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AN INVESTIGATION OF CAVITY PRESSURE AS A PROCESS AND QUALITY INDICATOR IN THE MICRO-INJECTION MOLDING PROCESS

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AN INVESTIGATION OF CAVITY PRESSURE AS A PROCESS AND QUALITY
INDICATOR IN THE MICRO-INJECTION MOLDING PROCESS

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ABSTRACT

Increased demand for micro-scale parts and devices is being met in many cases by micro-injection molding of polymer parts. However, part inspection is difficult due to the micro-scale dimension in the micro-injection molding process. In addition, process control also becomes challenging since the process is susceptible to slight changes in process parameters such as mold temperature, injection velocity, and packing pressure. To address these issues, a suitable process monitoring method such as cavity pressure monitoring can be employed to detect any process deviation that may cause defects in part quality. Cavity pressure has been found to be a reliable process indicator in injection molding for both part quality and process monitoring. Specifically, it has been found to provide real-time detection of part and process deviation. As such, cavity pressure measurement holds potential for monitoring part quality in micro-injection molding where direct part inspection is difficult and often costly due to part handling issues and microscopic feature sizes. The goal of this study is to determine the feasibility and robustness of using cavity pressure for process and quality monitoring of a molded hollow cylindrical cap.

Molding of the small cap was conducted using polypropylene under varying processing parameters to observe how cavity pressure responded to the different molding conditions. Initial investigation was carried out by varying different processing parameters that include injection velocity, pack pressure, and mold temperature. The investigation was followed by altering the switchover settings while keeping other

parameters unchanged. The final part of the investigation involved using the Design of Experiment approach to include a broader range of processing parameters.

Although the processing window for micro-injection molding was smaller than macro-molding, the cavity pressure curves were able to capture the differences in molding conditions. Furthermore, attributes obtained from the pressure curve such as peak cavity pressure and area under curve were found to have good correlation with part weight which was used as the quality metric. In terms of defects among the parts, both peak cavity pressure and area under curve were able to detect defective parts based on the measured peak cavity pressure value and the calculated area under curve. The finding from the current investigation demonstrates significant potential for cavity pressure to be utilized as an indicator of part quality as well as a process monitoring tool for the micro-injection molding process.

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CHAPTER 1

INJECTION MOLDING PROCESS

Conventional Injection Molding

Among all the processing methods of polymers, injection molding process accounts for approximately 32% by weight of all the plastic material processed [1]. It is one of the most important, versatile, widespread, and cost-effective operations in the mass production of complex plastic parts. This process involves melting plastic pellets and shaping this melt under high pressure in a closed mold to produce the plastic component required. Although injection molding is mainly applicable in the molding of thermoplastics materials [2], the process has also being extended to other materials such as thermosets, fibers, powder, and ceramics[1]. In terms of processing parameters, there are many variables that are interrelated to each other, such as pressure, temperature, viscosity, density, time, and velocity. Some of those variables vary throughout the processing stages. For example, a high velocity is required during the injection phase while a low velocity is needed in the packing phase. Therefore, a good interaction and combination among the variables are important in order to produce a high quality and economical plastic part. Despite the complexity, injection molding is important in manufacturing in part because intricate shapes and good dimensional accuracy parts can be easily replicated since the material is molten when being injected into mold [2, 3]. Moreover, injection molding is economical because most molded parts do not require secondary and assembly process. Mechanical properties as well as physical appearance

such as color are tailorable through the plastic materials/resins [4]. In addition to low manufacturing cost, such benefits like reduced cycle times and high process repeatability in large-scale production have it feasible in polymer manufacturing.

The machines required for injection molding process are categorized by the machine's capacity, which refers to the tonnage it takes to clamp the mold and the amount of materials that can be injected into the mold per cycle [4] . Although the tonnage and shot size vary from machine to machine, the operating principal is similar as illustrated in Figure 1. It begins with plastics pellets being fed into the machine through a hopper. The pellets then enter into the injection barrel through gravity. After entering the barrel, the plastic pellets are heated to the appropriate melting temperature depending on the type of polymer. The next phase is the plastication phase, where the screw begins to rotate, moving backward to blend the polymers, and prepare the correct amount of material for the initial shot. The moving platen is then moved to match the stationary platen and locked by the locking mechanism such as toggle mechanism. Next, the screw advances axially forcing the melt into the cavity of the closed mold. After this injection phase, the screw again rotates and moves backward to plasticate the polymer for the next shot. The mold is opened after the melt has solidified enough to be ejected [3, 5]. Examples of products fabricated through this process include cell phone casing, containers, paper clips, hangers, toys, and car bumper.
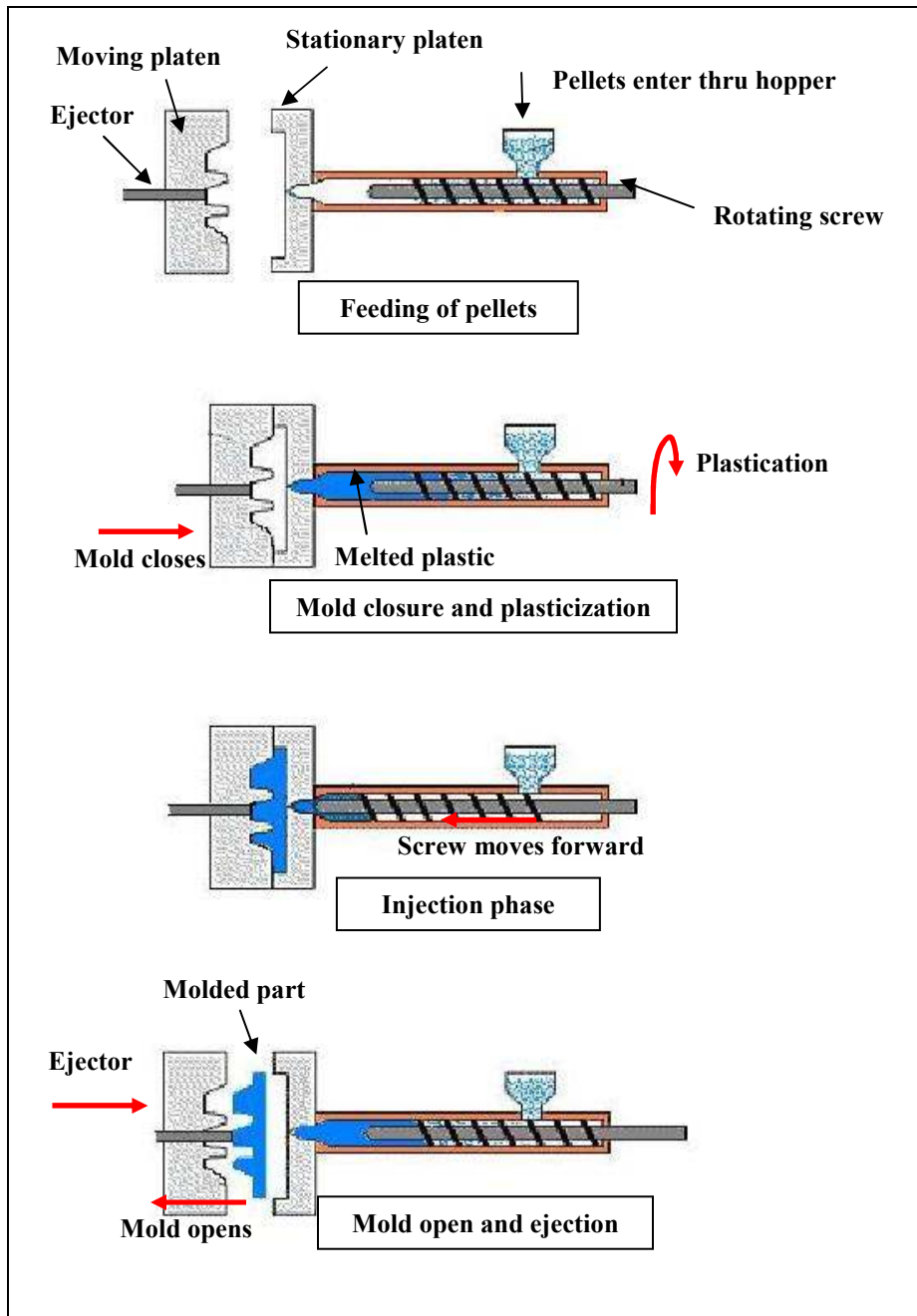
Figure 1: Injection Molding Process

