THE PROCESS CAPABILITY OF MULTI-CAVITY PRESSURE CONTROL FOR THE INJECTION MOLDING PROCESS

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ABSTRACT

Cavity pressure has been recognized as a critical process parameter for the injection molding of high quality thermoplastic parts. This interest has led to the achievement of closed loop cavity pressure control, but only at one point in the mold cavity. A system has been recently described which extends this capability to provide simultaneous control of cavity pressure at multiple locations in the mold through the addition of dynamic valves in the melt delivery system, each of which can be independently controlled to meter flow and pressure to its portion of the mold.

This paper describes the ability of the multi-cavity pressure control system to improve process capability and molded part quality. Experimental investigation has shown that the technology enables significant process flexibility to arbitrarily balance flow, move knit-lines, and control multiple part dimensions. In the presence of typical production process disturbances, moreover, closed loop multi-cavity pressure control was shown to increase the process capability index, Cp, from 0.52 for the conventional injection molding process to 1.5. After these capabilities have been discussed, several limitations of the process are described which lead to promising areas of future research.

INTRODUCTION

Injection molding of thermoplastics has emerged as the premier vehicle for delivering high quality, value added commercial products. Continued global competitiveness has increased standards for product capability and quality while requiring reduced product development time and unit cost. Despite advanced design methods and new process technologies, it is becoming apparent that the injection molding process is neither flexible nor robust enough to reliably meet these industry requirements. The lack of robustness is evidenced by the long product development cycles, excessive tooling costs, low process yields, and inferior product quality.

It is the polymer state (pressure, temperature, and morphology) which directly determine the molded part quality. As such, recent technology development has rightly focused on closing the loop between the machine parameters and the polymer conditions. If achieved, these advanced control systems would provide increased molded part consistency. However, even perfect control, i.e. the ability to profile the inlet melt temperature and pressure, will be unable to satisfy industry's increasingly stringent requirements. Due to its physical implementation, conventional injection molding is inherently a one degree of freedom process. The temperature and pressure distribution in the cavity is inextricably linked to the inlet melt conditions and the process dynamics forced by the mold geometry. As such, there is no way to simultaneously control the polymer melt at multiple locations inside the mold – there are no degrees of freedom available for adjustment (Suh).

As thermoplastic materials continue their thrust into advanced technical applications, access to only one degree of freedom will become even more constricting, prohibiting thermoplastic materials from entering many advanced applications. The risks of proving out the injection molding process for a technical application with multiple stringent requirements are too excessive. In fact, (Lassor) has testified that "we are already starting to see the migration of customers to other manufacturing processes for time-critical applications."

One method has been previously described which combines closed loop cavity pressure control with multiple degrees of freedom. This paper examines the capability of this new process to actually deliver value to the development and production of molded thermoplastic parts.

In theory, the closed loop control should provide heightened molded part consistency, while the multiple degrees of freedom provide fantastic process flexibility. These degrees of freedom could be used to compensate for complex material properties, reject input variation, and adapt to changing production requirements. With this production stage flexibility, the product time to market will inevitably be reduced while ensuring acceptable levels of product quality and process yields. Moreover, the improved process flexibility and capability permit greater risk in the conceptual design stages which may ultimately result in previously unattained product capabilities. In a final representation, this research provides the product designer additional freedom while simplifying the tasks of the tooling engineer and machine operator.

RELATED WORK

Product inconsistencies among a batch of molded parts is most frequently assigned to lot to lot variation in material properties. For instance, small changes in viscosity, density, or composition may occur when one material is substituted by another having similar flow properties, regrind is mixed with virgin material, a material is used after it has been stored over an extended period of time, or a switch is made between different batches of the same material grade (Poslinski). Small changes in material properties can clearly lead to inconsistencies in part weight, part dimensions, aesthetic, strength, etc. However, material inconsistency is only one source of variation – many others exist which are often not considered. Table 1 lists several sources of variation in the injection molding process.

Table 1: Sources of variation in injection molding

Type of variation	Source of variation
Material properties	Viscosity, density, composition, etc.
Machine to machine repeatability	Machine dynamics, tuning, wear
Press to press repeatability	Controls tuning, barrel and hydraulic wear
Shot to shot repeatability	Shot size, velocity, switchover, pressure, etc.
Process engineer repeatability	Selection of set-points, set-up, etc.
Operator repeatability	Cycle time, parts handling, etc.
Environment repeatability	Temperature, humidity, etc.
White noise	Small variations in all the above

A second major source of variation involves the process machinery. For instance, molding machines of different injection cylinder and clamp design will have very different machine dynamics, providing different levels of molded part quality for the same process set-points. Even identical models from the same manufacturer can induce significant quality variation given differences in controls tuning and varying amounts of wear in the melt and hydraulic delivery systems. Finally, parts molded from the same press may vary due to control variation in the shot size, injection velocity, switchover point, pack pressure, etc.

The third source of variation shown in Table 1 stems from the human interaction with the process. For instance, process engineers have different definitions of 'optimal' (Morris). As such, they can induce product inconsistency by selection of process set-points such as injection velocity, pack pressure, back pressure, cooling time, and ejection set-up. Similarly, press operators directly determine cycle time and part handling, and may influence some process settings. As such, all human interaction will inadvertently tend to introduce variation to the injection molding process.

An additional source of variation is the physical environment in which the molding process is operating. For instance, outdoor temperature may affect the effectiveness of evaporative coolers which may affect the temperature of the plant water. Indoor temperature can likewise have significant effect on the mold wall temperature as well as the post-molding behavior of the molded parts. Humidity can effect the dryness of the materials entering the barrel which may introduce various quality inconsistencies.

Because of these sources of variation, typical industry practice for ensuring molded part quality is to 1) place the process at what are perceived as optimal operating conditions, then 2) casually perturb the process to identify a local 'process window' which produces acceptable moldings. The correlation of process conditions to a molded part's final quality has been widely studied both experimentally and theoretically [1, 2, 3]. These studies enhance the physical understanding of the injection molding process. However, they only relate the process conditions to a few particular properties for a particular machine. With more and more research in this area, the power of this method is growing. Nevertheless, this method requires intelligent design or large number of experiments to create results that are application specific. With such a diverse variety of plastics and applications, it is not possible to experimentally exhaust all the studies.

New process technologies have been incorporated into the injection molding process to address specific quality issues. Ibar et. al. has recently developed a device which utilizes reciprocating action of one or more melt-accumulator pistons adjacent to the flow path to induce melt-flow oscillation in the post-filling stages of the molding process.[1,2,3] These flow-fields can be used to alter and improve the extent of orientation in amorphous plastics and the morphology of semi-crystalline plastics. By orienting and vibrating the material, the 'rheometric' process forces flow fronts to intermingle at the molecular level, diffusing knit-lines and increasing part strength. The process is also claimed to control shrinkage and internal stresses to reduce part warpage and birefringence.

Several recent efforts have described different methods of accomplishing similar results. Gardner and Malloy utilized ejector pins on a cam to induce melt oscillation after the filling stage.[4] Becker et. al. utilizes two injection units to 'push-pull' the melt.[5] Grossman et. al. accomplishes melt oscillation by inserting pistons into a multi-branched runner system.[6,7] Finally, Kazmer and Roe increased knit-line strength in a conventional hot runner system simply by closing one valve gate in the post-filling stage and allowing the melt solidification and shrinkage to induce flow across the cavity.[8] Knit-lines are one common structural defect which may be addressed with any of the above techniques.

Dimensional stability has become an increasingly significant issue as plastics penetrate further into technical applications with significant levels of functional integration. To achieve dimensional stability, cavity pressures during molding must be uniform throughout the cavity to assure low levels of molded-in residual stress and avoid post-molding warpage. Uniform pressure distributions are difficult to achieve given the high viscosity of the plastic melt and the flow resistance of most designs' thin wall sections and long flow lengths.

Low pressure foam molding has been developed as a method to produce parts with uniform melt flow and reduced residual stresses.[9] In this process, the part is molded at lower pressures by introducing a blowing agent into the resin during injection which creates a low viscosity foam in the cavity. With lower, more evenly distributed cavity pressures, shrinkage and residual stresses are fairly uniform. While foam molding is especially suited to manufacture of parts with thick wall sections, the chaotic nature of foam molding makes tight tolerances difficult.

