CONSISTENCY AND FLEXIBILITY OF MULTI CAVITY MELT CONTROL INJECTION MOLDING IN A COMMERCIAL APPLICATION

Deepak Kapoor, Raychem Elo-Touch Systems, Fremont California
David Kazmer[*]*, University of Massachusetts Amherst*

* Author to whom correspondence should be addressed:

David Kazmer
Assistant Professor, Dept. of Mech. & Ind. Eng.
University of Massachusetts Amherst
Eng. Lab. Bldg.
Amherst, MA 01003

(413) 545-0670
kazmer@ecs.umass.edu

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Abstract

The quality of injection molded products is determined by a complex coupling between polymer properties, mold geometry, and process dynamics. To increase the flexibility and consistency of the injection molding process, a method was devised to simultaneously control cavity pressure at multiple locations in a mold. This control was achieved by installing multiple dynamic valve stems into the feed system of a hot runner manifold, each of which can control polymer flow. This system was used in a commercial application with four gates to deliver consistent product quality and provide manufacturing-stage flexibility. Across all eleven measured dimensions, the process capability index Cp increased between 50 and 400%. Also, multiple dimensions could be independently and simultaneously adjusted by locally controlling material shrinkage.

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Introduction

Injection molding has established a firm foothold in the plastics processing industry as a reliable method for producing complex plastic goods in a single operation. Following the fundamental concepts of Design for Manufacturing (DFM) [1] to reduce the number of parts by consolidating multiple functions in a single design, injection molding is widely being used to manufacture complex parts. From the viewpoint of economics, material scrap, time taken to produce a part, part inventory, and assembly costs are reduced. Despite the widespread popularity of injection molding, this manufacturing process does not possess the flexibility needed to adapt itself to the changing industry requirements. As a result, production and design of complex parts are more challenging and product quality is more difficult to maintain. When design changes are encountered late in product development, it is difficult to produce the molded component with the new requirements because this involves re-cutting the mold to change dimensions. Design and manufacturing tasks can become long and cumbersome, and it is not uncommon to encounter numerous changes and iterations during product design and introduction which lengthen product time-to-market and which can potentially lower sales volumes.

Thermoplastics exhibit very complex rheological and thermal properties because of their molecular structure. The rheological behavior is significantly affected by changes in temperature, pressure, and shear rates, all of which are dynamic in the molding process. Thus, the state of the melt being injected throughout the mold cavity can not be precisely predicted or controlled. Closed loop control methods have been applied to improve the quality of the part to compensate for such changes in the material properties. These efforts can be divided into - a) control by monitoring machine parameters [2-6], and b) control by monitoring pressures in the mold cavity or near the gate [7,8]. The former, though relatively less expensive, has the drawback of trying to effect change far away from the mold cavity where the quality of the part is being determined. In contrast, closed loop control of cavity pressure is becoming more popular and studying melt dynamics in the cavity has been a recent research focus. Though information from the cavity is used for control, the effector is still the injection unit of the molding machine, and this compromises the benefits of cavity pressure control.

The controllability of molded part quality is further complicated given the possibility of fluctuations in material properties, mold conditions, machine settings, and operator interaction. Plastic raw materials are manufactured in numerous batches and even stringent quality control methods sometimes fail to prevent variations from batch to batch. Thus, a set of parameters that have been determined for processing thermoplastic resin on a machine for a particular batch may not provide the same results when the batch of material is changed.

Molded products are also made on many machines at different locations. A typical automotive component, for example, may be produced on twelve machines in three continents. Although the a machine manufacturer may make machines with the same specifications, some variations are inherent. Tonnage, shot size, and hydraulic component specifications may vary. Numerous electromechanical components can have different response times. All these factors ultimately affect the molding process dynamics and attribute properties of the molded part. Similarly, operators are known to adjust processing variables to suit their expectations of quality. The quality of the part may vary if two different operators use the same batch of material on the same machine and mold. Thus, different man-machine-process conditions influence part quality. Improved processing methods are needed for reducing sensitivity to such input variation and increasing the molded part consistency.

In spite of the strides made in concurrent engineering, product design still remains an iterative process. As design progresses, the number of changes that can be executed decrease as features get “locked in” or become prohibitive due to mounting expenses. Minor changes to product dimensions may be called for due to unforeseen problems in manufacture and/or assembly. Such decisions become difficult to implement once the cavity has been tooled into the mold steel. For example, in conventional molds, knit lines cannot be moved without blocking the existing melt transport system and re-cutting new runners and gates. The time expended in making such changes to molds increase the product time-to-market and can affect revenues [9]. It is thus necessary to have means to execute changes at later stages in the design or manufacturing cycles

Multi Cavity Melt Control

Consider the melt transport system in a conventional cold runner mold. It is evident that the geometry is “hard-wired” into the mold. The runner locations are fixed and the gate dimensions are also fixed. Once molding trials are conducted, the mold is accepted when the quality of the part meets specified requirements. If the problems cannot be solved by changing process parameters, the mold has to be re-tooled. Retooling often involves repositioning and/or changing dimensions of the runners, gates, or mold cavity to deliver acceptable part quality. Retooling of the mold is a time consuming and expensive process.