Micro-Injection Molding

Injection molding has been used to make parts in a wide variety of sizes from small size parts such as paper clips to large size parts such as car bumpers. However, the current global focus on miniaturization has led to an increased demand for increasingly smaller parts. These very small "micro-parts" weigh less than a milligram with the largest overall dimension on the order of 1mm or less. Examples of micro-parts include the micro-rotors, locking wheel, and micro-latches commonly used in the watch industry (see figure 2); micro-parts for medical applications; and the micro-pumps, micro-gears, pressure sensors, and ink-jet printer heads found in various other industries [6]. These micro-parts can be produced using other manufacturing processes such as UV-lithography, LIGA (a German acronym for lithography, electroplating, and molding), micro-EDM, deep reactive ion etching, excimer laser ablation, and micro-milling, among others. However, many of these processes are too expensive and time-consuming for manufacture of individual parts in large volume, they are suitable for the fabrication of mold inserts, which then are used to manufacture thousands of micro-parts through the micro-injection molding process. Since the cost of the materials needed is usually inexpensive as only small amounts of are required for these parts, this process has become the most effective method of producing large quantities of inexpensive micro-parts [7].
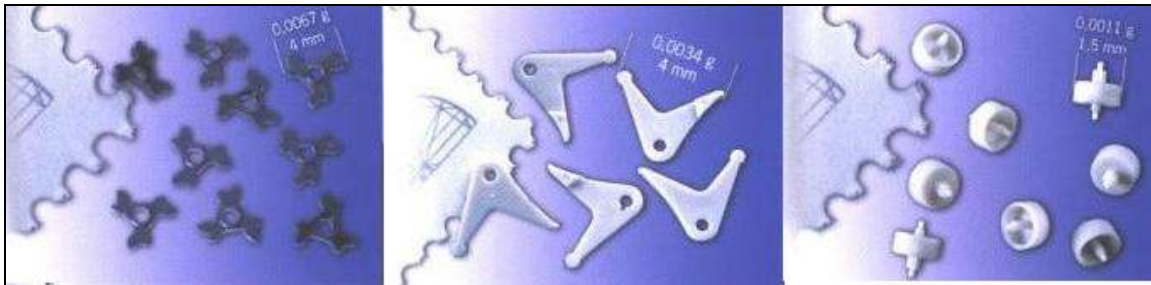
Figure 2: Examples of Micro Parts: Locking Wheel, Micro-Latch, Micro-Rotor [8]

Micro-injection molding uses the same fundamental process as conventional injection molding: First, the molds are closed, followed by the injection of the polymer melt to fill the cavity, and the subsequent cooling process to solidify the melt. Finally, the molds are opened and the part is ejected. Although the overall principal is the same for production of macro or micro-sized parts, difficulties arise with respect to the equipment and mold fabrication, simulation software, and processing when it is scaled down to the micron level.

Equipment and mold fabrication

Conventional injection molding machines and the equipment used to fabricate the molds are typically not suitable for micro-injection molding process due to the small dimension involved. Using conventional injection molding machine to manufacture parts with micro-dimension and high accuracy generates issues such as polymer degradation, shot volume, and shot accuracy since micro-parts are sensitive and susceptible to small variation that may be critical to the part quality and process. In terms of mold fabrication, conventional fabricating equipments encounter limitation in making mold with micro-

features. The conventional equipments are not well designed to cater for such high accuracy machining operations as the differences in tolerances between micro parts and conventional parts are huge.

Equipment

One area of concern involves the machinery needed to produce an accurate small shot. Given the size of the most standard plastic pellet, the minimum applicable diameter of the injection screw is 14 mm [9], meaning that any screw diameter smaller causes screw slippage and damages to the screw during plastication [10, 11]. However, an injection screw of this size makes it difficult to produce micro-parts weighing less than 0.1g as a small movement of this 14mm screw produces a volumetric shot size larger than required [9-11]. Hence, using conventional injection molding machine to produce micro-parts is not the ideal way.

In addition to the screw size, shot accuracy is affected by injection velocity and pressure. In micro-injection molding, high velocity and high injection pressure are required during the injection stage to avoid premature freezing and the hesitation effect. The hesitation effect is the formation of a thin stagnant layer of the polymer melt that is in contact with the mold surface. The high velocity and injection pressure applied to solve the premature freezing and hesitation effect are difficult to control and monitor because these parameters reduce the processing time. This issue is compounded because, while small variations in the process may not be apparent in conventional macro-part,

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they can be crucial in micro-parts. As a result, producing a consistent volumetric shot size through micro-injection molding is challenging.

Currently, new machines on the market designed specifically for micro-injection molding application are capable providing accurate and small shots for the micro-injection molding process. For example, the Battenfeld Microsystem 50 as shown in Figure 3 uses a separate plasticizing screw, a melt dosage control barrel, and a plunger injection system to control the metering accuracy of a small volume of melt [12, 13]. A second micro-injection molding machine, an electro-pneumatic machine known as the Sesame from Hull Corporation (see Figure 3), can control plunger position to within 5 μm. The size of the plunger for injecting the melt in this machine can be as small as 1.5mm diameter. With such a small plunger and screw movement resolution, this machine is capable of producing a more accurate shot size than the conventional injection molding machine [14].

Figure 3: Battenfeld Microsystems 50 (left), Sesame (right)[8, 15]

Mold Fabrication

Due to the small size and tight tolerance of micro-parts, most of the conventional machining methods are not suitable for fabricating micro-size cavity. New tool fabrication methods have been developed, combining the conventional machining and micro-electro-mechanical systems (MEMS) technologies to meet the needs of fabricating small and detailed cavities with the required tolerances and surface finishes [13]. Mold inserts for micro-features are composed of either metal or silicon with the latter exhibiting better surface qualities. However, silicon is not as durable or as long lasting as metal. Therefore, silicon is often used in small production runs which do not need long mold lifetimes [16].

Common methods of fabricating those micro-cavities are: a) LIGA method, for silicon tool, b) mechanical micro-machining processes such as micro-milling, micro-electro-discharge (EDM), micro-grinding, and micro-drilling, for metallic tools. The latter are popular among mold makers because they offer high precision machining capabilities by using techniques familiar to existing injection tool makers. However, the resulting surface is not as smooth as that from the LIGA method, the surface roughness (R_a) of the former being in the range from 0.3~1 micron, while the LIGA method produces surface roughness with R_a approximately of 50nm [17, 18]. The smooth surface has been shown to provide proper demolding even though without a draft angle [19]. Another advantage of LIGA method is its capability of replicating micro-features such as narrow grooves/channels and sharp corners that is not achievable by mechanical milling

[20]. However, the LIGA method usually takes a significant period of time. Therefore, it is used only when high aspect ratio and high quality surface finish are needed.

Simulation Software

In the conventional injection molding process, simulation software tools are widely used in the part and mold design process as well as to determine the optimal molding parameters before fabricating the mold and running the molding process. Doing so helps to save time and cost by eliminating unnecessary machining error and trial runs. However, simulation software tools development for micro-injection molding is technically behind than other aspects of this process. Many researchers who have applied conventional simulation tools to micro-injection molding found that these tools are not entirely suitable for micro-injection molding. Bibber [21] argued that it is difficult to obtain reliable results from current simulation software since little simulation software has been specifically developed for micro-injection molding. In particular, Yuan et al. [22] concluded that conventional simulation software cannot define accurately the small dimensions needed in simulating the micro-injection molding process. According to Weber et al. [17], factors causing uncertainties in simulation results include some the incapability of the software to take into account the surface roughness, the existence of side surfaces, and the viscosity in such a short filling time.

Process

Although the overall working principal in micro-injection molding is similar to the conventional injection molding process, there are some additional steps that are sometimes used to ensure that quality parts are produced. The two primary ones are external evacuation and mold temperature cycle [23].

External Evacuation

During the injection phase, air trapped inside the cavity compressed by the hot polymer melt. Under sufficient compression, the air may combusts and it may burns the plastic materials (diesel effect) [19, 23]. In conventional injection molding, this trapped air is seldom an issue as air in the cavity escapes through a small venting hole. However, in micro-injection molding, this small hole is approximately the size of the micro features, affecting the quality of the molded parts. As a result, an external evacuation system is sometimes needed to evacuate the air from the cavity prior to injection phase.

Mold Temperature Cycling

Due to the high aspect ratio involved in micro-features, the polymer melt freezes very quickly upon contact with the relatively cool mold surface, creating defects such as short parts and weld lines. To help combat these problems, the mold temperature is controlled in the micro-injection molding process. In this step, before the melt enters the cavity, the mold temperature is raised to near the glass transition temperature to prevent premature freezing [19]. After the cavities are filled, the temperature is lowered until the

strength of the molded part is sufficient for demolding. This dynamic change in temperature from a hot mold surface during the injection stage and a cold surface at demolding is known as variothermal temperature control. The importance of this temperature control is supported by Despa et al. [24] who found that injection velocity has little impact on the filling when the mold is heated. They concluded that heated molds lead to the complete filling of the micro-structure while a cold mold increased the risk of premature freezing and under filled [24]. However, the disadvantage of this temperature control is a significant increase in cycle time. Depending on the type of resin, up tp several minutes may be needed to heat and cool the mold [7, 18]. This extended cycle time not only reduces the production rate but also causes polymer degradation. In the micro-injection molding process, the polymer melt usually remains in the barrel for a significant amount of time due to the small amount of melt that is needed in every shot. This extended residence time often leads to thermal degradation of the material in the barrel.

As a result, several methods have been explored to reduce the time required for variothermal process while still achieving targeted temperature control. Mold heating can be done using water, oil, induction, and electric current [25-27]. However, water heating is limited as it can heat the mold to only 100°C unless the water is pressurized. Another disadvantage of this method is the response time; specifically Chang et al. [28] found that water heating took more than 10 minutes to raise the mold temperature from 60 °C to 100 °C while induction heating only took 2.5 seconds. Yao et al. [29] have actively been investigating the rapid thermal response (RTR) injection molding process, focusing on

raising and cooling the mold temperature in a short amount of time. They successfully constructed a mold insert consisting of a heating layer, an insulating layer, and a copper electrode. This mold insert was found to increase the mold temperature from 25°C to 250°C in 2 seconds and then cool it to 5°C in 9 seconds. Employing the same RTR injection molding process to replicate a high aspect ratio micro-well, the researchers concluded that a mold temperature above the polymer melting point is needed for good replication. Due to the rapid response of the RTR process, the entire cycle time was only 15 seconds [30].