Gas-assisted injection molding was developed to enable hollow molding of thick wall-sectioned parts while delivering uniform cavity pressures in the packing stage. The process differs from injection molding in that a gas is introduced into the molten core of a partially filled cavity at the end of the injection stage. With negligible viscosity, the gas transmits the gas pressure uniformly throughout the cavity which results in reduced residual stress and part distortion.[10] Unfortunately, gas-assist molding generates a new set of unfamiliar problems, for instance: blow through, in which the gas penetrates through the surface of the part; fingering, in which the gas escapes the designed gas channels and penetrates into thin areas of the part. Moreover, gas assist can reduce the dimensional stability when compared to molding with closed loop cavity pressure control.[11]

If low pressure molding does not relieve many of injection molding's limitations, work in high pressure molding promises to deliver a different set of process capabilities. In high pressure molding, the injection unit is redesigned to produce and deliver injection pressures above 400 MPa (60,000 psi). This enables very short fill times and rapid transition into the packing stage. While specialty polymers must be designed to withstand the shear rates and pressures, high pressure molding does yield a fairly uniform cavity pressure distribution and almost zero part shrinkage.[12,13] Unfortunately, mold development for this process is costly and many issues regarding control of residual stresses have yet to be resolved.

Process control systems for injection molding have become substantially more repeatable and capable of producing consistent products. A consistent product, however, does not infer high levels of quality or desirable product attributes. The most sophisticated control systems will ultimately be able to eliminate variation while making trade-offs between multiple production goals. However, the control system will not be able to resolve multiple conflicting goals since most of the process dynamics are embedded in the mold steel. This couples the process dynamics between different areas of the mold – any process change imposed to improve one part property can inadvertently reduce quality elsewhere in the part.

FLEXIBILITY

In conventional injection molding, the process dynamics and part properties are largely determined by the geometry of the mold and feed system. As such, there is minimal flexibility in the injection molding process. Changes in machine settings to improve one area of the part – melt temperatures, ram speeds, and injection pressures, for example – are transmitted through the runner system to the entire part during manufacture, thereby limiting the operator's ability to selectively improve the part properties. Re-tooling the mold steel is thus frequently required to achieve the process dynamics which are necessary to obtain the desired part properties.

Process flexibility is achieved by two fundamental mechanisms of the multi-cavity pressure control process. First, the multiple valves enable the process dynamics in each area of the cavity to be controlled independently. Shrinkage in one local area of the part, for instance, can be altered without effecting properties in other areas of the part. Second, closed loop cavity pressure control decouples the process dynamics of the filling and packing stages. In conventional molding, for instance, it is not possible to tool a mold to obtain fast flow rates in one area of the mold followed by low packing pressures – the large runner diameters which prove useful in the filling stage are detrimental in the packing stage. The removal of this limitation with multi-cavity control greatly increases the process flexibility.

Filling Stage Flexibility

There are numerous part defects which are determined predominantly by the flow rates in the filling stage of injection molding. Table 1 provides a description and cause of such typical part defects: hesitation, jetting, unbalanced filling, knit-lines, orientation, and race-tracking. Filling stage flexibility is desirable to control the flow rates in different areas of the cavity to achieve the desired process dynamics and part properties without re-tooling mold steel.

Table 1: Part defects caused by flow rates in the filling stage

Defect	**Description**	**Cause**	**Multi-Cavity Pressure Control**
Hesitation	Discolored bands on surface of part	Low flow rates cause cyclic cooling, then advancement of the melt during filling	Modulate flow rates to provide constant velocity at each melt front during filling
Jetting	Discolored swirls near gates and thin sections	High flow rates in a thin to thick region cause rupture and jetting of the melt front	Reduce flow rate just prior to melt front reaching area of jetting
Unbalanced fill	Part warpage, burn marks, or short shots	Uneven flow rates cause one area of the mold to fill early while other area remains unfilled	Route greater percentage of flow to areas where short shots are occurring and reduce pressure in over-packed areas
Knit-lines	Thin, visible line along surface of	Occurs where cool melt fronts meet	Meter flow to locate knit-lines in acceptable areas or sequence gate

	part		opening
Orientation	Anisotropic part properties, warpage	Stress tensors dependent upon melt shearing and elongation during flow	Route direction of flow to achieve desired orientation and vary flow rates to control magnitude.
Race-tracking	Burn marks in center of part, circular knit-lines	Flow races around the thick lip of a thinner center section, entrapping air as center section fills	Reduce melt flow in area leading to race-tracking and increase flow rates in center of part.

For instance, Figure 1 illustrates a multi-cavity mold which would result in a severely unbalanced fill. If conventional injection molding were utilized with this design of 2mm wall thickness, the proper manufacture of the small part at right would result in a short shot of the larger cavity, as indicated by the dashed line in the figure. To manufacture the larger cavity, a molder must resort to higher filling speeds and pressures which results in the immediate filling and over-packing of the smaller cavity as shown in Figure 2. The conventional molding process resulted in a filling of the small cavity within the first second of filling, followed by prolonged over-packing with cavity pressures above 80 MPa (12,000 psi) while the larger cavity continued to fill.

A tool designer could re-design the feed system to achieve a uniform filling for the two cavities, but would be unable to compensate for packing pressures or other material properties. As such, this type of mold design is very seldom utilized in industry.

Multi-cavity pressure control was employed to regulate the flow rates in the filling stage to avoid the unbalanced filling of this multi-cavity mold. Figure 3 is a plot of the cavity pressure histories for the small and large cavity. A steeper slope of cavity pressure (30 MPa/sec) was used for the large cavity to produce a full part. A time delay and lesser slope of cavity pressure (10 MPa/sec) was used to avoid over-packing of the smaller cavity. Moreover, the pack pressures of each part are specified independently, with benefits which will be discussed in the next section.

To assist the product designer and process engineer in utilizing this process flexibility, it is necessary to establish the relationship between the slope of cavity pressure and the melt flow rate. To determine this relationship, parts were molded with multi-cavity pressure control at many different slopes of cavity pressure for the single cavity mold insert shown in Figure 4. For each part molded, the time was recorded when the melt first registered on the pressure transducer near the entrance of the cavity, t_1. The time was then recorded when the melt registered on a pressure transducer farther in the cavity, t_2. Knowing these times and the cavity geometry, the volumetric flow rate can be determined for each cavity pressure slope:

$$Q = \frac{L \cdot w \cdot h}{t_2 - t_1} \tag{1}$$

Figure 5 graphs the resulting relationship between cavity pressure slope and flow rate for eighty different molding trials at two different wall thicknesses. For a given wall thickness, a higher slope will generate a proportionally higher flow rate during filling. This is consistent with the analytical relation for Newtonian flow:

$$\dot{m} = 12 \cdot w \cdot \rho \cdot \frac{h^3}{\eta} \frac{\partial p}{\partial t} \tag{2}$$

For a given pressure slope, the mass flow rate will vary significantly with wall thickness due to the varying flow resistance. According to equation (2), a 2 mm wall thickness imposes roughly 3.3 times $\left(\left({}^{3}\!/\!_{2} \right)^3 \right)$ the flow resistance of a 3 mm wall thickness. This is roughly consistent with the experimental findings: the slopes of the 3 mm and 2 mm linear fits are 3.5 cc/MPa and 1.5 cc/MPa, respectively – a factor of 2.3. There is some deviation between theoretical and experimental results attributable to the non-Newtonian viscosity of the polymer melt. At thinner wall thicknesses, shear rates are higher which produces a lower viscosity and lower slope of cavity pressure than theoretically predicted.

According to equation (2), the curves should pass through the origin, i.e. a zero flow rate occurs at a pressure slope of zero. In actual molding, the data shows that there is a minimum pressure slope, greater than zero, required to propel the melt front to the end of flow before cooling causes the melt to solidify, i.e. there is some minimum flow rate required so that the heat transfer due to convection of the melt through the cavity overcomes the heat transfer due to conduction to the cooling lines. According to this data, those minimum pressure slopes are 8 MPa/sec and 18 MPa/sec for the 3 mm and 2 mm wall thicknesses, respectively.