Unfortunately, retooling is necessary since ***there is no control on the flow of the melt beyond the injection unit. As such, injection molding behaves as a one degree of freedom process*** [10]. Instead, a system has been proposed by means of which the number of such changes in tooling can be minimized. One of Nam Suh's axioms of design states that "independence of functional requirements should be maintained" [11]. This axiom was applied to investigate the injection molding process and introduce multi-cavity melt control [10] over the volume and pressure of melt flowing into the mold cavity. This is accomplished by independently operated valves at each gate, each valve acting as a separate degree of freedom.

As shown in Figure 1, the valves meter the flow of melt from the runners into the mold cavity. The pressure drop and flow rate of the melt is dynamically varied by the axial movement of each valve stem which controls the gap between the valve stem and the mold wall. By de-coupling the control of the melt at different valve stem positions, melt control at each gate can override the effects of the molding machine and provide better time response and differential control of the melt. Each valve acts as an individual injection unit, lessening dependency on machine dynamics. For closed loop control, manifold pressure transducers were used in the runner drops instead of in the cavity. This implementation not only provides lower cost and greater reliability, but also renders a conventional appearance for the system.

The primary objective of this research was to investigate the capabilities of multi-cavity melt control when compared with conventional injection molding. After establishing the dynamic control over the valves, molding trials then followed to characterize the process and provide information on the quality of the molded parts. After establishing quality metrics for a product, multi-cavity melt control was compared with conventional valve gate controlled molding on specific quality issues that will be described in later sections.

Experimental Set Up

The Product

The part used for this research was a Hewlett-Packard printer output tray. A schematic of the part is shown in Figure 2. The part was gated at four locations, almost at diagonally opposite corners. The original mold used for the part was a three-plate cold runner mold with tolerances on several critical part dimensions at multiple part locations. Aesthetic problems like burns, blush, and splay also existed [12].

A Krauss Maffei 550-48 (Krauss Maffei Machine Co., Florence, KY) providing a clamp force of 56 kN (550 tons) was used for the molding trials. Kona Corporation (Gloucester, MA) manufactured the hot runner manifold used in this project. The hot runner manifold had nine temperature zones that were controlled by a D-M-E manifold temperature controller. Hydraulic cylinders located on the hot runner manifold moved the valve stems to regulate the flow of the plastic into the mold cavity. The cylinders received their oil supply from an external hydraulic power unit. The hydraulic power unit (The Hope Group, Northboro, MA) delivered oil at 17.5 MPa (2450 psi.) at 1.52 liters/s (24 gpm) to a hydraulic manifold feeding servovalves. Four Moog 631 Series Servovalves from Moog

Corporation (East Aurora, NY) received oil from the inlet, and drained oil to the outlet port of the manifold.

Since there was to be independent control on the valve stems, it was necessary to have individual pressure transducers for each axis of control. Cavity pressure transducers are the ideal form of feedback but are expensive in terms of acquisition, installation, and maintenance. The pressure transducers were located in the runners and assumed to provide a fair estimate of the pressure in the mold cavity. Four manifold pressure transducers (PT 4676, Dynisco Corporation, Gloucester, MA), rated at 0 - 140 MPa (0 - 20000 psi.) with an output of 0-10 VDC were mounted on the manifold, one each at the runners leading to the gates at the locations shown in Figure 2.

The inputs to the system were data files in a time-based, pressure format (time on the abscissa and manifold pressure on the ordinate). For each ‘axis’ or gate, there was an input file, which represented the ideal set of values determined based on anticipated part quality attributes. These files were input through the LabVIEW® (National Instruments, TX) software that transferred the input commands to the PMAC® (Delta Pi Tau Systems, CA) motion controllers. The motion controllers controlled the flow of oil into the cylinders by comparing the desired value to the observed manifold pressure transducer. The feedback signals were also acquired by a NI-AT-MIO 64® (National Instruments, TX) data acquisition card.

Process Control

Conventional Molding

Conventional molding was conducted by directing the valves to be either in a fully open state or a fully closed state dependent on the condition of the injection forward signal. In the control system used in this research, conventional valve gate molding was simulated by signaling the valves to fully open by setting the input profiles to a peak pressure of 140 MPa (20,000 psi.), which was greater than the supplied injection pressure. To try to attain this pressure, the valves would open fully and allow the condition of the melt at the nozzle to be transferred to the mold cavity.

Multi Cavity Melt Control

Multi cavity melt controlled molding uses closed loop control of cavity pressures. The input pressure profiles for closed loop molding were based on knowledge gained from the output profiles by molding under open loop conditions. This provided an estimate of the filling time and pressure, fill-to-pack transition times and pressure, and packing pressure. With this control profile, the cycle was initiated and valves actuated to maintain the specified pressure. A simple proportional-integral-derivative (PID) control was found to be adequate to generate the responses necessary. The need to re-tune the system did not arise and the control system was robust enough to handle different cavity pressure profiles that were experimented.

