A COMPARISON OF VELOCITY TO PRESSURE TRANSFER CONTROL STRATEGIES FOR INJECTION MOLDING

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Abstract

Injection molders commonly use a ram position setting to control switchover. As in-mold sensors have become more widespread, using them to control switchover ensures more consistent part quality than machine-based control.

Herein we explore several control strategies applied to an array of different mold configurations and materials. We evaluate each method's ability to minimize in-cavity variation when material viscosity changes. The results provide the molder with information for choosing a control strategy appropriate to each application.

Introduction

What is the "best" way to control velocity to pressure switchover in injection molding?

Several studies exist that compare switchover methods [1,2,3,4,5]. However these studies tended to be run under near steady state conditions with a single lot of each material or a change to regrind with a very limited viscosity shift. The results show only minor variation that is difficult to extrapolate. Furthermore most of the results to date have been for ASTM style test-bars or single, easy-to-fill molds. Here we expand on the subject by comparing the behavior of different control strategies with both thin-wall and thick-wall parts. For each part type we used four different materials.

As Kazmer explains [6] there are three major causes of variation in the process: machinery, human operators and raw material properties. The latter is caused by lot-to-lot variation in material and can create substantial change inside the cavity using only machine controls. This in turn affects the quality of the parts [7].

We begin with the following premises:

- The part quality is determined by four plastics variables as delivered inside the cavity: melt temperature, flow, pressure and cooling [8].
- Pressure and flow as measured with in-cavity sensors correlate to various part qualities [7,9,10]
- A good (or "best") process should maintain the in-cavity plastic conditions during normal variation in material viscosity.
- The process control should be automated, requiring no process adjustments by the operator.

In this study, we created material viscosity variations that are often seen in actual production molding with changes in material lot delivered. The machine was repeatable in speed and pressure control and we kept melt temperature, mold surface temperature and cooling time constant. Once a stable process was running we changed the material and observed the results inside the cavity. We measured flow (from time) and cavity pressure. We also measured part weights. The cavity pressure integral correlates reasonably well with measured part weight.

Using this technique we can judge how well each switchover method controls in-cavity pressures with the variation in material that can be expected in production.

Materials

We selected the materials in Table 1 and molded parts using the manufacturers' suggested setup parameters or, if not available, industry guidelines.

Table 1: Materials

	Semi-Crystalline		Amorphous	
Material	Nylon	PBT	PC	Acrylic
Manufacturer	DSM	LG	Idemitsu	LG
Trade Name	Akulon	Lutrel	Tarflon	PMMA
Low Viscosity	K222D	GP2300	IR1900	1F870S
High Viscosity	K222D‡	GP2300‡	IR2200	1H830
Viscosity Shift	~ 6%	~ 5%	11-20%	20-40%
Barrel Temp.	246 °C	282 °C	343 °C	204 °C
Mold Surface† (thick/thin °C)	44 / 40	68 / 64	76 / 69	71 / 67

We chose materials that are in common use throughout the injection molding industry. We chose the nylon because it flows easily but does not pack significantly. The PBT is 30% glass filled and was rather difficult to process. The polycarbonate (PC) has a pressure sensitive viscosity and the acrylic is highly sensitive to shear. Thus we have a broad selection of materials with different behaviors. All were dried per the manufacturer's recommendations before processing.

‡ We were not able to obtain pairs of semi-crystalline materials with a specific viscosity shift. Since we did not want to use different compounds with different cooling rates, we tried to break the molecular chains by first processing the nylon and PBT wet, grinding the parts and using the regrind for the lower viscosity material. In the case of PBT, we blended partial regrind. We did not get quite as dramatic a shift in viscosity as we would wish for demonstrating lot-to-lot variation but it did show some.

† We sampled parts only when the mold surface temperature was within approximately ±1 °C of the listed mold temperature (measured by in-cavity sensors). Note that the mold surface runs hotter with the thicker parts.