Packing Stage Flexibility

There are numerous other part defects which are determined predominantly by the cavity and temperature distribution during the packing stage of injection molding. Table 2 describes several typical part defects related to the packing stage dynamics: sink, flash, shrinkage, warpage, and residual stress. By controlling the cavity pressure in each area of the cavity independently, multi-cavity pressure control enables the flexibility to selectively alter part properties and eliminate part defects without re-tooling mold steel.

Table 2: Part defects influenced by pressures in the packing stage

Defect	**Description**	**Cause**	**Dynamic Feed Solution**
Sink	Discoloration opposite ribs	Higher volumetric shrinkage causes inflection of surface opposite ribs	Increase pressure in thicker regions
Flash	Film at edge of part	High pressures cause mold deflection and force molten plastic into opened crevices	Reduce pressure in areas prone to flash
Shrinkage	Deviation of dimensions from tool steel	Volumetric shrinkage causes molded part dimensions to shrink	Increase pressure where reduced shrinkage is desirable
Warpage	Out of plane part distortion	Non-uniform volumetric shrinkages causes non-linear, out of plane deformations	Specify pressure distribution to minimize non-uniform shrinkage
Residual Stress	Dimensional creep, performance degradation	Solidification locks in stress fields caused by pressure, orientation, and cooling	Profile pack pressure decay to reduce residual stresses while cooling

The last section illustrated the process flexibility which enabled the proper filling of an unbalanced multi-cavity mold. Referring back to the geometry of Figure 1, the smaller cavity was filled instantly and over-packed with pressures exceeded 100 MPa (14,500 psi) with conventional injection molding. By utilizing multi-cavity pressure control, however, the pressure history in Figure 3 was attained. Not only was the smaller cavity filled more slowly, but packing pressures were delivered at a specified level of 28 MPa, 25 MPa below the packing pressures of the larger cavity.1 This separate control of cavity filling and packing pressures is not possible in conventional injection molding.

The experimental validation also showed that the level of packing pressures in the cavity may be widely specified, from 0 MPa to 100 MPa (14,500 psi). Higher levels of packing pressures are not commonly used in industry and were not examined in the experimental portion of this research.

In a multi-gated part, shown in Figure 4, the goal of the control system is to control the cavity pressure ***distribution*** throughout the part during the packing stage. This can be achieved by utilizing multi-cavity pressure control to specify the pressures P_1 and P_2 simultaneously. Figure 6 plots the cavity pressure response for the 220 x 50 x 3 mm rectangular plaque drawn in Figure 4. The pressure profiles show that packing pressures of 25 MPa and 32 MPa were imposed at the ends of the part: a 7 MPa pressure differential. Subsequent testing indicated that the maximum pressure differential which could be imposed between P_1 and P_2 was approximately 13 MPa.

This ability of multi-cavity pressure control may be used to selectively alter specific part properties. For instance, cavity packing pressures in one area of the part may be increased to reduce the amount of sink without adversely affecting other areas of the part. Alternatively, the cavity pressures in another area of the part may be reduced to eliminate flash along that adjacent edge of the part. Or, the packing pressure distribution across the part may be manipulated to bring the part within tolerances or minimize warpage and residual stress. Figure 7 is a graph of the relationship between cavity pressure and linear shrinkage for the 3 mm, multi-gated rectangular plaque.

The gray box in Figure 7 indicates the assumed range of linear shrinkage, data supplied by the material supplier for use in estimating tool steel dimensions.14 It is not possible to precisely predict the mold shrinkage so tool designers have historically used conservative shrinkage estimates and relied upon multiple tooling iterations to achieve desired tolerances. Difficulties do not usually

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1 As a side note, Figure 4 also re-iterates the decoupling of the filling and packing stages. In this figure, trace two (2), the area with lower flow rates, was also the area with higher specified packing pressures.

arise when the whole part shrinks uniformly – the level of pack pressures may be increased or decreased to bring the part within tolerance. The primary difficulty arises when unforeseen process dynamics impose non-uniform cavity pressures, uneven cooling, or molecular orientation which cause non-uniform shrinkage. In these instances, a set of process conditions may not exist which will result in adequate part properties, so tool changes must be utilized.

With multi-cavity pressure control, an estimate of 0.6% shrinkage may be used as an initial estimate for tooling. The process flexibility enables the molded part dimensions to meet design tolerances by varying the cavity pressures in the molding process without re-tooling. The entire cavity pressure distribution can be easily increased or decreased, or the shape of the pressure distribution can be varied across the part. As previously indicated, melt flow in the packing stage limits the pack pressure differential to 13 MPa across a flow length of 200 mm for a 3mm wall thickness. This pressure range corresponds to a ± 0.15% dimensional freedom across this particular part – enough to compensate for unexpected material and process variation without re-tooling. Similar design methods may be utilized to adjust for sink, flash, warpage, and residual stress.

CONSISTENCY

To evaluate the consistency of both the conventional process and multi-cavity pressure control, an experimental design was utilized to simulate the commercial production of a typical part. For a typical production run of 100,000 parts per month, three to five identical single cavity molds would need be tooled and sent to different molders where the parts would be molded. Each molder may be given an identical sheet of process parameters with which to mold the products, however, each molder is free to decide which of their machines is most suitable for molding the product.

Since molding machines have different screw and barrel designs – not to mention different clamp tonnage, shot size, and injection pressure capacities – the process behavior will vary significantly even though the same ‘process conditions’ are used on every machine. Moreover, molders are given some latitude to optimize the process parameters of their machine for use with the given mold. For instance, mold open time, cushion size, barrel temperature profile, and switchover points are variables that the molder must determine independently. (Or, if they used ‘standard’ setting across molders and molding machines, the machine-specific behavior might result in severe product defects.)

Table 3 lists the half-factorial design of experiments utilized for this investigation, an L8 with four variables of two levels (Box). The levels do not represent the boundaries of the process window for a given application, rather they are a very small subset of that process window. The levels of each of these process conditions was chosen to emulate the range of noise which would be encountered in the scenario described above. For instance, a ± 5°C fluctuation in melt temperature represents the variation in actual melt temperatures across different molding machines and molders. The ± 8°C range of mold temperatures reflects variation in water flow rates and temperatures through the tool which are not tightly specified. Similarly, the levels of injection speed and hold pressure shown in the table are indicative of the machine to machine variations in barrel, hydraulic, and controller systems.

Table 3: Experimental design for process consistency

Run Number	**Melt Temperature**	**Mold Temperature**	**Injection Speed**	**Hold Pressure**
1	277 °C	57 °C	25 cc/sec	50 MPa
2	277	57	30	60
3	277	74	25	60
4	277	74	30	50
5	288	57	25	60
6	288	57	30	50
7	288	74	25	50
8	288	74	30	60

For each molding trial involving a temperature change, the set-points were entered into the molding machine controller – all machine parameters not listed in Table 3 were left unaltered. The machine was left idle for thirty minutes during which time the melt and/or mold temperatures would equilibrate. Afterwards, twenty shots were molded with a consistent cycle time of 29 to 31 seconds. All these parts were discarded. Then six parts were molded utilizing the conventional process followed by another six parts utilizing multi-cavity pressure control. The parts were measured one week later in a 21°C environment using a dial caliper with an accuracy of 0.008 mm (0.0005 in). All process data and part measurements were analyzed using RS/Explore, a statistical analysis package available under license from Bolt Bareneck and Newmann, Inc. (New York, NY).

The cavity pressure response of the final run of each molding trial is graphed in Figure 8 for the conventional injection molding process. Given the relatively small range of input noise, the magnitude of variation is quite surprising. There is variation in the slope of cavity pressure between 1 and 2 seconds, the time and nature of the filling to packing transition between 2 and 3 seconds, as well as the final level of pack pressures near 8 seconds.