Process Monitoring Method

Although some of these concerns mentioned in the earlier paragraphs have been addressed, at least partially, there is still room for improvement in the process. Because micro-injection molding is a relatively new technology, emerging in the 1970's [20], researchers and manufacturers are motivated to continue conducting both theoretical and practical research in the field to meet the increasing global demand of miniaturized parts production. One of the most important areas of this investigation involves developing a stable process monitoring method for detecting process deviation and predicting part quality.

Similar research in conventional injection molding, has found that the processes and the polymer melt behavior in the mold, crucial for finished part quality, cannot be monitored directly. There have been attempts to study these processes and this behavior by means of machine parameters, such as hydraulic pressure; however those methods do

not provide promising results because solidification and melt compressibility cannot be detected [31]. Moreover, machines parameters involve much interaction between different machine process settings and are always affected by the machine behavior. On the other hand, cavity pressure is a direct indication of the condition of the polymer melt inside the mold, providing real-time monitoring of each phase during the process. Continuously recording cavity pressure not only results in useful information about melt behavior during the different stages but also allows for early detection of deviations in the process. Process and machine settings in conjunction with the cavity pressure allow for part quality to be predicted accurately.

Because of the importance of the relationship between cavity pressure and the injection molding process, much research has focused on this measurement as the closed-loop controlled parameter in the conventional injection molding process since the 1970's. Plant and Maher [32] found that cycle time is minimized by monitoring the cavity pressure profile as it provides the correct gate freeze-off time. They also concluded that cavity pressure is a direct indication of how the polymer melt behaves in the mold during the molding process. Golden et al. [33] determined that the application of cavity pressure control in the injection molding process could provide better consistency in both process and part quality, while Abu Fara et al. [34] investigated the possibility of attaining reasonable control of cavity pressure during the process. In addition, extensive research on controlling of this cavity pressure has also been conducted by Gao et al. [35-37]. They successfully developed cavity pressure control systems that operate throughout the

injection, packing, and cooling phases. With the systems, parts weight variation was found to be within 0.05% for more than 100 molding cycle.

In terms of relating cavity pressure to part quality, experiments conducted by Angstadt et al. [38] showed that cavity pressure has the potential to be a significant indicator of part quality. The general shape of the cavity pressure curve provides useful information regarding molding stages, process variation, and major part defects. This information can be enhanced by accurate models developed to relate part quality with cavity pressure attributes for a particular combination of machine/mold/polymer.

More recently, Min [39] has monitored the quality of injection molded parts by employing indirect control parameters, including maximum cavity pressure, part weight, maximum nozzle pressure, and cavity pressure at the end of holding phase. In this study, he obtained an optimized processing condition by correlating optimal shrinkage and the aforementioned parameters. Part weight and maximum cavity pressure appeared to be more accurate parameters in reflecting the molded part quality than the other two. These results support the potential of cavity pressure to as an indicator of part quality [39]. In a real-world application, Payne et al. [40] successfully demonstrated how such a process monitoring system utilizing both cavity pressure and hydraulic pressure improves part quality, process consistency, productivity, and profitability in a large scale manufacturing facility..

Specifically related to the micro-injection molding process, Whiteside et al. [41] found that cavity pressure is a better indication of part quality than injection pressure. This is because injection pressure is a measurement based on the pressure value

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experienced by the screw, whereas cavity pressure is a direct measurement of the change of phases and pressure inside the cavity. Their experimental work compared different molding conditions, injection pressure, and cavity pressure. Their results demonstrated that injection pressure showed little response to changes in the molding conditions. On the other hand, cavity pressure responded to process changes reflected in the peak and the integral values. Similar finding from Tat Ming Engineering Works Ltd. [31], an injection molding company based in Hong Kong, suggested that peak cavity pressure is the ideal attribute for monitoring thin wall injection molding, a feature common to most micro-injection molding processes.

Although cavity pressure has been used for basic process monitoring in micro-injection molding, little research has been conducted on the behavior of the pressure curve in response to process variation [13, 41]. To address this need, the research presented herein will investigate the robustness of cavity pressure to detect process deviation and predict part quality in the micro-injection molding. If promising results are obtained, the part quality can be determined without physical inspection; meaning an automated sorting system can be used in manufacturing plants to separate defect parts with minimum need of human interactions, thereby reducing cost associated with handling and inspection.

CHAPTER 2

METHODOLOGY

Experimental Apparatus

The experimental work was conducted on a 17-ton Cincinnati/Milacron Fanuc Roboshot Si-B17 as shown in Figure 4. This machine is an electric servo-driven injection molding machine having a screw diameter of 16 mm. A hollow micro-cap (see Figure 5) with a 1mm outer diameter, overall height of 3mm and wall thickness of ~0.1mm was molded for the study. The top portion of the part consists of a ~0.5mm thick cap with diameter of 2mm. A 0.793 mm diameter eject pin was inserted on the moving platen through the 1mm diameter cavity hole to act as a core pin. On the stationary platen, a flush-mount pressure transducer is installed and acted as part of the cavity. Both cavities on moving and stationary platen were machined out of a 2.5 in. x 2.5 x 0.5 inch stainless steel insert which were then mounted in larger mold plates. The platen assemblies were fitted on MUD U-type mold frame. The final produced part weighs approximately 2.4 milligrams with aspect ratio of ~30 on the annular wall section. Figure 6 shows the size of two micro-molded caps relative to a U.S. dime.

Figure 4: Milacron Roboshot Si-B17
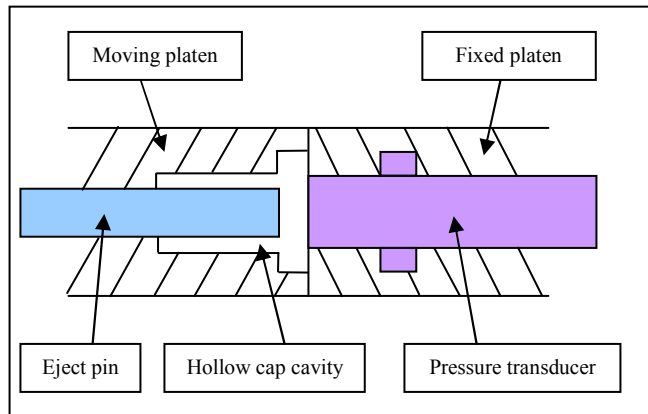
Figure 5: Construction of Hollow Cap Cavity

Figure 6: Molded Hollow Caps Relative to a U.S Dime

Cavity melt pressure was measured using a 1 millimeter diameter Kistler 6183A piezoelectric pressure transducer as shown in Figure 7. The voltage signal was amplified by a Kistler 5122 charge amplifier, conditioned by a SCB-68 signal conditioning module, and then received by a NI PCI-6229 National Instrumentation data acquisition card. The resulting pressure data was then recorded by using National Instrument Lab View graphical programming software. Both pressure signals and elapsed time were recorded for each shot at a sampling frequency of 100 hertz. Figure 8 shows the overall experimental apparatus.

Figure 7: Kistler 6183A Pressure Transducer
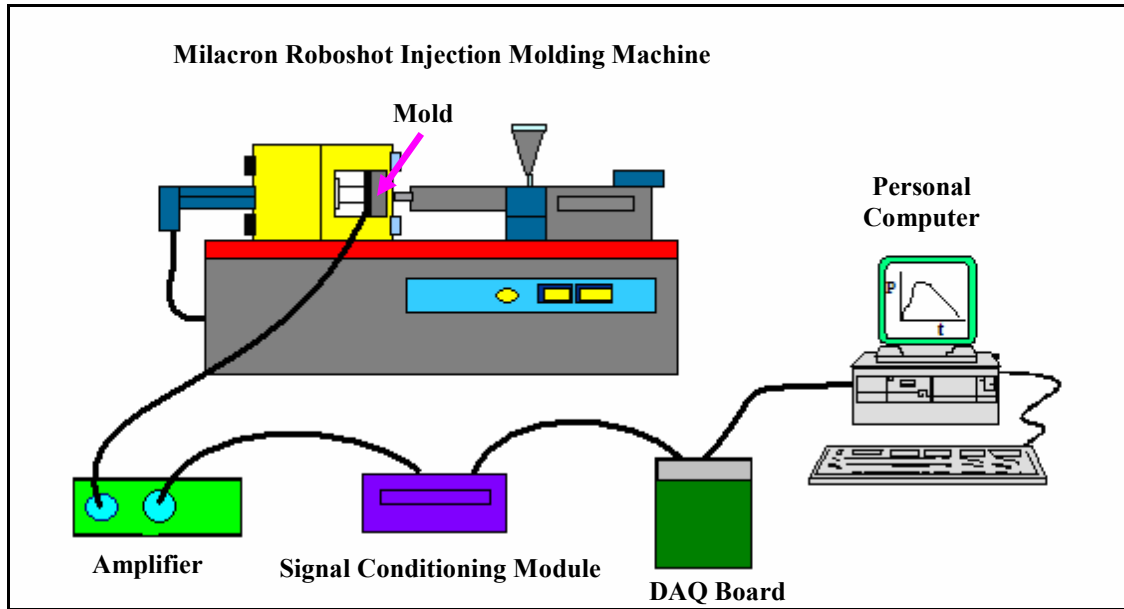
Figure 8: Connection of Experimental Apparatus

Two types of polymer were employed in this study: polypropylene – a semi crystalline material, and polystyrene – an amorphous material. Table 1 shows the properties for two different polymers. In the current study, most of the experiments were conducted by using polypropylene which polystyrene was used only to investigate the difference in cavity pressure behavior between the two different types of polymer.

