actual thermomechanical history experienced by the material. This is especially important, because this work confirms that the actual processing

conditions experienced by different materials (e.g., temperature, velocity, pressure, etc.) are not readily identified by the machine settings. According to statistical analysis, injection speed setting is the most significant factor influencing the CPPs for all three materials (POM, HDPE, and PC), while the effects of mold and melt temperature depend on the material and the specific CPP under consideration. The metering size was mainly determined by the average material temperature, which was attributed to both shear rate and heat transfer between mold surfaces and the melt. The process conditions tend to exhibit better repeatability at higher injection speed than at lower injection speed for POM, whereas the opposite was found for HDPE. The peak injection pressure during filling and average injection pressure during 0.2 s packing have better repeatability than other CPPs for all three materials studied, while the plunger stroke at 0.2 s packing and the average plunger velocity during filling exhibited the highest COVs.

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