Figure 9 displays the cavity pressure response from the last run of each molding trial utilizing cavity pressure control, as well as the input pressure profile indicated by the dotted line. It is clear that this process delivers more consistent cavity pressures in the presence of variation with the following characteristics:

- the cavity pressure slopes are very uniform during the filling stage;
- the transition between the filling and packing stages varies slightly due to valve timing imprecision, and;
- the pack pressures are very flat and consistent.

Filling Stage Consistency

The average slope of cavity pressure was estimated for each run in each molding trial. This was evaluated by first passing the raw cavity pressure data through a second order low-pass digital Butterworth filter to reduce the effects of process noise. Then, the start of filling was identified as the point at which the cavity pressure exceeded 0.5 MPa, normally around 1.0 seconds. Finally, a linear fit was performed over the next 1.0 seconds of data to arrive at a mean slope for cavity pressure.

A regression analysis was then performed over the entire experimental design to relate the effect of each process perturbation on cavity pressure. Figure 10 lists the estimated effect of each noise parameter on the slope of cavity pressure. The dark vertical line in the center of each bar represents the estimate while the smaller vertical bars represent the 95% confidence interval. Any confidence interval crossing zero indicates that noise parameter has little impact on the system response. For instance, increasing the melt temperature is estimated to increase the slope of cavity pressure about 2.5 MPa/sec while increasing the mold temperature is estimated to have little effect.

The results shown in Figure 10 agree with intuition. Increasing the speed of the ram would increase the volumetric flow rate into the cavity which, in turn, should increase the slope of cavity pressure. Moreover, increasing the melt temperature reduces the melt viscosity which in turn reduces the pressure drop through the barrel, nozzle, and feed system and will result again in higher cavity pressures. Increasing the pack pressure should not effect the filling stage dynamics (unless the machine's controller responds to packing pressure inputs in the filling stage control algorithm.)

The dotted intervals in Figure 10 represent the effect of the same noise parameters with multi-cavity pressure control. As anticipated, the effects of the noise parameters have been significantly reduced due to the closed loop control. Interestingly, the input noise affects the multi-cavity pressure control trends in the same manner as the conventional process, albeit to a lesser degree. Increasing the melt temperature and ram speed increase the slope of cavity pressure, though not to the same extent as in the conventional process. In this regression, mold temperature was found to have a slight, though distinct, effect on slope which is logical – increasing the mold temperature reduces the amount of heat transfer during filling, thereby keeping the melt fluid and the cavity pressures lower.

Using Newtonian flow models, these results indicate that the flow rates in the filling stage may vary 15% for conventional models. Flow rate has a dominant effect upon the level of defects such as flash, knit-lines, and over-packing as well as some part properties related to orientation (see **Error! Reference source not found.**). As such, applications which are difficult to mold may experience lower process yields or systematic defects when subject to typical process variation.

Multi-cavity pressure control enables significantly better process capability. First, the flow rates in the filling stage can be immediately and selectively controlled to move the molding process away from potential defects. In the conventional molding process, this previously required design and tooling changes. Second, the experimental investigation has shown that closed loop cavity pressure control can maintain the slope of cavity pressure about four times better than the conventional molding process. With this capability, multi-cavity pressure control enables the molding of more robust and consistent thermoplastic parts.

Packing Stage Consistency

The packing pressure was defined as the pressure at 7.0 seconds, one second before the end of fill. The half-factorial design table (Table 3) was again augmented with the cavity packing pressure of each run in each molding trial, and a regression analysis performed over the experimental design using RS/Explore. This was done to determine the net effect of each noise parameter on the cavity pack pressure. The results for both the conventional molding and the multi-cavity pressure process are shown in Figure 11.

In the figure, the conventional molding process is indicated by the dashed horizontal lines while multi-cavity pressure control is shown with the solid lines. The trends are as expected. Increasing the melt temperature reduces the melt viscosity and pressure drop through the feed system which causes an increase in pack pressure. Mold temperature has no effect in the closed loop cavity control process, though there is a significant negative correlation in the conventional process. Increasing the speed has little effect with multi-cavity pressure control but a significant positive effect on the packing pressure in the conventional process, likely due to the small pressure spike at 3.0 seconds which endures throughout the packing phase (see Figure 9). Finally, increasing the pack pressure produced increases in the cavity pack pressure for both the multi-cavity pressure control and conventional molding process, as expected.

For every noise parameter, multi-cavity pressure control significantly reduced the amount of process variation as could be expected from a closed loop process. Moreover, the process response could be further improved by tightening the tolerance limits which were set at 4 MPa (600 psi) as shown in Figure 9.

Consistent control of the packing stage is necessary to produce consistent parts from molder to molder as well as shot to shot. Any variation in the process dynamics will be transmitted directly to the part properties, resulting in excessive sink or flash, inappropriate shrinkage or warpage, or end-use performance degradation. To investigate the effect of process variation on final molded part properties, the width of each molded part was measured at the location of the pressure transducer. Figure 12 graphs the results of the regression analysis results showing the effect of the noise parameters on linear dimensions. As before, the dashed and solid lines indicate the conventional and multi-cavity pressure control processes, respectively. It is interesting to note that multi-cavity pressure control has reduced the sensitivity of part dimensions to most input variables with the exception of mold temperature.

Typically, ± 0.2% is a standard commercial-grade tolerance.15 For example, if a dimension was specified as 10 cm, the tolerances for that dimension would normally be specified as 10.00 ± 0.020 cm. For such a tolerance, any one of the noise sources in this experimental validation could significantly reduce the production yield in the conventional injection molding process since the corresponding effects on part dimension are greater than 0.2%. Multi-cavity pressure control should produce more consistent parts with fewer defects by reducing the effects of variation.

Table 4 summarizes the results from measurement of the molded parts as defined by the process capability index, Cp (Farnum). Note that the standard deviation from the average (expressed as a percent of length) for multi-cavity pressure control is roughly one-third of the conventional process. If industry's tolerance specification is defined at 0.2%, then the process capability of the conventional and multi-cavity pressure control process can be calculated with the results expressed in the table.[2]

Table 4: Consistency results for conventional process

Performance Measure	**Conventional Molding**	**Multi-Cavity Pressure**
Standard deviation from average, %	0.064	0.020
Maximum over average, %	0.106	0.026
Minimum under average, %	0.148	-0.024
Process capability, **Cp** , for industry standard 0.2% tolerance specification	**0.52**	**1.67**

PROCESS LIMITATIONS

In this section, several sources of limitations with the multi-cavity pressure control process are reviewed. These arise from two sources: first, the capabilities of the pressure control scheme are still governed by the physics of the injection molding process. As such, there are fundamental boundaries for the extent of flexibility and consistency of the multi-cavity pressure control process.

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[2] A Cp of 1.0 represents a centered process with three standard deviations on either side, corresponding to a production yield of 99.73%. While the molding community generally accepts yields of 95%, higher Cps are desirable. A Cp of 0.5 represents a yield of 86% and is not acceptable.

Second, the addition of flow metering elements in the feed system and supporting hydraulic subsystems are new sources of process noise and instability – these may negatively impact the process capability and point to design modifications in future work.

Limitations from Process Physics

FILLING STAGE

During the filling stage, the slope of cavity pressure governs the melt front advancement and subsequent part properties listed in Table 1. As such, the design or process engineer would like to arbitrarily select the cavity pressure profile and flow rate at each gate. There are limitations to the minimum and maximum slopes which may be profiled, however, as shown in Table 5. For a specific wall thickness and melt resistance, the cavity pressure is approximately proportional to the volumetric flow rate. Thus, the maximum slope of cavity pressure is limited by the flow rate capacity of the molding machine. At lower flow rates, cooling of the melt may result in significant increases in viscosity. To maintain a minimum pressure slope, the control system further reduces flow rates, which results in further cooling, and eventual solidification, of the melt which results in a short shot.

Table 5: Range of cavity pressure slopes for 2 mm and 3 mm wall thickness

	2 mm Wall	**3 mm Wall**
Maximum Pressure Slope	25 MPa	46 MPa
Minimum Pressure Slope	7.5 MPa	18 MPa

Knowledge of these limitations is critical to the design engineer when considering the manufacturability of a candidate design. For instance, a design may require a knit-line to be placed outside of a visible surface. The flow rates through each gate may be chosen to fulfill this requirement from Figure 5, but are subject to the limitations listed in Table 5.