The Mold, Parts and Cavity Sensors

The mold used in this study is a two cavity cold runner mold. It has inserts on the A (fixed) half that let us quickly switch between a thick wall and thin wall part. The thick wall part is 4 mm thick and the thin wall is 0.75 mm thick. The two parts are formed diagonally across the center of the mold as shown in Figure 1.

We evaluated data from 1 of the 2 cavities for this study. We saved data for both. Figure 2 shows the sensor locations and part dimensions. All cavity pressure sensors were calibrated in our lab to current NIST standards.

Machine

We used the Arburg 320A *Allrounder*, 55 ton electric in RJG's lab for this study. This machine reacts to external switchover signals in ~10 mS. It drops injection pressure (developed during filling) from peak to hold pressure in ~ 60 mS. The machine provided an analog voltage output signal for injection pressure from which the viscosity changes were calculated.

We measured and controlled switchover position using a stroke and velocity encoder with a resolution of 0.03 mm (converted to volume in the calculations).

Measurements and Calculations

We gathered and stored all of the data using RJG's *eDART*™ system. With the number of sensors attached to each Lynx port, the eDART sampled data at 500 samples per second. The calculations in the *eDART* assume that start of filling begins when the screw reaches the shot size after moving forward from its decompress position. We use the following in the analysis:

Effective Viscosity: This is the area under the injection pressure curve from the start of filling until a selected volume has been injected into the cavity. Each process is evaluated relative to the percent change in the effective viscosity.

Injection Integral: The area under the pressure curve from the start of filling until the end of hold. Typically the cavity pressure injection integral correlates with part weight. Correlations from this study are shown in Figures 3 and 4, though the resolution accounts for some scatter.

Peaks: The maximum value of pressure. Peaks are the simplest computation for detecting shorts or flash in parts. Peaks sometimes correlate to dimensions in thin-wall parts.

Fill and Pack Time: This is the time from the start of filling until a pressure curve reaches 98% of its peak. We have found through experience that this portion of the pressure curve correlates to texture and gloss in parts.

Processes

The goal of this study is to evaluate how different switchover techniques control in-cavity variation when subjected to typical changes in material viscosity. We designate each technique as a "process" because each one involves proper setups of speeds, positions, switchover value and sensor selected. The processes developed are all DECOUPLED MOLDING^{SM} type processes [11].

The *eDART* was set up to send the switchover signal to the press on a rise in temperature or on a pressure threshold or screw position. The time from the recognition of the threshold until the press receives the signal is about 5 mS. The temperature transfer control allows a delay after the rise in temperature before sending the switchover. This delay is controlled by adding a volume of screw travel from the time the temperature rises.

Decoupled I (D1)

Fill the part at a single speed until the part is full as detected by a sudden rise in end of cavity pressure then transfer to hold pressure to maintain cavity pressure. Slower speeds must be used to avoid large overshoots in pressure after switchover. Some of the process robustness can be lost at slower speeds because of the lower shear rates involved [12]

Decoupled II (D2)

Fill the part to about 95% full as fast as the material and part quality will allow. Then transfer to hold. The hold pressure packs the part, adds material for shrinkage and prevents discharge until the gate is sealed or the part is solid.

Decoupled III (D3)

Fill the part to about 95% full as fast as the material and part quality will allow. Then use the machine's velocity control to set up a second speed profile to pack the part until transfer, usually on cavity pressure. Set the pack speed for minimal overshoot with hold turned off. Then add hold pressure at a level that does not increase pressure in the part nor discharges material. This is a "standard" Decoupled III process. Variations are required for certain part characteristics.

Process Regulation (PREG)

"Process Regulation" is not a transfer method. It is a n optional feature of the Arburg press that adjusts the hold pressure after transfer to try to replicate a reference pressure curve for a cavity sensor. We used the sensor near the gate ("post gate", PST) to provide the signal to

the process regulation. End of cavity could be used but we thought it too distant (in pressure drop) to regulate.

Like decoupled II, process regulation transfers before the part is full. In thin-wall parts we used the post gate pressure to transfer. In thick wall the post gate pressures are so low during fill that we used volume as in **D2 VOL**.