Unfortunately, one of the valves rarely responded to closed loop commands. Upon later examination, this valve pin was found to be cracked at its mounting threads and, in its broken state, eluded any form of control. This resulted in a loss of process consistency and flexibility. However, the reported results were obtained in areas of the part removed from this failed valve, and are even more remarkable in light of this fact.

Process Capability

Consistency Results

One of the foremost concerns in manufacturing any product is that of repeatability or consistency [13]. Recently, economic benefits have forced companies to outsource parts, and this adds to the difficulty in maintaining consistent product quality and tight part tolerances. Cavity pressure has been found to be an important indicator of part dimensions [14,15]. Multi cavity melt control renders improved cavity pressure control compared to the injection unit because a) the valve is smaller than the machine ram and the system inertia is reduced, and b) proximity of the of the gate to the valve ensures quick response.

To check the ability of the system to maintain dimensional consistency despite the presence of noise factors, an experiment was run simulating the disturbances that could be felt in real production scenarios. The noise parameters used in the study were melt temperature, hold pressure, hold time, injection velocity, and screw pressure. The eight-run design of experiments used in this investigation is shown in Table 1. Other machine settings were: injection pressure of 8.3 MPa (hydraulic), mold temperature of 60 ^{o}C, plasticizing stroke of 66 mm., transfer point of 5 mm., and melt cushion of 2.54 mm. For each run above, parts were molded by conventional and multi-cavity molding. In every run, the first ten molded parts were discarded and the next five saved for analysis. When the temperature setting was changed, the machine cycled for about thirty minutes before the parts were saved for analysis. The values of the two levels for each of the variables represent the expected shifts in process parameters due to the machine, melt viscosity, or the operator [16]. For each of the five parts saved from each of the runs in the two cases, part dimensions and weights were measured.

The melt pressure traces from the fourth molding shot in each of the eight runs for conventional molding are shown in Figure 3. Two distinct regimes are observed in the pressure profiles in Figure 3, with each regime composed of four lines. The reason behind this is the two levels of each input into the machine. One regime corresponds to the first four cases where the hold pressure was 4.8 MPa (48 MPa at the nozzle), and the second regime corresponds to the case where the hold pressure input was 4.1 MPa (41 MPa at the nozzle). This indicates that in the case of conventional molding, the pressure in the mold is susceptible to changes in machine conditions and these changes in the machine settings are transmitted into the mold cavity. Other changes can be witnessed in injection rates and switchover time from filling to the packing stage.

Figure 4 shows the pressure profiles from the fourth shot of each of the molding runs for the multi-cavity melt control process. The dark line shows the input pressure trace. The excellent performance of the system is evident from the overlapping traces. Despite changes in the machine settings according to the eight runs in Table 1, the traces almost overlap. The output profiles do not follow the desired profile at the end of fill because the machine switches to lower packing pressures before the desired filling profile is completed. Since the valves only vary the flow impedance, and do not act as a source of melt pressure, it is not possible for the specified profiles to be followed.

The holding stage is known to contribute to the overall quality of the part, affecting part dimensions, strength, and aesthetics. A dimension specified as #2 in Figure 2 has been used for statistical analysis – the requirements for this printer tray specifies this dimension as 65.00 ± 0.15 mm. To measure critical dimensions on the parts that were molded, a Coordinate Measuring Machine (CORDAX 1808-M DCC MEA, Sheffield Measurements Division, Dayton, OH) was used. Table 2 presents a summary of the values of the dimensions averaged over the five parts molded in each of the eight runs for both molding scenarios. Figures 5 and 6 show the effects plots for the two molding trials, which were generated using RS/1 (BBN Software Products, Cambridge, MA). The predictor variables are on the abscissa and the response variable plotted on the ordinate.

The range of dimensions on the Y-axis in conventional molding is 0.06 mm compared to the range of dimensions of 0.008 mm produced with multi-cavity melt control. This shows that the effects of the predictor variables (imposed process variation) have been reduced in the second case. Melt temperature and hold pressure are the main predictor variables inferred from the slope of the lines in the effects plots. Changes in melt temperature and packing pressure, significant in conventional molding, are effectively nullified with multi-cavity melt control. The effects of injection velocity, hold time, and screw RPM are also minimal. The capability of the new system to maintain specific holding pressures in the cavity irrespective of the hold pressures generated by the molding machine is a key factor in changing part dimensions at specific locations which will be discussed later in a section on flexibility.