PACKING STAGE

The goal of Dynamic Feed is not only to control the level of packing pressure at a discrete point in the cavity but also to control the ***distribution*** of packing pressures across the cavity as well. The magnitude of cavity packing pressures is limited only by the pressure capacity of the molding machine. However, the gradients of the cavity pressure in the packing stage are constrained since molten plastic will flow from an area of high pressure to one of lower pressure through the part. Such flow during the packing stage is minimal, driven only by the compression and solidification of the melt. As such, the magnitude of the cavity pressure gradients is dependent upon the melt viscosity, solidification dynamics, wall thickness, and distance between gates. Table 6 lists the maximum pack pressure differential which can be maintained for the 220 x 50 rectangular plaque (Figure 4) at 2 mm and 3 mm wall thicknesses.

Table 6: Achievable Pack Pressure Differential

	2 mm Wall	**3 mm Wall**
Pack Pressure Differential	29.5 MPa	12.9 MPa
Confidence Interval	1.6 MPa	2.3 MPa

This data is critical to the design and process engineer trying to manipulate the pack pressure distribution to manipulate part properties, such as part dimensions. For a specific application, the wall thickness, distance between gates, and material properties will determine the maximum pack pressure differential which can be maintained – commercial flow analyses can provide good estimates of the limitations on cavity pack pressure distribution.16

Temperature Effects

Part properties are determined by the pressure and temperature history in the cavity during the molding process. Cavity pressure control was enabled by the addition of flow metering elements with a system response time of 0.050 sec – on the order of the process dynamics being controlled. However, temperature control is inherently a much slower process – process response is on the order of seconds or minutes – which greatly limits the possibility of controlling temperatures to substantially impact the part properties during the molding cycle. As such, the temperature history of the part is determined solely by the process physics once the melt and mold temperatures have been set. Structural properties (part dimensions, warpage, knit-line strength) and cosmetic properties (gloss, sink, blush) may vary significantly with melt and mold temperatures.

It may be possible to compensate for some effects of temperature deviation by altering the cavity pressure distribution, as the experimental results have shown. If models were developed relating temperature and pressure to part properties, then the effect of measured deviations in melt temperatures could be estimated which, in turn, could be compensated by altering the cavity pressure distribution. For instance, a 10 °C change in mold temperature might increase the mold shrinkage by 0.1% which could be offset by an increase of cavity pressure of 12 MPa for the reduction in mold shrinkage by 0.1%.

Unfortunately, there are some part properties (surface gloss, for instance) which are mostly determined by mold temperature for which multi-cavity pressure control, by itself, would be ineffective in controlling. Kim et. al. utilized small heating/cooling plates within the mold steel to selectively control the magnitude and distribution of mold temperatures during the molding process.[17] Together, control of the temperature and pressure dynamics in the mold cavity could be achieved.

Limitations from System Design

As a prototype manufacturing process, the present system has functioned well, enabling verification of the control strategy and process concept. This system has greatly enhanced the capability and flexibility of the injection molding process as the experimental results. However, the entire multi-cavity pressure control system was installed on a molding machine designed for conventional use. This resulted in some interesting process consistency issues due to the timing between the molding machine's controller and the multi-cavity pressure control previously described. Moreover, there was significant interaction between the multiple valves in the feed system, interactions which were assumed insignificant throughout development of the control strategy.

Due to these effects, the process consistency of the adaptive algorithm was reduced from its theoretical optimal. The closed loop control system was utilized to actively monitor for process inconsistencies and indicate when parts should be discarded. As such, the yield of the 2000 parts which were molded during the experimental validation and met the cavity pressure specifications was approximately 70%. The following discussion highlights the sources of inconsistency and points to areas for future system design.

RESPONSE TIME

At the beginning of the molding cycle, the injection molding machine sends a signal to the control system indicating the start of injection. The control system opens the valve stems, the molding machine accelerates the ram, and the melt begins to flow into the cavity. Near the end of the filling stage, the valve stems are moved to a semi-closed position for control of the packing stage. This research has shown that the timing of switchover is critical and must be adaptively fine-tuned to within 0.050 sec to obtain a smooth transition.

Table 7: Response times of several control elements

Control element	**Source of delay**	**Response time**
Hydraulic spool position	Actuation of spool in valve	0.020 sec
Pressure transducers	Transmission of pressure through long mercury capillary	0.020 sec
Hydraulic signal amplifiers	Amplification of 24 DC to 2 V, 10 amp	0.010 sec
Control system	Selected in system development	0.010 sec

Table 7 lists the response times of several process control elements. While each of these devices has a response time less than 0.020 sec, the system response time (pressure transducer → control system → signal amplifier → spool position → valve stem actuation) is on the order of 0.050 sec. This indicates that small deviations in process consistency, such as start of injection or ram acceleration or valve stem positioning, may result in significant deviations in the transition between the filling and packing stages. While not an extensive problem, the system response times did result in a reduction in the consistency of cavity pressure profiles. Figure 13 plots the cavity response for transition times ranging from -0.100 seconds to +0.100 seconds away from the nominal (centered) transition time. An improved control design would reduce the system response time while an improved valve design would reduce the sensitivity of cavity pressure to response deviations.

HYDRAULIC PILOT

Each of the valve stems was controlled by a proportional servo-valve mounted on the hydraulic manifold of the molding machine. Surprisingly, the pressure to the hydraulic manifold for the actuation of the valve stems is also the supply pilot pressure to the molding machine's hydraulic pump.18 The hydraulic manifold is normally used for valve shut-offs, core pulls, or hydraulic slides – activities which do not dynamically require fluid flow during the filling and packing stages of injection molding.

With multi-cavity pressure control, however, the frequent opening and closing of the valve stems requires continuous hydraulic flow throughout the filling and packing stages. More specifically, the transition between the filling and packing stages requires a significant amount of hydraulic flow to quickly move the valve stem from a mostly open to a mostly shut position, just at the time when the molding machine is also transitioning from the filling to the packing stage. This results in an instability as the valve stem actuation and reduces the molding machine's pilot pressure which causes a brief, though noticeable, decay in the injection cylinder's hydraulic pressure. The multi-cavity pressure controller's adaptive gain scheduling compensates for this effect automatically, though requires several iterations (shown in Figure 8 of the companion paper) to converge to an acceptable response. Moreover, small instabilities around the transition time, as discussed in the previous section, can lead to unacceptable process dynamics. In future designs, a hydraulic accumulator between the valve stems and the injection unit would eliminate this problem.

VALVE INTERACTION

The control system strategy presented in the companion paper was developed for one branch of a feed system, assuming negligible interaction between multiple valves. In reality, when a valve stem is moved from an open to a closed position, a volume of melt is displaced by the movement of the valve stem. Some of this volume is forced into the cavity ahead of the valve stem and results in a temporary increase in cavity pressure – this effect was considered in control system development. However, the remaining portion of the displaced volume of material is forced back into the feed system and results in an increase in ***<u>injection pressure</u>*** which subsequently effects the pressure dynamics at the other valves – this effect was not considered in control system development.

Figure 14 illustrates this undesired valve interaction. The dark line is the normal cavity pressure response when a valve stem is moved from 70% open to 30% open at 1.5 seconds and the other valve stem remains stationary. There is an immediate slight increase in cavity pressure when some of the melt in front of the valve stem is forced into the cavity. This is followed by a slight decay in cavity pressure as the melt dynamics adjust to the increased flow resistance. By 1.8 seconds, the dynamics are stable and the cavity pressure begins to rise.

The dotted curve indicates the response when that same valve is moved from 70% open to 30% open at 1.5 seconds and the second valve is opened from 0% open to 100% open at the same time. In this case, the behavior at the first valve is the same until 1.6 seconds when the second valve's interaction becomes noticeable. A vacuum has been created in front of the second valve. Moreover, the flow resistance through the second valve is much less than that of the first valve. Both of these effects result in a lengthy decay and delay in control of the cavity pressure at the first valve. Fortunately, the magnitude of this interaction is not as significant during the molding process since the valve stems are not normally manipulated to this extent. Future system designs could reduce the valve interaction by minimizing the volume displaced by the valve stem.