Table 2: Summary of Processes

Process Code	Setup	Transfer
D1 EOC	Single slow speed fills & packs; hold cavity peak.	Cavity full: Rise in end of cavity pr.
D2 PST	Single fast speed to 95% full then hold pressure to maintain cavity pressures after transfer.	Gate sensor pr.
D2 TE		T. at EOC+ vol.
D2 TM		T. at MID+ vol.
D2 VOL		Screw position
D3 EOC	Fast fill speed to press position then slow speed until transfer. Hold set to maintain and not overshoot cavity pr.	End of cavity pr.
D3 PST		Post gate cavity pr.
D3 TE		T. at EOC+ vol.
D3 TM		T. at MID+ vol.
D3 VOL		Screw position
PREG	Single fast speed to 95% Hold controlled by press	PST (thin), volume (thick)

Procedure of Experiment

Combining all of the above forms the experiment. There are eight different molding conditions: a thin-wall and a thick wall part made with four different materials each. For each of the eight conditions, we set up as many control techniques as we could while running the lower viscosity material. We sampled three parts for each process. We also recorded the setup conditions for each process setup. Then we switched to the higher viscosity material. After the material had stabilized at the higher viscosity we restored each of the process setups, and again recorded data and sampled three parts.

Tables 3 and 4 present all of the results in summary form. In them we document which processes had the least variation in in-cavity variables relative to the average viscosity change introduced for each. Since we had different viscosity variations with different materials, we analyzed the data by dividing the change in each in-cavity pressure parameter by the average change in effective viscosity. Thus a value in the table for peak such as "0.75" would indicate that with a 10% viscosity increase you could expect a change of 10% x 0.75 = 7.5% in the parameter measured.

Discussion of Process Capabilities

D1 EOC (transfer at cavity full) is reasonably capable in thick wall parts, especially semi-crystalline parts that flow easily and do not require controlled packing. It also is capable of control of the early part of the process (fill & pack time and post gate peak) if the material does not compress greatly (as in the Nylon). However, as more compressible materials are used (lower rows on chart), the pressures built up during filling drive higher peak pressures at transfer followed by discharge through the gate. In thin wall molding, the D1 process can control fill and pack times and peaks to some extent. But the second cavity becomes short because of the sudden reaction to the first filling and no subsequent pack phase. In thin-wall, high pressure situations we were not able to set up a D1 EOC process. At high speeds they created extremely high peaks (and flash). At lower speeds they could not fill the parts.

D2 processes controlled by screw position (D2 VOL) are workable only with fairly easy to process parts such as the nylon. In more compressible or harder to flow conditions **D2 VOL** allows much larger changes in cavity pressures than in-cavity control. Using a temperature sensor for transfer (**D2 TE** or **D2 TM**) improves Decoupled II processes with easier processing conditions (thick-wall or easy to flow, low compression processes).

D3 pressure controlled (**PST and EOC**) processes perform acceptably across a broad range of materials and wall thicknesses. They provide excellent control of packing, which controls peaks and integrals. These in turn provide good control of part weights and dimensions. However the D3 controls have a de-compression phase that can allow the fill and pack time to extend. This could cause a loss of the ability to pack into a texture. Using a faster pack speed can mitigate the problem at the expense of cavity pressure overshoot. Note that **D3 PST** is often impossible in thin wall, high pressure molds. This is because the dynamic pressure peak is often higher than the pressure at which the gate needs to be packed.

Process regulation appears as a viable control in a variety of conditions, though it did not score as high as the D3 processes. It has a difficult time controlling the thin wall, high pressure parts because it can only know about the pressure at the gate and hence not control the end of cavity. The technician setting up a process regulation should thoroughly understand what it will try to do and make decisions accordingly. The most important point is to know how long the cavity pressures can be controlled. The regulation must be stopped before that point or it will attempt to add or remove pressure after the cavity wall freezes off.