Industry has used a metric called the process capability index, defined below, to report the ability of the process to maintain consistency.

$$C_p = \frac{USL - LSL}{6\sigma} \tag{1}$$

Using standard deviation values from Table 2, and specifications 65.00 ± 0.15, USL = 65.15 mm., and LSL = 64.85 mm. The process capability values are calculated as:

$$\begin{aligned} C_p &= \frac{65.15 - 64.85}{6 \times 0.0262} = 1.9 \\ C_p &= \frac{65.15 - 64.85}{6 \times 0.0054} = 9.26 \end{aligned} \tag{2}$$

In fact, the C_p of 1.9 for conventional molding is usually acceptable, but the C_p obtained with the new molding method is revolutionary. The drawback of the above index is that it does not consider the average and nominal value of the dimension. Another index, C_{pk}, is used to describe the capability of the process to maintain an average as close to the nominal as possible. The average in the conventional molding case, 65.1667 mm., is out of the specification limits and that of the new molding method is 65.1306 mm is within specification limits. C_{pk} is defined as:

$$C_{pk} = \min\left[\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right] \tag{3}$$

In conventional molding, the one-sideed process capability index can be calculated as:

$$C_{pk} = \min\left[\frac{65.15-65.1667}{3\times 0.0262},\frac{65.1667-64.85}{3\times 0.0262}\right] = -0.212 \tag{4}$$

With multi-cavity melt control, this index increases to:

$$C_{pk} = \min\left[\frac{65.15-65.13}{3\times 0.0054},\frac{65.13-64.85}{3\times 0.0054}\right] = 1.23 \tag{5}$$

If the system were to operate under these circumstances, the percentage of non-conforming parts in the conventional case would be 73.57% [17]. In the latter, the percent non-conforming is 0.001%. Through this experimental investigation, multi-cavity melt control has shown the capability of maintaining better part consistency than conventional molding by means of controlling the pressure profiles. On every set of the eleven dimensions measured, the process capability obtained with multi-cavity melt control was 1.5 to 5 times that obtained with conventional molding.

Flexibility Results

Heightened quality and customer awareness coupled with increased use of engineering software in design and production has simplified the process of design change and has facilitated quick response to market needs. Despite this, current injection molding techniques are incapable of the flexibility needed to alter design attributes in the mold. In this research, Multi Cavity Melt Control has been used as a method to effect such responses in the injection molding industry. This section describes an experimental study conducted to demonstrate the capability of the design to change part dimensions and discusses the results and implications of the same.

The molding industry is confronted with applications requiring dimensional control in molded parts. Increased use of injection molded parts calls for processes that facilitate quick production response to part design changes. Unfortunately, the dimensions of an injection molded part, primarily controlled by the dimensions of the mold, cannot be changed so easily. The mold used to produce the part, once manufactured is ‘hard-wired’. Multi cavity melt control provides multiple degrees of freedom to the molding process that make small dimensional changes possible by tuning the material shrinkage. As demonstrated in earlier sections, multi-cavity melt controlled molding provides the ability to maintain specific pressures in the manifold cavity by means of control profiles for each of the feed valves used in the mold. Independent control of the valves, placed strategically in the mold, makes it possible to input differing control profiles at each gate, satisfying the need for dimension control at multiple locations in the part. Independent control of the valves then gives added flexibility to control dimensions at multiple locations in the part.

The design of experiments shown in Table 3 was used to investigate the dynamic and differential control of the cavity pressures. Since holding pressure is critical to part dimensions, changes were made to the holding pressure at each of the four gates keeping the fill profile unchanged. The fill profiles basically simulated an open loop condition in which the valves were asked to open fully. The flow was then suddenly regulated to attain the hold pressure demanded by the control profile. Table 3 shows the nine experimental runs with a specific hold pressure at each gate. The experiment is a 3^{4-2} design where each of the four gates is a factor and the three values of the holding pressures is a factor level. The holding pressure are 20.7 MPa (3000 psi.), 41.4 MPa (6000 psi.), and 62.1 MPa (9000 psi.).

The other machine settings were: injection pressure of 8.3 MPa (hydraulic), hold pressure of 4.8 MPa, injection speed of 50%, plasticizing speed (screw RPM) of 50%, hold pressure time of 7 seconds, manifold temperature of 250 ^{o}C, mold temperature of 60 ^{o}C, transfer point of 5 mm, and melt cushion of 2.54 mm. In each of the runs above, the profiles were changed on the control system. Since there were no thermal transients, the first five shots molded were discarded after which the next five were saved for analysis.

The process flexibility of the system is demonstrated in Figure 7 where mutliple manifold pressure profiles can be maintained in the mold cavity of a single part. In the same cycle, three different magnitudes of melt pressure were exerted at different gates in the same mold cavity. In conventional injection molding, the melt pressure would be the same at all gates. This level of process control has not previously been achieved by any molding technology thus far. Each gate can exert a specific holding pressure. The profiles are those of run number 5 where the control pressure for the holding stage at Gate 1 is 41.4 MPa (6000 psi.), Gate 2 is 41.4 MPa (6000 psi.), Gate 3 is 20.7 MPa (3000 psi.), and Gate 4 is 62.1 MPa (9000 psi.). During the filling stage, all four gates are fully open. The fill-to-pack transition is indicated by the vertical pressure drop at 2 seconds. Moments later, the differential hold pressure regimes come into play and the hold pressure at each gate is controlled accordingly. At Gate 3, the pressure drops down to reach about 19 MPa, which is not too different from the commanded pressure of 20.7 MPa. Similar control is exerted at other gates.

The material shrinkage and dimensions change at differing locations in the part based on the pressure contours and histories around the gates. The ability to change the dimension with the control profiles and the added capability of having more than one degree of freedom and hence independent control at the gates could be defined as flexibility. This property of the system can be used to make changes to the values of individual C_{pk} performance metrics mentioned in the previous section.