CONCLUSIONS

This research has assessed the process capability of multi-cavity pressure control for some simple mold geometries. The experimental work has found that the process capability has been significantly enhanced by adding process flexibility and enhanced consistency to the conventional injection molding process. In particular, multi-cavity pressure control was shown to enable the process flexibility to control flow rates and packing pressures at each portion of the cavity, useful in moving knit-lines, balancing flow, or controlling part dimensions. When subjected to typical process perturbations during production, moreover, the multi-cavity pressure control was found to increase the molded part consistency. The conventional injection molding process exhibited a process capability index, Cp, of 0.52 compared to multi-cavity pressure control's Cp of 1.5. This added consistency enables both higher production yields and tighter production specifications.

The research also pointed out some significant process limitations of the multi-cavity pressure control process. Some of these were implementation issues, such as valve interaction, time sensitivity, and hydraulic performance - all can be easily corrected through valve, hydraulic, and control redesign. Other process limitations, temperature effects and cavity pressure interactions, are due to the inherent process dynamics of injection molding. They can never be removed and must therefore be considered in part and tool design.

Multi-cavity pressure control is clearly a unique process. Its ability to locally control the pressure dynamics in the cavity are very powerful. In essence, each dynamic valve is an injection unit leading directly to the gate. What remains to be seen, however, is if the beneits to quality and product development time () outweigh the added cost and complexity of implementation (costs). With this in mind, another stage has been begun: commercial validation for a fairly complex printer housing with four valves.

ACKNOWLEDGMENTS

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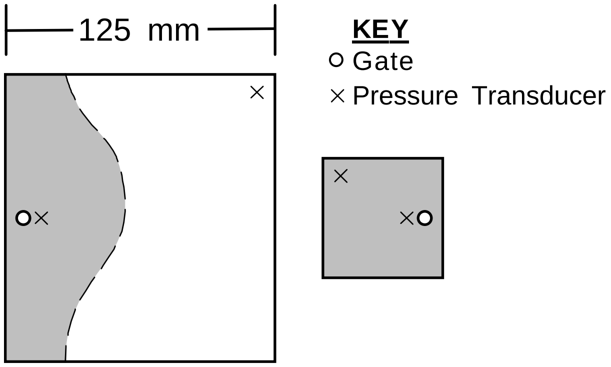

Figure 1: Unbalanced Two Cavity Geometry

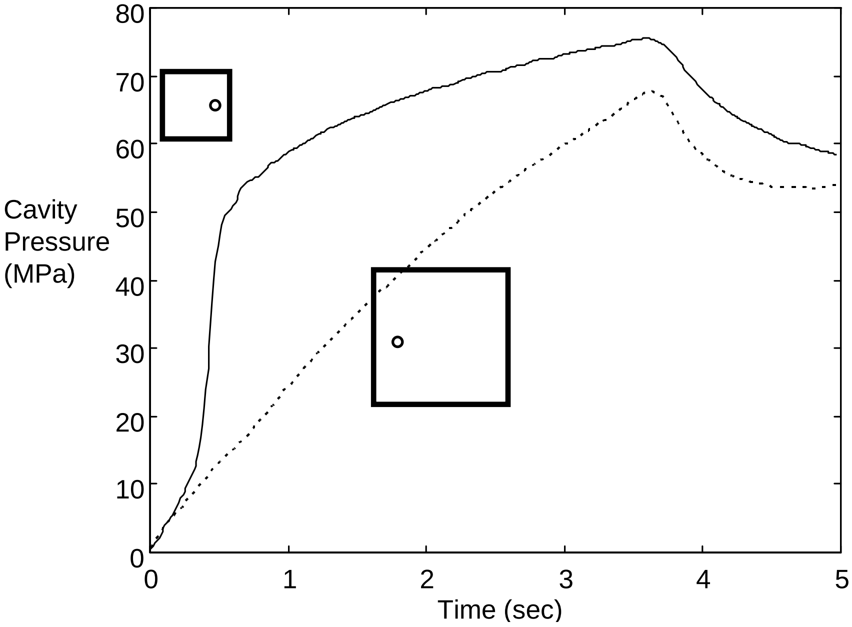

Figure 2: Cavity Pressure History for Unbalanced Mold with Conventional Injection Molding

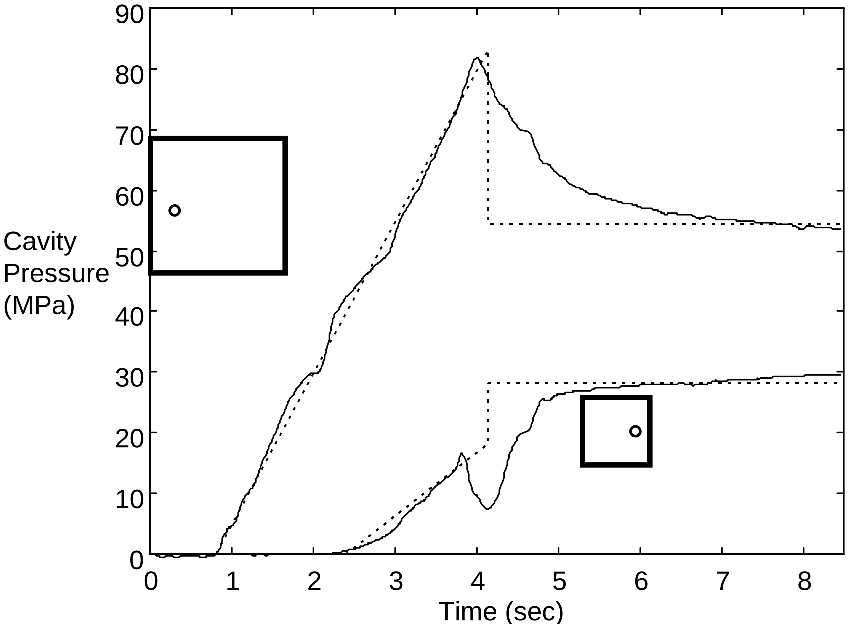

Figure 3: Cavity Pressure History for Unbalanced Mold with Multi-Cavity Pressure Control