Table 1: Materials Properties of Polypropylene and Polystyrene

	Polypropylene	Polystyrene
Density	0.9 g/cc	1.05 g/cc
Melt Flow Rate	11 g/10 min	9g / 10 min
Processing Temperature	200 ℃ - 232 ℃	171 - 282 °C

<u>Experiment Trials</u>

Because part removals from the mold and data collections were done manually, all the experimental trials were performed in the semi-automatic mode. For each trial, numerous shots were performed before actual samples were taken. This is done to allow the molding machine to reach stability or steady state. Several different experimental trials were conducted throughout the course of this work. A detailed explanation of each will be presented in the experimental setup section of individual chapter from Chapter 4 to Chapter 6. However, the following paragraphs will outline summary information regarding the experimental trials.

(I) Initial Trial

Before utilizing cavity pressure as process indicator, the sensitivity of pressure curve was investigated. Different molding conditions such as injection velocity and pack pressure were varied to check the capability of cavity pressure in sensing the differences. Here, only one molding parameter was varied among the trials within the same set of experiment. In addition to processing parameter, different types of polymer were employed in the experiment as well.

(II) Part Quality and Cavity Pressure

The next investigation was on how cavity pressure responds differently with respect to different part quality. Here, different switchover settings were used to provide different types of short part, all other process parameters remained unchanged.

For every trial with different switchover setting, 20 shots were produced and the weights were measured. The part weight is considered as the part quality indicator since it is a parameter that is quick and easy to measure.

To study the effect of pack heated mold and pack pressure on cavity pressure curve, two additional trials were conducted with heated mold and pack pressure. The trials were conducted based on the previous trial that produced the best quality parts in the previous experiment.

(III) DOE Trial

The final part of the investigation was to expand the processing range window to investigate the effect of processing parameter on part weight and the correlation between cavity pressure and part weight. The experimental trials were conducted using a 3-parameter, 3-level orthogonal array. The three machine parameters chosen for this set of experimental trials were mold temperature, melt temperature, and pack pressure. For every trial with different combination of processing settings, 30 shots were produced and the weights were measured.

CHAPTER 3

STRUCTURE OF THE THESIS

The structure of the thesis has been organized as a compilation of conference-ready papers. The outline of the thesis starts with a general abstract, introduction/background, methodology, chapters of conference-ready papers, conclusion, and references. Each chapter from Chapter 4 to Chapter 6 acts as an individual conference paper with the general structure of a conference paper. Therefore, some of the information found in the intermediate chapters such as introduction and experimental setup maybe repetitive because these chapters are meant to be stand-alone papers. To provide a general overview, the following section shows the abstracts for each paper that make up Chapter 4 to Chapter 6.

Chapter 4: In-situ Cavity Pressure Monitoring in the Micro-Injection Process

Cavity pressure has been found to be a reliable process indicator in injection molding for both part quality and process monitoring. Specifically, it has been found to provide real-time detection of part and process deviation. As such, cavity pressure measurement holds potential for monitoring part quality in micro-injection molding where direct part inspection is difficult due to part handling issues and microscopic feature sizes. The goal of this study is to determine the feasibility and robustness of using cavity pressure for process and quality monitoring of a molded hollow cylindrical cap. Although the processing window for micro-injection molding was smaller, the different

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shapes of cavity pressure curves showed that the pressure was able to respond differently to different molding conditions.

Chapter 5: Process Monitoring in the Micro-Injection Molding Process

Due to the micro-scale dimensions in the micro-injection molding process, it is difficult to inspect the part quality without using costly microscopic observation methods. To address this issue, a suitable process monitoring method such as cavity pressure monitoring can be employed to detect any process deviation that causes defects in part quality. The objective of this study is to investigate how cavity pressure responds to different molding conditions that lead to varying part quality of a molded hollow cap.

Chapter 6: Quality and Process Monitoring in the Micro Injection Molding Process

Due to the tendency of miniaturization in technical products, the market of MEMS/MST (Micro-Electro-Mechanical Systems/Micros-System Technology) has been growing rapidly since the last decade. In order to meet the market demand in micro-parts, there have been lots of research efforts focusing in developing new fabrication method for micro-parts or improving existing techniques. Micro-injection molding is one of the most economical ways to manufacture micro-parts. However, there are issues on process and part quality consistency involved. The micro-scale dimension and small processing window makes part inspection and process control become challenging. Furthermore, the process is susceptible to slight changes in process parameters such as mold temperature,

injection velocity, packing pressure. To address this issue, cavity pressure is employed to monitor the molding process and predict part quality. The objective of this investigation is to study the robustness of cavity pressure as process and part quality in a wider range of molding conditions by employing the DOE approach.

CHAPTER 4

IN-SITU CAVITY PRESSURE MONITORING IN THE MICRO-INJECTION MOLDING PROCESS

Introduction

In micro-injection molding, similar to other manufacturing processes, one important objective is to obtain a consistent part quality. However, physically inspecting micro-parts is usually more difficult than inspecting conventionally molded parts primarily because of the difference in size[11]. Inspecting micro-parts requires extra attention because the part features and defects are smaller and therefore more difficult to detect. To address this issue, a number of microscopic and surface evaluation measurement techniques including atomic force microscopy (AFM) and scanning electron microscopy, have been applied by manufacturers and researchers. These methods provide accurate inspection results, however they are time, labor, and capital intensive.

One possible method for reducing the cost of inspection while still guaranteeing quality in micro-injection molding is to use cavity pressure measurement for detection of part deviation, as currently used in the conventional molding process. This process includes relating process variation and part quality by monitoring the cavity pressure curve during the molding process. In the conventional injection molding process, it has been found that cavity pressure can provide early detection of process and part deviation[38, 42, 43]. This pressure is also an important parameter in the injection molding process, as it is a direct indication of the phases throughout the molding cycle.

The injection molding process cycle can be observed by continuously monitoring the cavity pressure curves during the molding process. As a result, the relation between cavity pressure and the injection molding process has been the focus of much research in conventional injection molding[34-36].

An example of how cavity pressure curves behave in a conventional injection molding process is shown in Figure 9. It is a combination of different pressure curves under different processing conditions of a conventional size molded part. From this figure, it is obvious that pressure curve can vary dramatically as a result of changes in different molding parameters. This is beneficial, as one wants cavity pressure to be a sensitive and responsive indicator of process variation. Despite the differences in slope, peak value, area, and cycle time among the curves, they share similar trend: rise during filling and packing stage, a slight rise during holding phase, and then the curves decay smoothly when the part started to cool down and shrink.
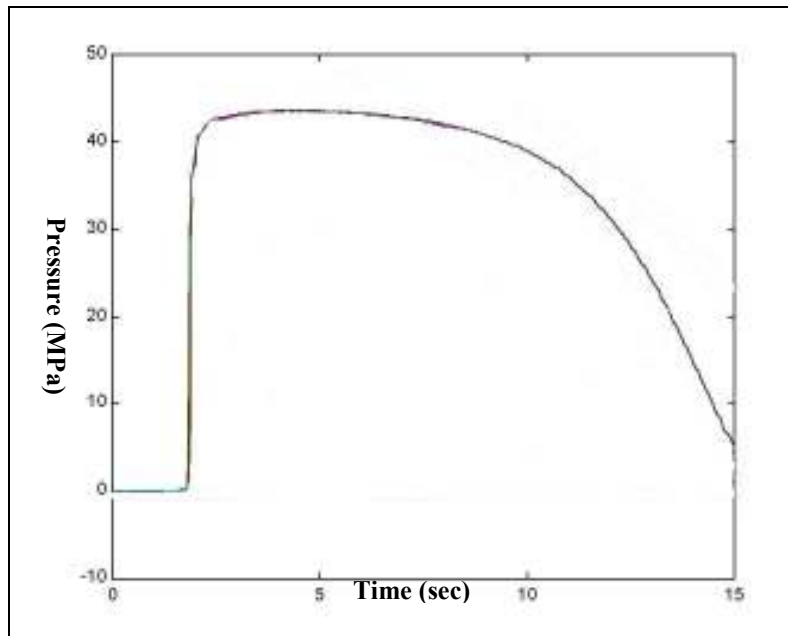
Figure 9: Pressure Curves for Conventional Injection Molding Process[44]

In micro-injection molding, although cavity pressure has been used to perform simple process monitoring[13, 41], to date, little research has been conducted to relate the behavior of the pressure curve to changes in process parameter and part quality.

Experimental Setup

The experimental work was conducted on a 17-ton Cincinnati/Milacron Fanuc Roboshot Si-B17 as shown in Figure 19. This is an electric servo-driven injection molding machine having a screw diameter of 16 mm. A hollow micro-cap (see Figure 20) with a 1mm outer diameter, overall height of 3mm and wall thickness of ~0.1mm was molded for the study. The top portion of the part consists of a ~0.5mm thick cap with diameter of 2 mm. A 0.793 mm diameter eject pin was inserted on the moving platen

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through the 1mm diameter cavity hole to act as a core pin. On the stationary platen, a flush-mount pressure transducer is installed and acted as part of the cavity. Both cavities on moving and stationary platen were machined out of a 2.5 in. x 2.5 x 0.5 inch stainless steel insert which were then mounted in larger mold plates. The platen assemblies were fitted on MUD U-type mold frame. The final produced part weighs approximately 2.4 milligrams with aspect ratio of ~30 on the annular wall section. Figure 21 shows the size of two micro-molded caps relative to a U.S. dime.