Conclusions

We hope that this study provides a framework for selecting appropriate switchover methods for various processes. One should be able to look at the Tables (3 and 4) and find a material and wall thickness representative of his molding process. Selecting the in-cavity conditions that are important to the part quality from the columns leads to a cell that ranks the control strategies.

Acknowledgements

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Key Words: Cavity Pressure, Cavity Temperature Switchover, Transfer, Decoupled, Viscosity

Figure 1: Parts and Runner

Figure 2: Part Dimensions and Sensor Locations

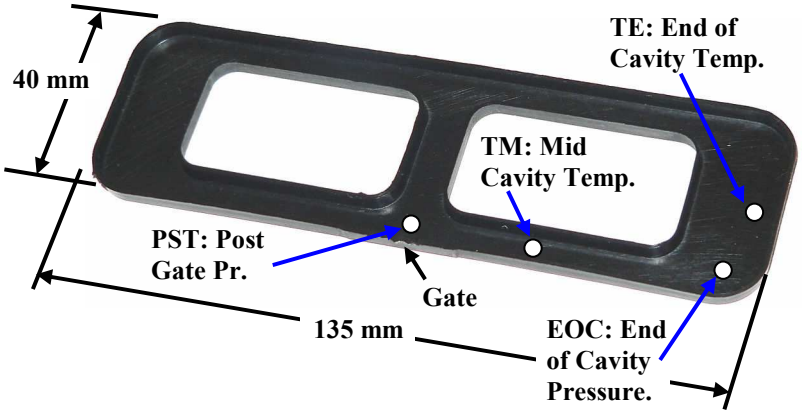
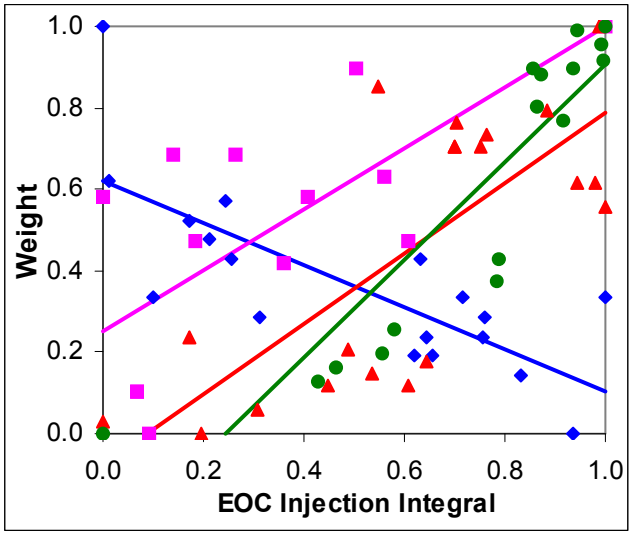
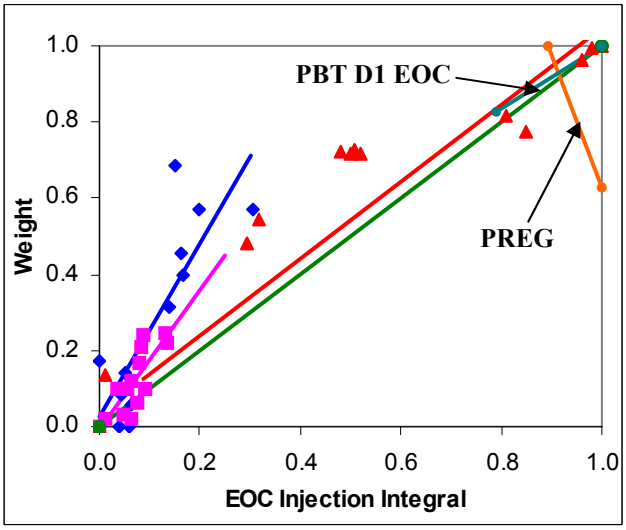


Figure 3: Correlations of Weight to End of Cavity Injection Integral - Thick Wall Parts (values normalized)



Nylon	PBT	PC	Acrylic
R = -0.75	R = 0.7	R = 0.75	R = 0.9

Figure 4: Correlations of Weight to End of Cavity Injection Integral in Thin Wall Parts (values normalized)