In general, changing the pack pressure at the gate closest to a dimension provides the major effect on part dimensions. A high hold pressure results in a higher dimension. Additionally, independent control of the valve stems provides the capability to vary dimensions at one location without interfering with dimensions at another location. This flexibility does not exist in conventional molding because hold pressure changes intended to influence one area of the part can be transmitted to other areas of the part through the static feed system.

This effect can be explained with an example focusing on dimensions #11A and #11B. Dimension #11A is preferentially influenced by Gates 1 and 2, and dimension #11B by Gate 4. Table 4 shows the two dimensions in Runs 4, 5, and 6. In these runs, Gate 1 and Gate 2 pressures remained unchanged while the pressure at Gate 4 was 41.4 MPa, 62.1 MPa, and 20.7 MPa in runs 4, 5, and 6 respectively. Dimension #11A remained almost unchanged while dimension #11B increased as the holding pressure was increased. Such observations were also made on several other dimensions and are available upon request from the authors. The system has tremendous capabilities of providing a wider range of dimensions than conventional molding as the cavity pressures can be changed almost infinitely within the limitations of the system.

Discussion

The improved flexibility and consistency of multi-cavity melt control when compared to the conventional injection molding process is clear from the previous sections. Further discussion is warranted regarding system performance as well as potential ramifications on the molding industry.

System Performance

The capability of multi-cavity melt control in controlling cavity pressure is a function of both valve design and process conditions. The reverse taper design reported in this article was synthesized after difficulties controlling flow were experienced with a conventional valve pin [10]. The new valve pin design was able to control the cavity pressure to a time response of 100 mSec. An improved time response is possible with further design optimization, but will come at the expense of an increased pressure drop to the cavity and/or higher shear rates in the feed system.

The valve pins truly act as valves, and can not act as a source of polymer flow. This behavior was observed in Figure 4. If sufficient melt pressure is not supplied by the injection unit of the molding machine, then it is not always possible for the pressure profiles to be followed. This control approach does require a significant shift in the way the molding process is set-up. Rather than specifying the flow rate and pressure profile on the machine, cavity pressure profiles are now entered for each cavity. These curves require some additional expertise in the process engineer. However, the relationships between quality and input profiles are not complex and build on the operator's existing process knowledge. Further development is underway to provide guidelines and training materials for commercial translation. It is the authors' intent to make the technology as accessible and robust as possible.

It should also be mentioned that in multi-gated parts, the ability to independently control flow can be limited due to coupling between different areas of the cavity. For instance, a very high pack pressure in one area will tend to pack out other areas of the part. If a nearby valve is told to deliver low pack pressures, the valve pin will fully shut to restrict flow to the cavity but that area of the cavity may still experience higher pressures from the other valve gate. The amount of pressure differential which can be maintained has been previously studied [10] and is a function of the melt viscosity, distance between gates, and wall thickness. In this application, approximately 30MPa could be maintained between adjacent gates. However, this pressure coupling does not occur across multiple cavities and still permits significant flexibility in multi-gated parts.

Ramifications

The concept of multi-cavity melt control is a powerful enabler for the molding industry. One exciting repercussion of the approach is the potential impact on the product and tooling development process. Currently, numerical mold filling simulations and expert judgments are combined to estimate the process behavior and make critical design decisions. If these decisions are incorrect, then tooling modifications may be required. Multi-cavity melt control’s flexibility permits correction for many design inaccuracies during the mold commissioning stage without retooling. A larger repercussion, moreover, is the potential to standardize the mold development process assuming standard feed system design, constant material shrinkage, and validated flow lengths for a family of materials at a given wall thickness. Then, multi-cavity melt control could be used to tune in the desired part properties during mold commissioning. For example, if gates were placed close to critical dimensions A and B as shown in Figure 8, tolerances could be maintained, design changes easily incorporated, and part properties of one attribute preferentially changed without being detrimental to another attribute. Design implications of this capability have been explained elsewhere [18]. Such a change in the development process could substantially reduce the tool development costs, shorten the development cycle, and hasten time to market.

The described process is also significant in that it moves polymer control from the molding machine to the mold itself. This reduces the molding machine to a ‘polymeric pump.’ Variations in injection pressure, flow rates, pack pressures, or pack times are all compensated through the closed loop cavity pressure control as reported in this article. The market repercussions could be significant, as 1) an old machine without closed loop control can provide consistency equal to modern machines, and 2) a mold commissioned on an Ube 350 ton molding machine in the United States is ensured to produce consistent parts on a Mitsubishi 390 ton molding machine overseas. The mold becomes its own self-contained quality control mechanism. As such, the potential productivity and quality gains are substantial.