Figure 10: Milacron Roboshot Si-B17
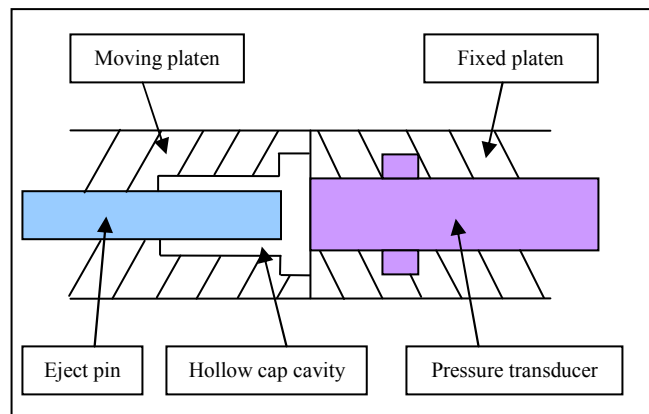
Figure 11: Construction of Hollow Cap Cavity

Figure 12: Molded Hollow Caps Relative to a U.S Dime

Experimental Trial

In order to study the feasibility of employing cavity pressure to monitor process variation and micro-molded part quality, different molding conditions were utilized to investigate how cavity pressure responds to the differences in molding parameters such as injection velocity and pack pressure. Table 2 shows the molding conditions for two different experimental trials that illustrate the effect of injection velocity. In this set of experiments, all other settings were hold constant except for injection velocity. Additionally, three experimental trials were conducted to show how cavity pressure responds to differences in the pack pressure. Here, only pack pressure settings were changed while other processing parameters remain unchanged. Molding conditions for these three trials are shown in Table 3.

Table 2: Molding Conditions for Trials with Different Injection Velocities

	Trial 1	Trial 2
Pack Pressure (MPa)	75	75
Injection Velocity (mm/s)	**304.8**	**152.4**
Switchover Position (mm)	3.04	3.04
Barrel Temperature (ºC)	210	210

Table 3: Molding Conditions for Trials with Different Pack Pressure

	Trial 1	Trial 2	Trial 3
Pack Pressure (Mpa)	**75**	**50**	**0**
Injection Velocity (mm/s)	152.4	152.4	152.4
Switchover Position (mm)	3.01	3.01	3.01
Barrel Temperature (ºC)	210	210	210

In addition, different types of polymer: polypropylene (crystalline material) and polystyrene (amorphous material) were used to determine if there are any observable differences in cavity pressure curve between an amorphous and a semi-crystalline polymer. The materials properties of the polymers are shown in Table 4.

Table 4: Materials Properties of Polypropylene and Polystyrene

	Polypropylene	Polystyrene
Density (g/cc)	0.9 g/cc	1.05g/cc
Melt Flow (g/10 min)	11 g/10 min	9 g/10 min
Processing Temperature (ºC)	200 ºC - 232 ºC	171 - 282 ºC

Results and Discussion

(I) General Behavior

In micro-injection molding, cavity pressure curve behaves similarly to the one in convention injection molding: the curve starts to rise during filling and packing, and decays during cooling as the polymer shrinks. Figure 13 shows the different filling stages and different phases of micro-injection molding cycle for of a hollow cap. Although the processing window is much smaller in micro-injection molding process, the cavity pressure curve is still able to illustrate the progression of the molding cycle inside the cavity.

There are two obvious steps in pressure rise as shown in Figure 13. The first step corresponds to the filling stage of polymer melt in the thick cap section. The pressure continues to rise as the melt is injected into the cavity and covers the transducer. The initial portion of the second step of the curve shows the filling stage of thin wall. Once the entire cavity has been completely filled, the pressure increases rapidly and reaches the maximum value. After that, the curve drops immediately and decays due to part shrinking.

From the figure, it is obvious that micro-injection molding not only has a smaller processing window but also has a less smooth curve. The processing time is shorter due to the small scale of the micro-molded part as it takes less time to fill the cavity with polymer melt. In conventional injection molding, the curve formed a smooth curvature before dropping rapidly during the freezing phase of melt (see Figure 9). However, in our study, a sharp peak is formed due to rapid dropping of the pressure. The sharp pressure

drop after the maximum pressure point indicates that the effect of rapid shrinking. This sharp pressure drop is due to rapid freezing of polymer melt after entering the cavity. This is a common phenomenon in micro-injection molding and it is due to high surface to volume ratio. In this study, rapid freezing was also caused by the fact that the mold was not heated. The mold in this experiment was at ambient temperature - approximately 23°C throughout all the trials; the cold mold surfaces accelerated the freezing process. In spite of these differences, there were some observations obtained from the general shape of cavity pressure and that will be discussed in the following paragraphs.
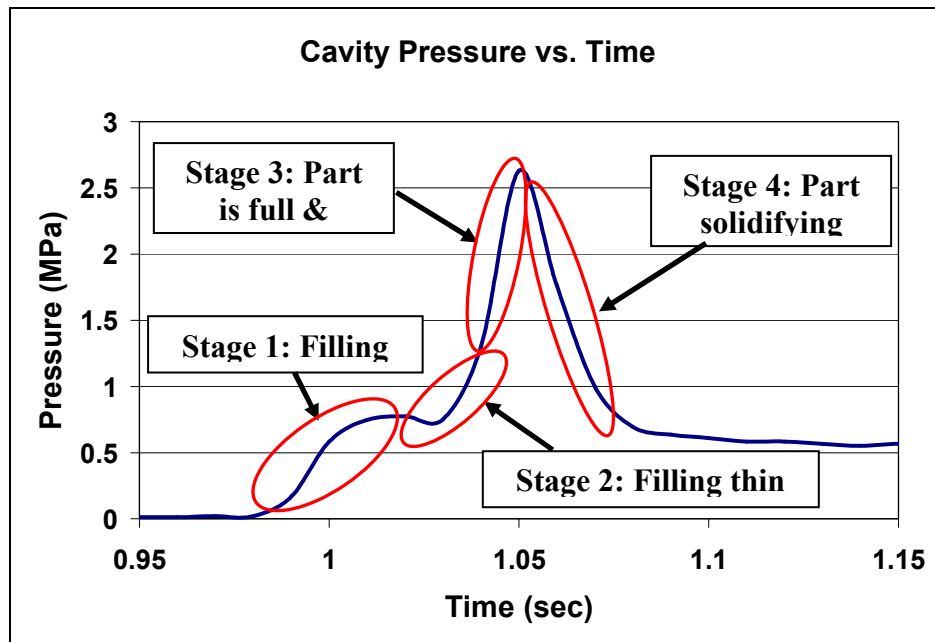
Figure 13: Filling Stages of Hollow Cap

Figure 14 shows the cavity pressure curves for both a good part and short part in micro-injection molding process. The pressure curve that resulted in a good part has two

distinct steps in the pressure rise as illustrated in the previous paragraph (see Figure 13). However, the short part, the curve shows a slight rise and then a slight drop failing to reach the second stage of pressure increase. This indicates that the polymer melt failed to fill the entire cavity. Short parts occur for several reasons such as low injection pressure, low pack pressure, inadequate shot volume, premature switchover, and low melt temperature. In our experiment, inadequate shot size was created by having premature switchover point.
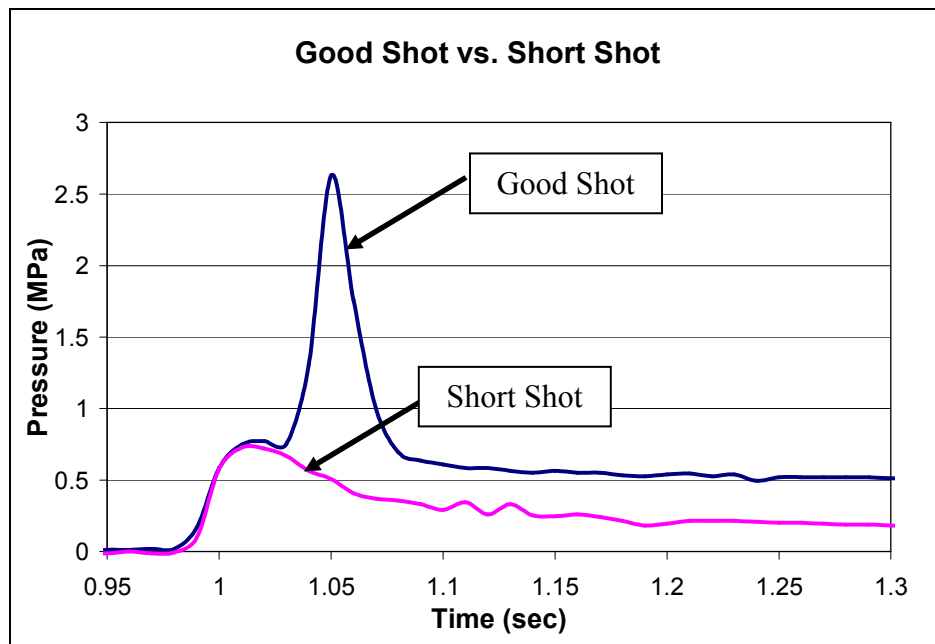
Figure 14: pressure curves for good part and short part.