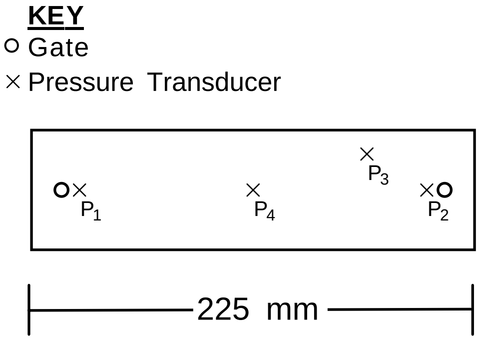

Figure 4: Multi-Gated Cavity Geometry

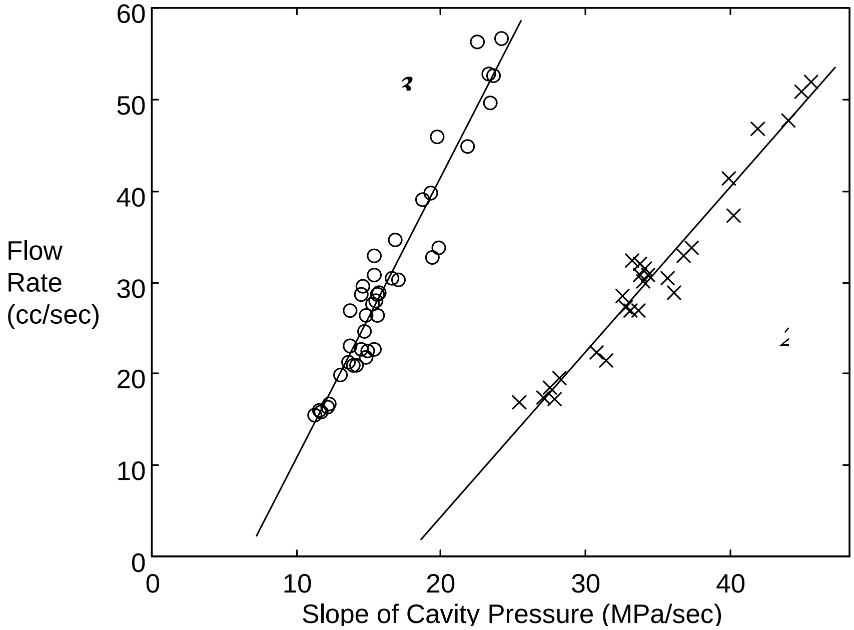

Figure 5: Flow Rate as a function of Cavity Pressure Slope

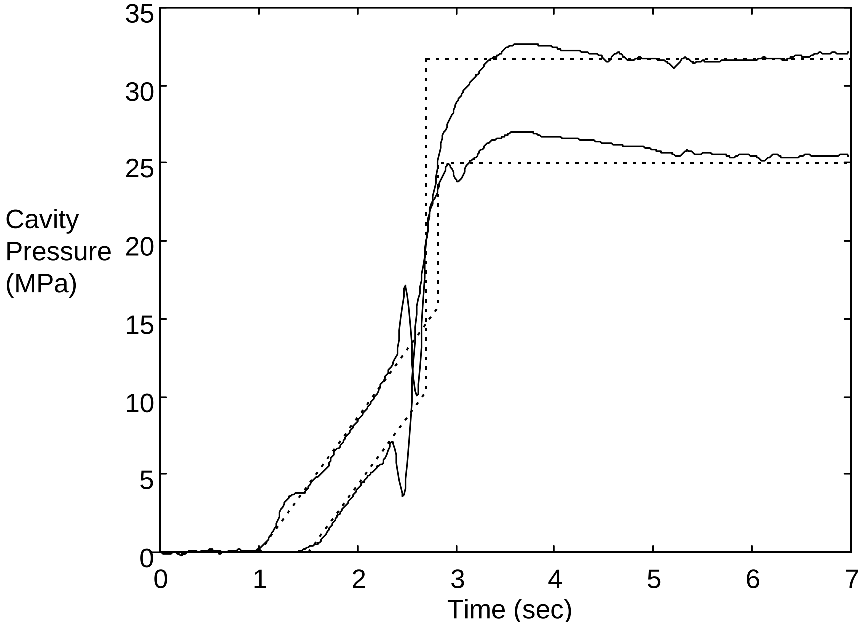

Figure 6: Simultaneous Pack Pressure Control in Multi-Gated Part

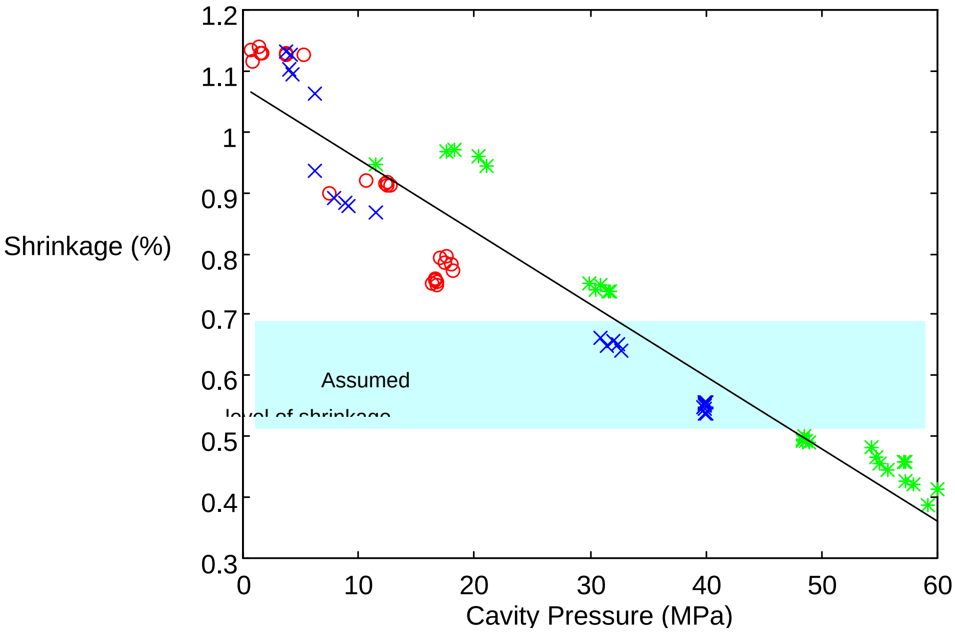

Figure 7: Dimensional Shrinkage as a Function of Cavity Pressure

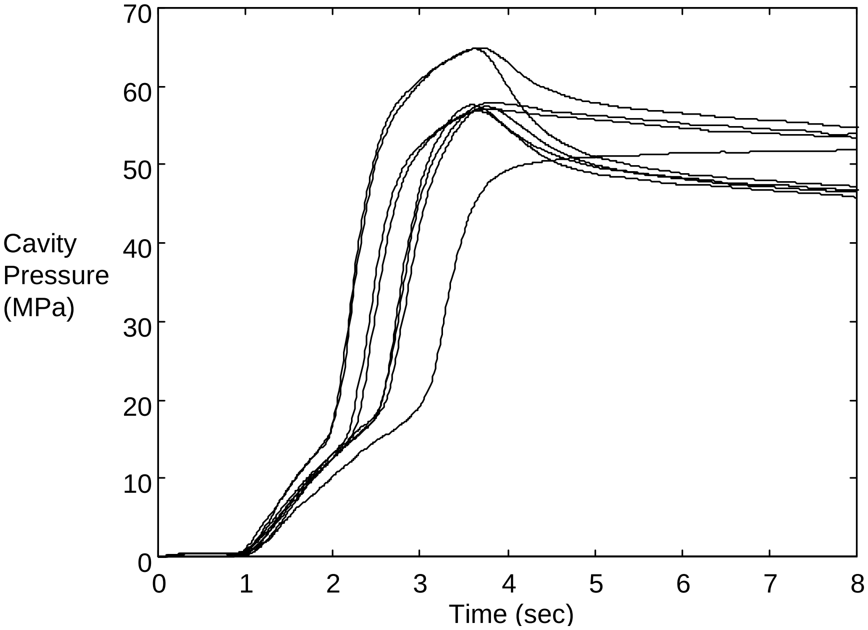

Figure 8: Cavity Pressure Repeatability for Conventional Injection Molding

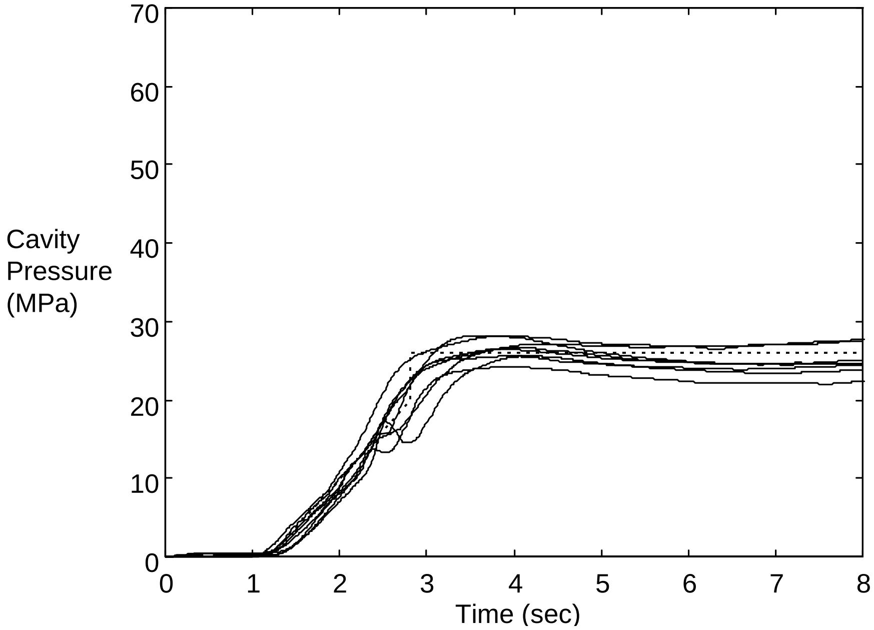

Figure 9: Cavity Pressure Repeatability for Multi-Cavity Pressure Control