Conclusions

Through the described experimental investigations, multi-cavity melt control has shown improved part consistency when compared to conventional molding. On eleven different dimensions measured, the process capability, Cp, obtained with multi-cavity melt control was 1.5 to 5 times that obtained with conventional molding. The flexibility of the system was also demonstrated by individually adjusting part dimensions by locally controlling material shrinkage. Measured dimensions could be adjusted by approximately 0.1% without retooling, a significant amount in tight tolerance applications. In complementary studies, sequential valve gate control was also demonstrated, where in addition to gate timing, fill rates, transition times, and hold pressures were independently controlled at different gates. In this set of experiments, on eleven different dimensions measured, the process capability, Cp, obtained with multi-cavity melt control was 1.4 to 8.6 times that obtained with conventional molding. Visually significant effects were also achieved with respect to knit-line location, burn marks, etc. but were not reported here due to space restrictions.

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Table 1: Experimental runs

Run No.	Melt Temp. (deg C)	Hold Pressure (MPa)	Injection Velocity (%)	Hold Time (sec.)	Screw RPM (%)
1	250	4.8	70	9	20
2	250	4.8	50	9	50
3	250	4.8	50	7	20
4	250	4.8	70	7	50
5	260	4.1	70	9	20
6	260	4.1	70	7	50
7	260	4.1	50	7	20
8	260	4.1	50	9	50

Table 2: Dimensions for both molding cases

Open Loop		Closed Loop	
Run No.	Dim. #2 (mm.)	Run No.	Dim. # 2 (mm.)
1	65.1994	1	65.1264
2	65.1788	2	65.1196
3	65.1968	3	65.1132
4	65.1854	4	65.1256
5	65.136	5	65.122
6	65.1506	6	65.1246
7	65.148	7	65.1282
8	65.1386	8	65.1306
Mean	65.1667	Mean	65.1237
Std. Dev.	0.0262	Std. Dev.	0.0054

Table 3: Design matrix used in flexibility study

Run No.	Gate 1 (MPa)	Gate 2 (MPa)	Gate 3 (MPa)	Gate 4 (MPa)
1	20.7	20.7	20.7	20.7
2	41.4	20.7	62.1	41.4
3	62.1	20.7	41.4	62.1
4	20.7	41.4	41.4	41.4
5	41.4	41.4	20.7	62.1
6	62.1	41.4	62.1	20.7
7	20.7	62.1	62.1	62.1
8	41.4	62.1	41.4	20.7
9	62.1	62.1	20.7	41.4

Table 4: Contrast in dimensions along part length

Run No.	Dim. #11A (mm.)	Dim. #11B (mm.)
4	118.4452	74.4454
5	118.4432	74.4716
6	118.4456	74.4316