Nylon	PBT	PC	Acrylic
R = 0.82	R = 0.81	R = 0.96	(2 points)

Table 3 - Thin Wall (0.75 mm) Process Comparison: Ratio of Change in Value to Change in Effective Viscosity

	Fill & Pack Time	Peak Post Gate	Peak End of Cavity	Injection Integral End of Cavity
Nylon	D2 TM 0.11 PREG 0.21 D2 VOL 0.26 D2 PST 0.3	D1 EOC 0.03 D2 PST 0.04 PREG 0.13 D2 TM 0.27	PREG 0.32 D2 VOL 0.42 D3 EOC 0.85 D2 TM 0.89	D3 EOC 0.19 D2 VOL 0.29 D2 TM 0.88 D2 PST 2.03
PBT	PREG 0.12 D1 EOC 0.14 D3 EOC 0.26 D3 VOL 0.4	D2 VOL 0.12 D3 EOC 0.13 D2 TM 0.16 D2 PST 0.17	D3 EOC 0.14 D3 VOL 0.26 PREG 0.44 D1 EOC 0.81	D3 TM 1.90 D3 EOC 2.65 D2 PST 2.66 PREG 2.67
PC	D3 EOC 0.89 D3 PST 1.27 Short D3 VOL 1.87 Short PREG 4.7	D3 PST 0.81 Short D3 EOC 0.92 D3 VOL 1.1 Short PREG 2.42	D3 EOC 0.25 D3 PST 3 Short PREG 3.92 D3 VOL Short	D3 EOC 1.10 D3 PST Short D2 TM Short 4 PREG 6.89
Acrylic	PREG 0.1 Short D1 EOC 0.4 Short D3 EOC 0.6 D2 TM Short	PREG 0.10 Short D3 PST 0.10 Short D3 EOC 0.20 D1 EOC Short	D1 EOC 0.47 Short D3 EOC 0.59 D3 PST Short D2 TM Short	D3 EOC 1.45 D1 EOC Short D3 PST Short PREG Short

Table 4: Thick Wall (4 mm) Process Comparison: Ratio of Change in Value to Change in Effective Viscosity

	Fill & Pack Time	Peak Post Gate	Peak End of Cavity	Injection Integral End of Cavity
Nylon	D2 TM 0.26 D2 TE 0.38 D1 EOC 0.40 PREG 1.8	D2 TM 0.00 D1 EOC 0.00 D3 EOC 0.02 D2 PST 0.02	D2 TE 0.00 D2 PST 0.02 PREG 0.07 D2 TM 0.10	D3 EOC 0.08 D1 EOC 0.08 D3 PST 0.08 D2 TM 0.21
PBT	D1 EOC 0.04 D3 VOL 0.07 D3 EOC 0.10 PREG 0.1	D3 PST 0.18 PREG 0.36 D3 EOC 0.53 D2 VOL 0.59	D3 EOC 0.04 PREG 0.11 D2 VOL 0.13 D2 TM 0.18	D3 EOC 0.06 D3 PST 0.17 D3 VOL 0.27 D2 TM 0.34
PC	D3 VOL 0.04 D2 TE 0.07 D2 TM 0.21 D3 EOC 0.3	D3 PST 0.01 D2 TM 0.03 D3 EOC 0.07 PREG 0.10	D3 EOC 0.02 PREG 0.07 D2 TE 0.08 D3 PST 0.11	PREG 0.05 D3 PST 0.25 D3 EOC 0.25 D2 TE 0.29
Acrylic	D1 EOC 0.00 D3 VOL 0.36 D3 PST 0.40 D3 EOC 0.4	D3 EOC 0.00 D3 PST 0.04 PREG 0.12 D1 EOC 0.52	D3 EOC 0.03 PREG 0.05 D3 PST 0.06 D1 EOC 0.50	PREG 0.06 D3 PST 0.42 D3 EOC 0.42 D1 EOC 0.74