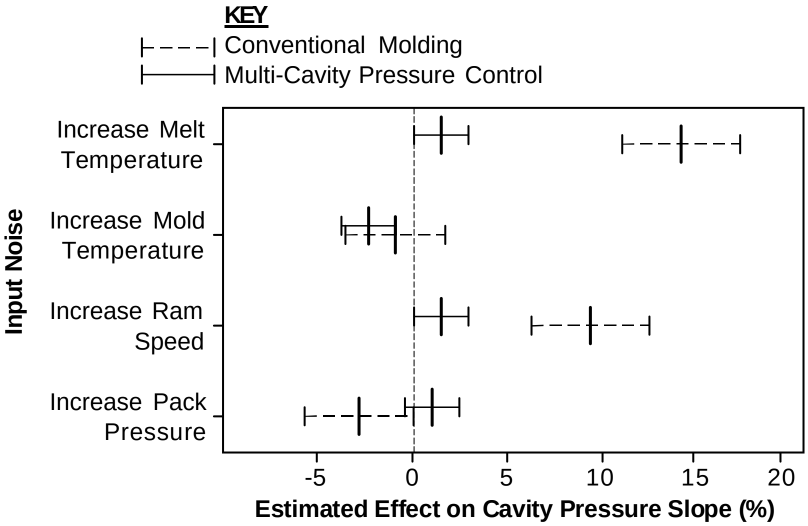

Figure 10: Estimated Effect of Input Noise on Cavity Pressure Slope

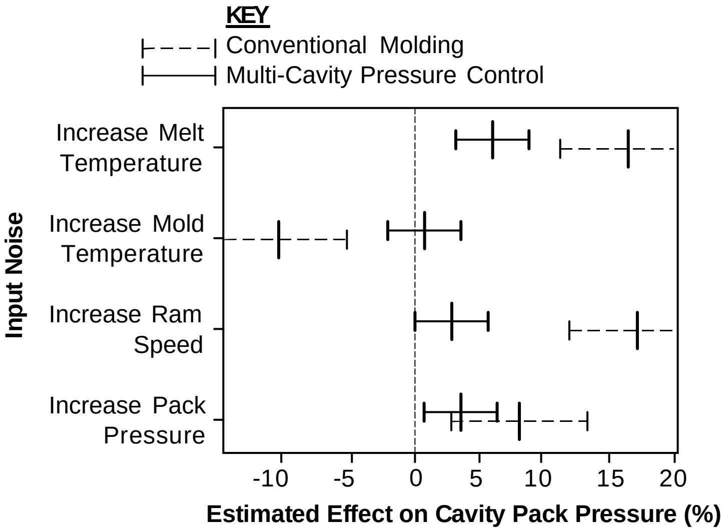

Figure 11: Estimated Effect of Input Noise on Cavity Pack Pressure

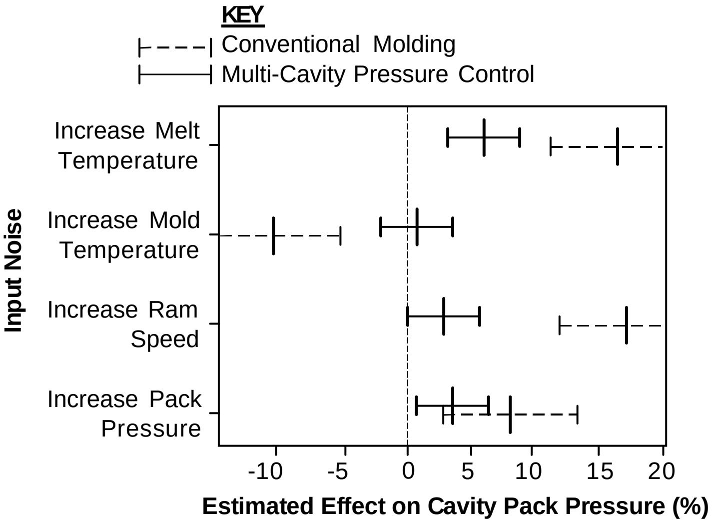

Figure 12: Estimated Effect of Input Noise on Part Dimensions

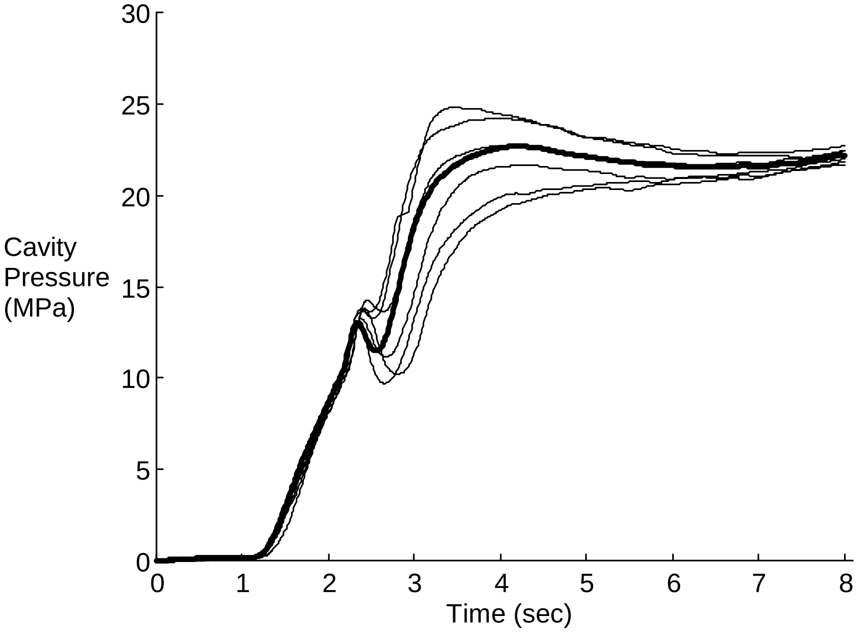

Figure 13: Cavity Pressure Response to ± 100 mSec Errors in Transition Time

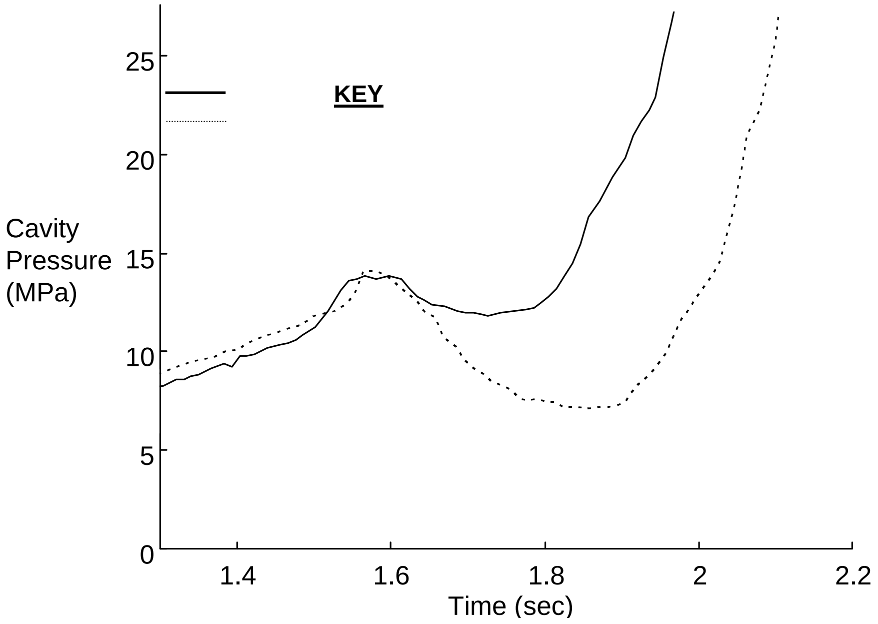

Figure 14: Interaction between Multiple Valves

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