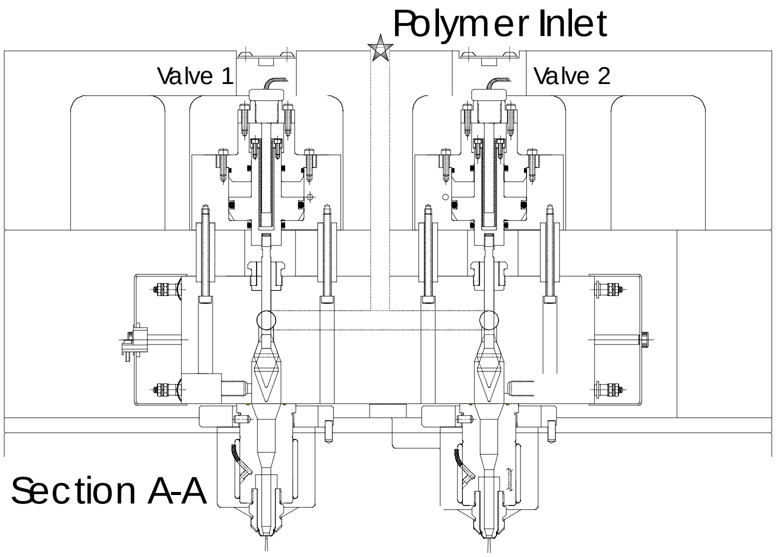

Figure 1: Valves to meter the flow of melt into the cavity

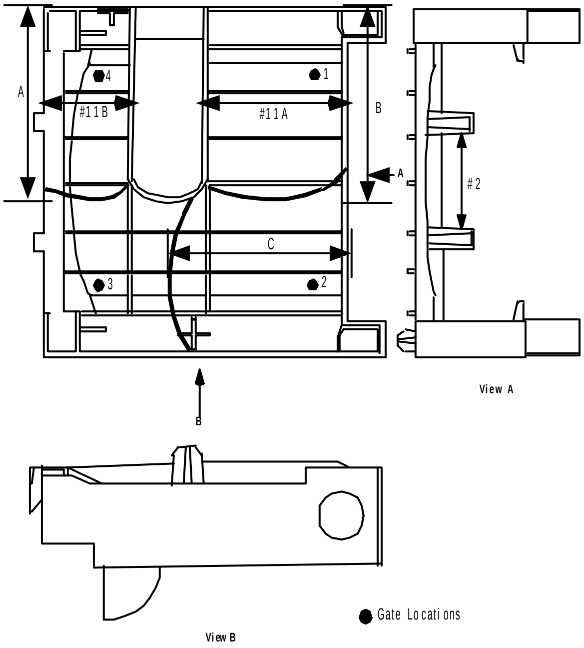

Figure 2: Printer output tray

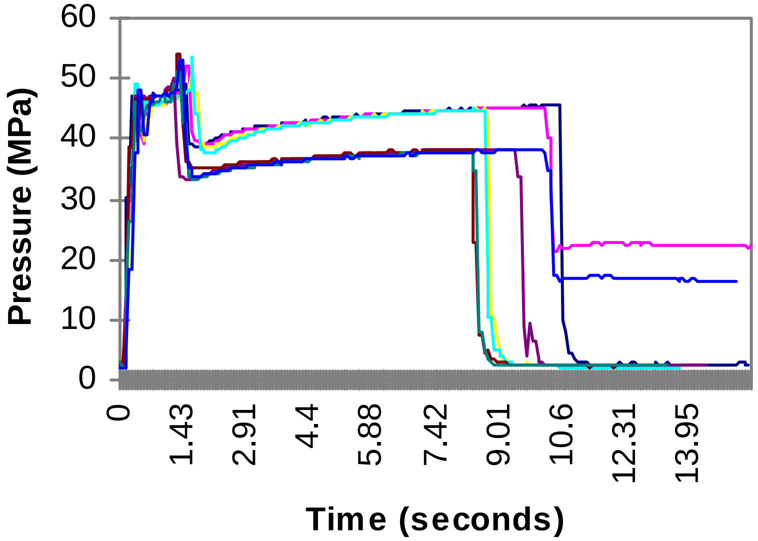

Figure 3: Melt pressure profiles for conventional molding

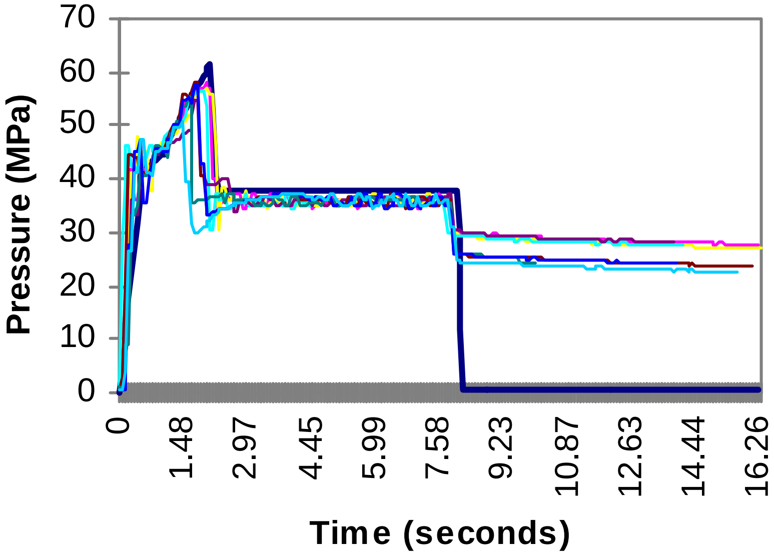

Figure 4: Melt pressure profiles for multi cavity melt control molding