(II) Effect of Polymer Type

The next trial was conducted to investigate how two different types of polymer - polypropylene – (semicrystalline) and polystyrene (amorphous) behave in micro-injection

molding. During the experiment, the molding parameters between the trials were set to be identical. In conventional injection molding, semicrystalline material has a plateau in the pressure curve before decaying rapidly as shown in Figure 15. This is due to the tendency of semicrystalline material molecules to organize into cells of roughly parallel groups of folded chains during the crystallization stage [44].
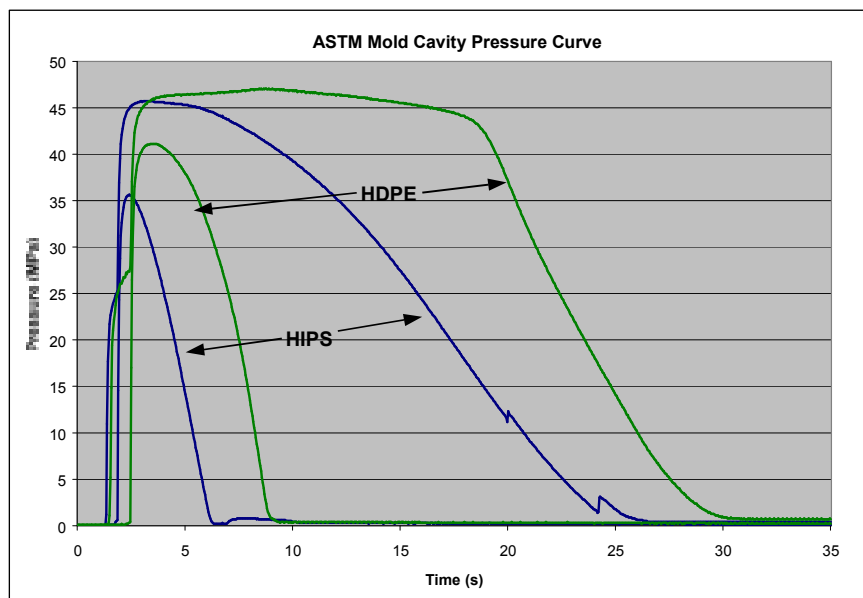
Figure 15: Comparison of Pressure Curves for HIPS and HDPE in Conventional Injection Molding

However, in this study, there was no such difference between the pressure curves for amorphous and semicrystalline polymer as shown in Figure 16. The pressure curves looked identical for two different types of polymer used. One of the possible explanations is that the cooling phase happened so rapid that the shrinking of the semicrystalline material took place before the material molecules were organized. However, further investigation is needed to validate this hypothesis.
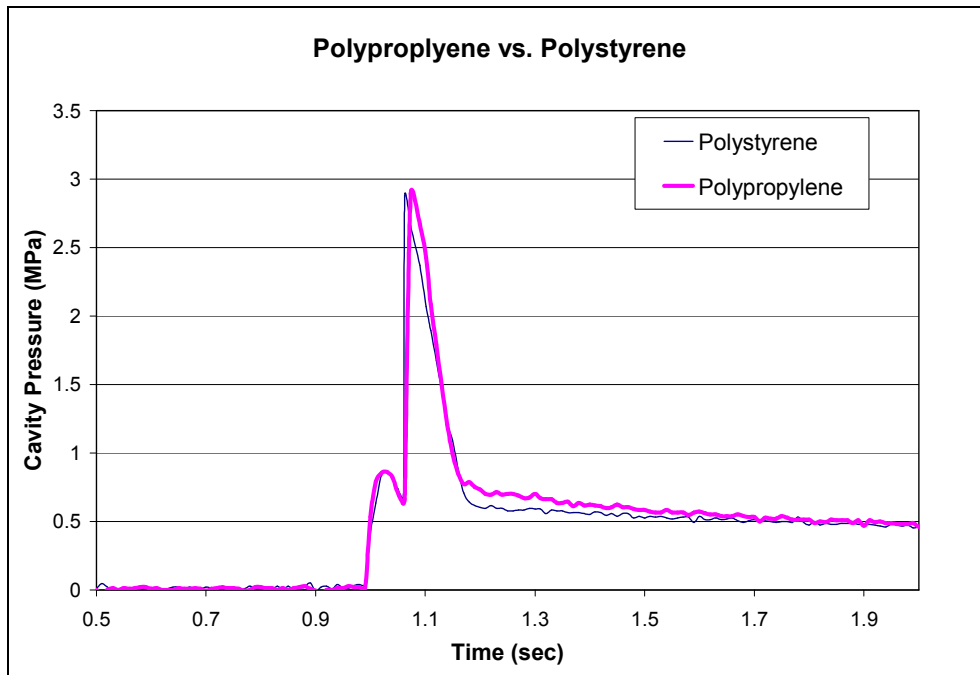
Figure 16: Comparison of Pressure Curves for PS and PP in Micro-Injection Molding

Another possible explanation is the incapability of cavity pressure to sense the differences between the polymer types in micro-injection molding as the processing time is so short and the overall cavity curve occupies a much smaller time scale, therefore, affecting the robustness of cavity pressure curve as a process indicator in micro-injection molding process.

(III) Effect of Different Velocity

Figure 17 shows the results obtained from two different injection velocity trials. As shown in Table 1, all the molding parameters were unchanged except injection velocity. As shown in the figure, trial with higher injection velocity reaches packing phase and cooling phase earlier. This is because higher injection rate injects the material

faster and causes the cavity to be filled faster. The difference in filling rates between the trials is easily noticeable from the figure; the blue line (higher injection velocity) has a steeper slope at the filling stage. Despite the difference in the filling stage, both trials share the same cooling rate (slope of cooling phase) and final cavity pressure value.

Two Different Injection Velocities
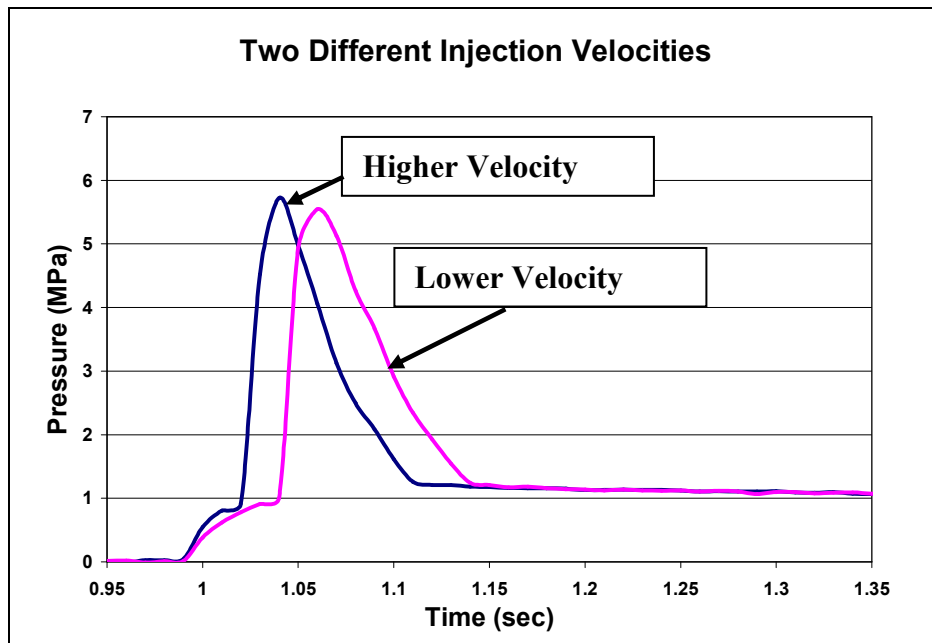
Figure 17: Different Injection Velocities

(IV) Effect of Different Pack Pressure

The next discussion is on the effect of pack pressure on cavity pressure curve. Figure 18 shows how pressure curves respond differently to different pack pressure settings. Here, only pack pressure settings were varied while other settings remained unchanged. As can be seen from the figure, the three curves are similar before the switchover point. The curves start to behave differently after the switchover happens due

to different pack pressure settings. After the switchover point, the entire filling phase is solely relying on pack pressure. As a result, higher pack pressure produces higher cavity pressure and faster filling rate. The result is reasonable as higher pack pressure forces more polymer melt into the cavity in a shorter time frame.

The 75 MPa line reaches packing stage earliest as the filling is completed by higher pack pressure. High pack pressure also produces a higher peak cavity pressure value. The 50 MPa line reaches packing phase slower and has a lower peak cavity pressure. Here, although the pack pressure is lower, it still able to fill up the part completely, but at slower rate. On the other hand, the 0 MPa line does not reach packing phase at all. From Figure 18, it is clear that the polymer melt stops filling the cavity once the switchover takes place causing the pressure to drop immediately. It can be deduced from the cavity pressure curve behavior that short part is produced from this trial.

Different Pack Pressure
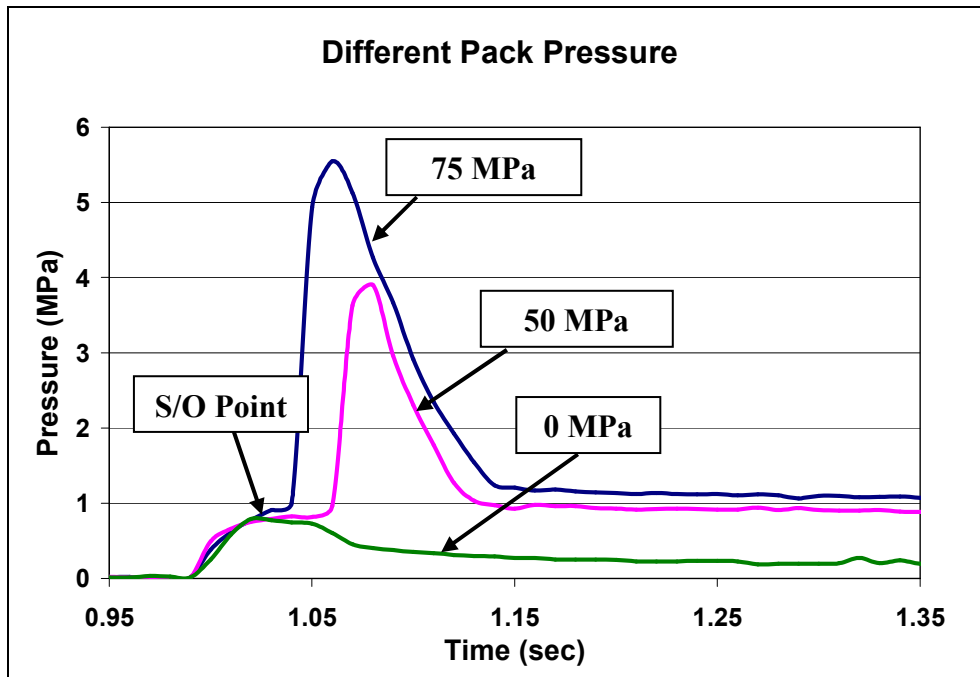
Figure 18: Different Pack Pressure Settings

Conclusion

In this study, several different molding conditions were created to investigate the ability of cavity pressure to respond to process variation in injection molding of a micro part. The general shape of cavity pressure curves show that cavity pressure responds differently to different molding conditions. This signifies the huge potential of cavity pressure to be utilized as an indicator of part quality and process variation. The processing window for micro-injection molding is smaller than in conventional injection molding process. Also, the time from the start of filling of the cavity to the part freezing occurs in just a few seconds. Rapid freezing of polymer melts are easily noticeable among all the trials.

CHAPTER 5

PROCESS MONITORING IN THE MICRO-INJECTION MOLDING PROCESS

Introduction

The global trend towards product miniaturization has increased the market demand for micro-parts. LIGA and micro-machining processes are some of the proven methods that are capable of fabricating micro-parts. While these processes are too expensive and time-consuming for manufacture of individual parts in large volume, they are suitable for the fabrication of mold inserts, which can then be used to manufacture thousands of micro-parts using the micro-injection molding process. Since the cost of polymeric materials is usually inexpensive and only small amounts of materials are required to mold such small parts, this process has become an effective method of producing micro-parts inexpensively and in large volume [7]. Furthermore, the advantages of polymers such as tailorable chemical, mechanical, and physical properties make the micro-injection molding process one of the most favorable fabrication methods for micro parts.

Micro-injection molding uses the same operating and processing principles as conventional injection molding. First, the molds are closed, followed by the injection of the polymer melt to fill the cavity. The melt then cools and finally, the molds are opened and the molded part is removed to complete the cycle. Although the overall principal is the same for both molding processes, due to the unique challenges inherent in working at a size scale a few orders of magnitude smaller than typical injection molding, micro-

injection molding requires further research and development for it to become a viable and effective option.

The micro-injection molding process has a smaller processing window compared to traditional injection molding, with the filling time and packing time normally being much shorter. This presents the difficulty in controlling and monitoring the entire molding process. The process is also more susceptible to slight changes in process parameters such as mold temperature, injection velocity, metering size, and packing pressure. Therefore, good process repeatability and a high-quality mold are essential in order to achieve consistently high quality micro-parts.

Micro-injection molding is not just about scaling down part size. Issues such as changes in molding capability of micro-features and freezing time arise when the part geometry is reduced in size. Scaling down the process from the conventional injection molding process also involves changes in the molding process and mold design. One example in terms of process changes is the application of higher melt temperature and higher injection velocity, and the introduction of cyclic mold heating process to prevent premature freezing due to the high surface area to volume ratio of micro-parts [19].

In general, micro-injection molding is still a relatively immature process where achieving a good process consistency and part quality remain challenges. As a result, quality inspection becomes crucial in order to ensure detection and segregation of defective parts. However, due to the micro-scale dimensions involved, it is difficult to inspect part quality without using costly microscopic observation or machine vision methods. To address this issue, cavity pressure is employed in this study to determine its

robustness as indicator of part quality and process behavior. In the conventional injection molding process, it has been found that cavity pressure can provide early detection of process and part deviation [38, 42, 43]. Previous studies have also shown that cavity pressure has significant utility as an indicator of part quality and process variation. Specifically, the present study addresses how cavity pressure responds to different switchover settings that result in varying part quality of a small hollow cap. In addition, the correlation between different parameters is discussed and presented.

Experimental Setup

The experimental work was conducted on a 17-ton Cincinnati/Milacron Fanuc Roboshot Si-B17 as shown in Figure 19. This is an electric servo-driven injection molding machine having a screw diameter of 16 mm. A hollow micro-cap (see Figure 20) with a 1mm outer diameter, overall height of 3mm and wall thickness of ~0.1mm was molded for the study. The top portion of the part consists of a ~0.5mm thick cap with diameter of 2 mm. A 0.793 mm diameter eject pin was inserted on the moving platen through the 1mm diameter cavity hole to act as a core pin. On the stationary platen, a flush-mount pressure transducer is installed and acted as part of the cavity. Both cavities on moving and stationary platen were machined out of a 2.5 in. x 2.5 x 0.5 inch stainless steel insert which were then mounted in larger mold plates. The platen assemblies were fitted on MUD U-type mold frame. The final produced part weighs approximately 2.4 milligrams with aspect ratio of ~30 on the annular wall section. Figure 21 shows the size of two micro-molded caps relative to a U.S. dime.

Figure 19: Milacron Roboshot Si-B17
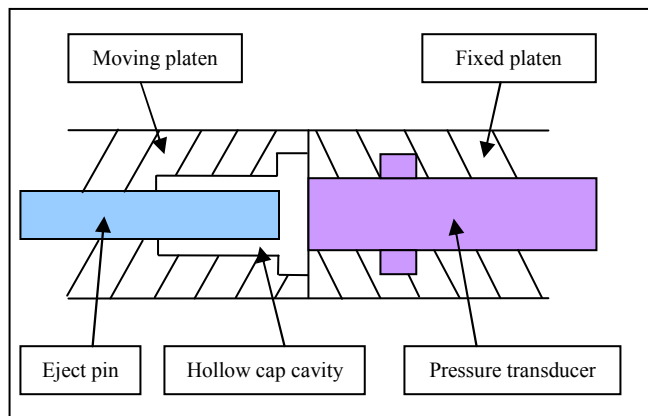
Figure 20: Construction of Hollow Cap Cavity
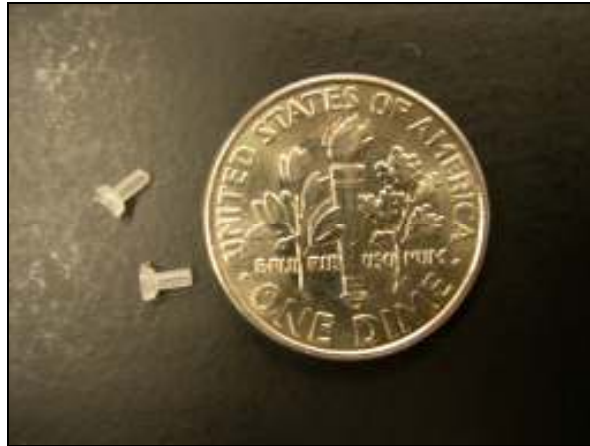
Figure 21: Molded Hollow Caps Relative to a U.S Dime

In terms of processing material, the type of material used in the present experiment is polypropylene - a crystalline material. The materials properties are shown in Table 5.