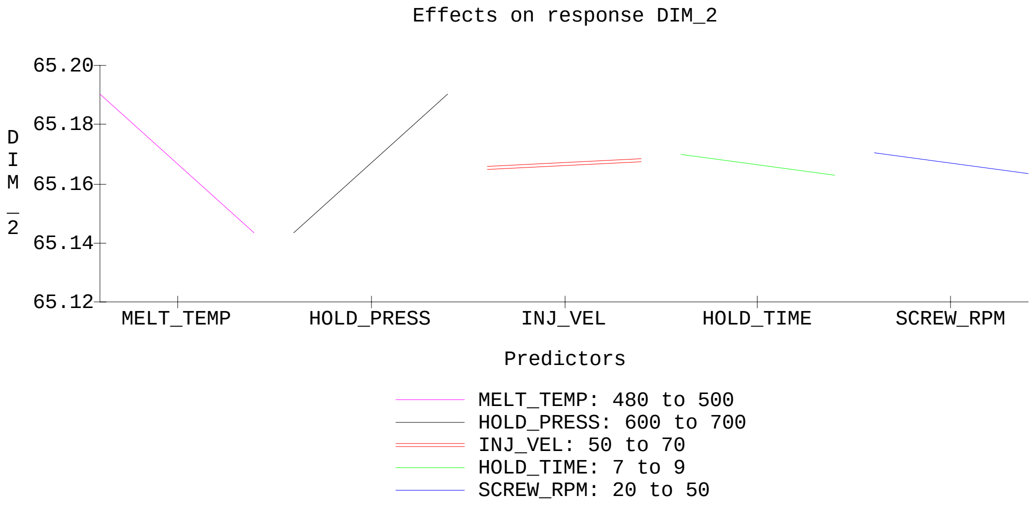

Figure 5: Effects plot for conventional molding

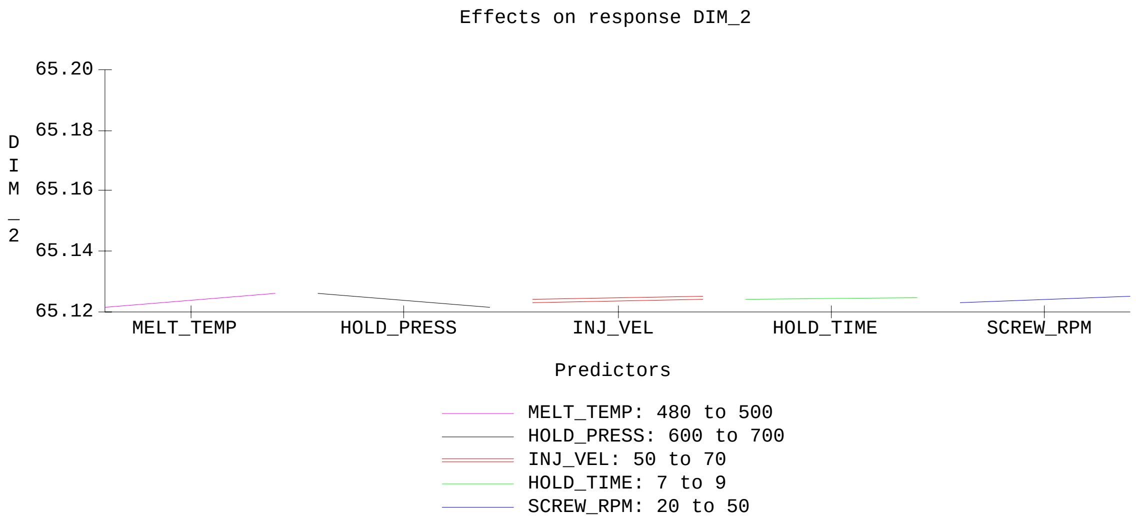

Figure 6: Effects plot for multi cavity melt control molding

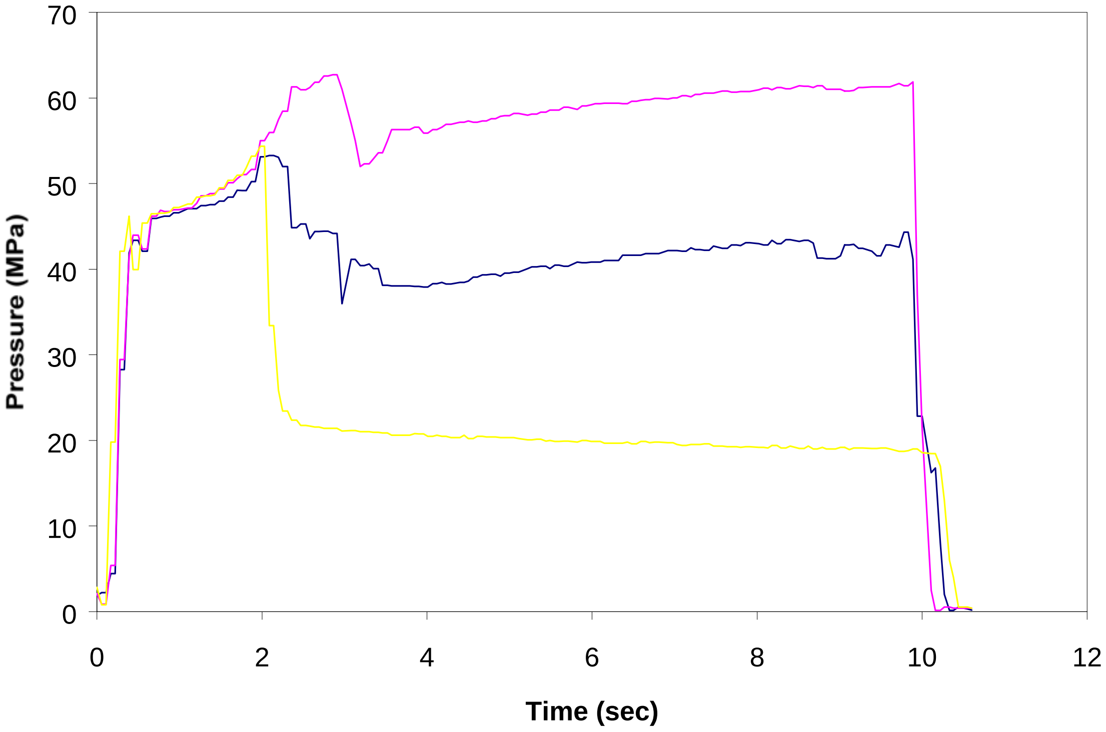

Figure 7: Output pressures at multiple gates in a single cycle

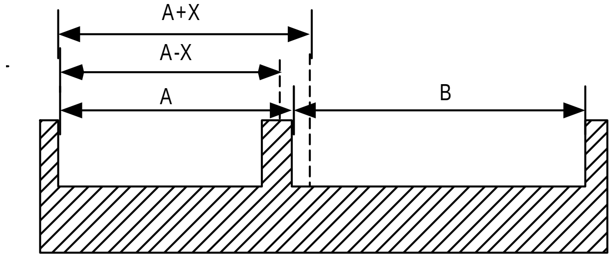

Figure 8: Schematic of flexibility in dimensions