Table 5: Materials Properties for Polypropylene

Density (g/cc)	0.9 g/cc
Melt Flow (g/10 min)	11 g/10 min
Processing Temperature (°C)	200 °C - 232 °C

Cavity melt pressure was measured using a 1 millimeter diameter Kistler 6183A piezoelectric pressure transducer as shown in Figure 22. The voltage signal was amplified by a Kistler 5122 charge amplifier, conditioned by a SCB-68 signal conditioning module, and then received by a NI PCI-6229 National Instrumentation data acquisition card. The resulting pressure data was then recorded by using National Instrument Lab View graphical programming software. Both pressure signals and elapsed time were recorded for each shot at a sampling frequency of 100 hertz. Figure 23 shows the overall experimental apparatus.
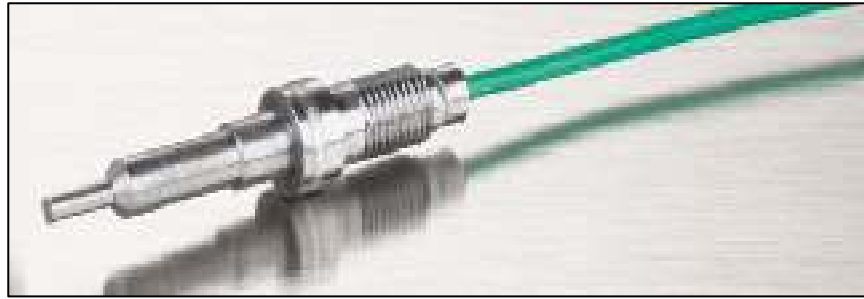
Figure 22: Kistler 6183A Pressure Transducer
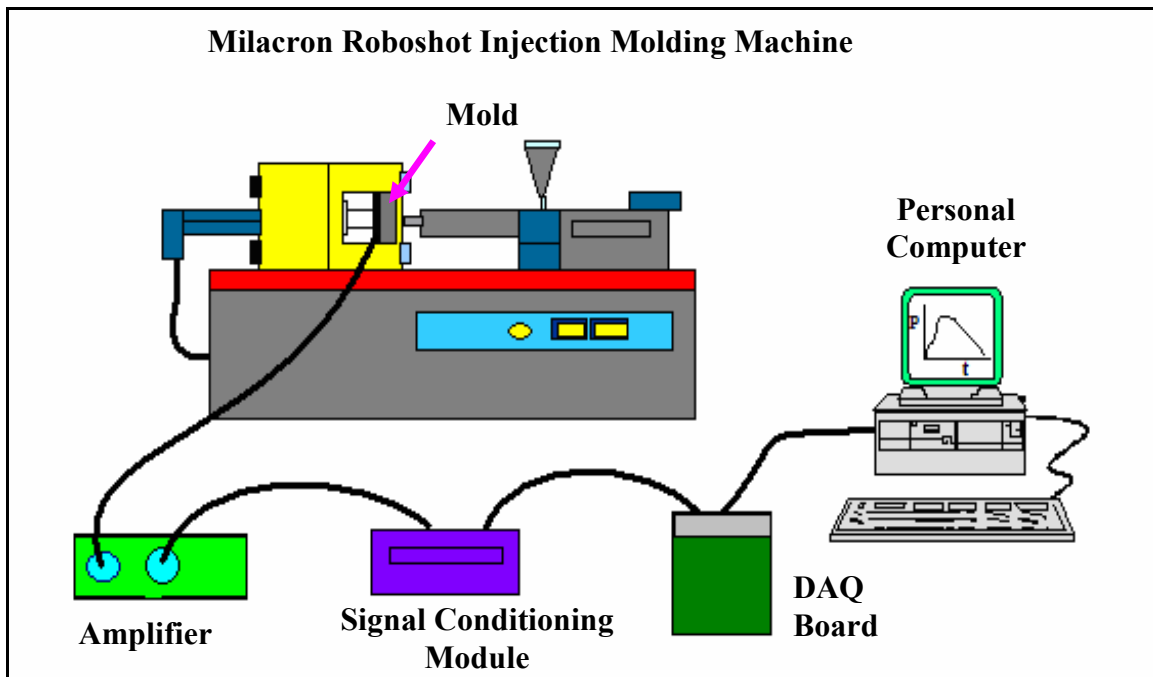
Figure 23: Connection of Experimental Apparatus

Experimental Trial

Switchover is a change of phase from velocity controlled injection to pressure-controlled packing in the injection molding process. In the injection phase, the screw advances to inject polymer melt through the nozzle. The velocity of the screw is specified and the injection pressure varies throughout the injection phase to maintain the desired

velocity. At switchover, the process is then controlled to a pressure set point (packing phase) and screw velocity and position are controlled to maintain the required pressure profile. Switchover can be triggered based on position of the screw or on the injection pressure. In the present experiment, it is based on the position of the screw. The smaller the switchover value is specified, the higher travel of the screw, which also means that switchover happens later in the process. The switchover is denoted by the screw position (mm) where a zero mm screw position corresponds to a screw that is in its maximum forward displacement ("bottomed out").

Switchover setting is chosen as the parameter of interest due to the fact that it is crucial in injection molding process. An early switchover setting results in a short part while a late switchover can produce over pack or flash on the part because of excessive materials in the cavity. The pack pressure was set to 0 MPa in all trials in order to observe the sole effect of switchover in the process. In other words, the 0 MPa pack pressure is set to prevent any influence of packing on cavity pressure and filling of the cavity.

The first 5 sets of experimental trials were conducted by adjusting the V-P switchover setting for each trial from ~3.04mm to ~2.24mm with incremental step size of ~0.2mm while other settings remained unchanged as shown in Table 6.

Table 6: Molding Parameters for the first 5 Trials

Settings for all five trials	
Injection Velocity (mm/sec)	152.4
Pack Pressure (MPa)	0
Pack Time (sec)	6
Barrel Temperature (ºC)	210-210-210
Shot Size (cc)	0.862
Max Pack Velocity (mm/sec)	254
Switchover settings for trial 1-5	
Trial	Switch Over(mm)
1	3.04
2	2.84
3	2.64
4	2.44
5	2.24

After studying the sole effect of switchover in the process, two additional experimental trials were conducted at switchover point of 2.24 mm with heated mold and one of them with pack pressure settings. This particular trial (2.24mm) was selected because it produced the best quality parts during the previous experimental trials. The introduction of mold heating and pack pressure to the process will be used to study the impact of these two parameters on the cavity pressure curve and part quality. Table 7 shows the setting for these additional trials.

Table 7: Settings for trials with heated mold and Pack Pressure

Trial	1	2
Injection Velocity (mm/sec)	152.4	152.4
Pack Pressure (MPa)	0	40
Pack Time (sec)	6	6
Barrel Temperature (ºC)	210-210-210	210-210-211
Mold Temperature (ºC)	50	50
Shot Size (cc)	0.862	0.862
Max Pack Velocity (mm/sec)	254	254

Before the actual sample data was taken in each trial, the molding machine was stabilized by running the machine until there was no drift observed in the injection pressure. After that, twenty shots were produced and corresponding data was collected. All of the samples were weighed using appropriate balances: A Sartorius M2P for weighing the hollow micro-cap, and a Sartorius BP 210S for weighing the runner. In the present study, the part weight is considered as the part quality indicator since it is a parameter that is quick and easy to measure.

Results and Discussion

Process, part quality, and cavity pressure data obtained from all trials was collected and compared among the trials. Within each trial, shot to shot variation was evaluated as well. As such, the following discussion is separated to two portions: (1) Effect of switchover, and (2) Shot to shot variation

I. Effect of Switchover

General Curve Behavior and Attributes

In the micro injection-molding process, although the processing time is shorter due to the small scale of the micro-molded part, different stages of cavity filling can still be observed in pressure curve as illustrated in Figure 24. At stage 1, pressure is initially detected when polymer begins filling of thick cap section. At stage 2, pressure then rises again when the polymer melts enter the thin wall section. At stage 3, pressure rises dramatically when the part is full and starts packing. Finally at stage 4, the curve starts to decay when solidifying of the melt happens. As can be seen in the figure, the entire process described above takes less than 0.2 seconds.
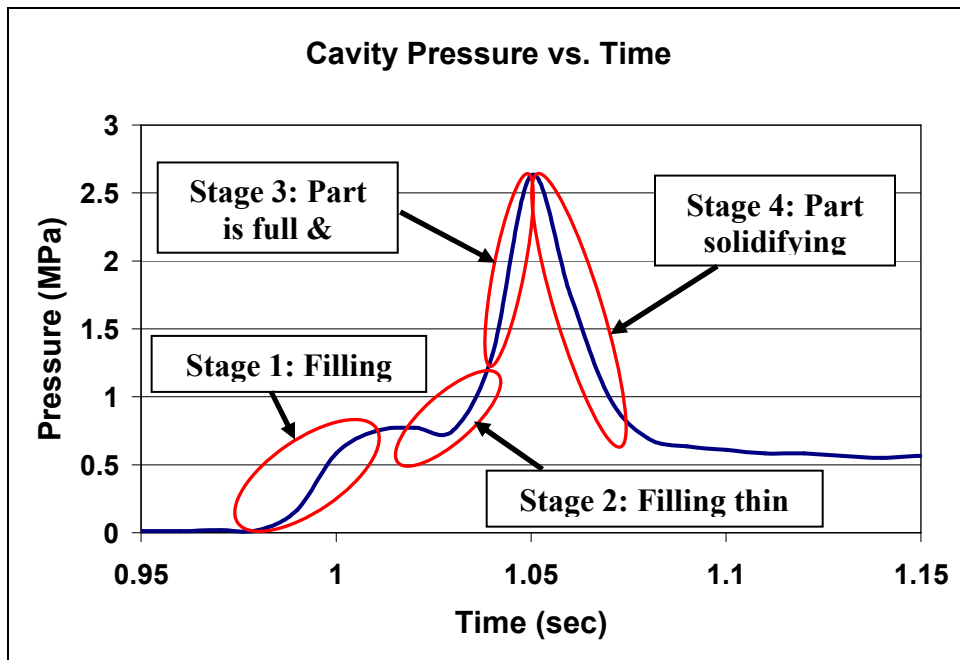
Figure 24: Cavity Pressure Curve for Hollow Cap

In addition to observing the general shape of the curve, cavity pressure data is correlated to part quality by deriving quantitative values representing the features of the curve. In the present study, peak pressure and area under the curve are the two attributes obtained from the curve as shown in Figure 25. According to an article published by Tat Ming Engineering Works Ltd.[31], the choice of the most suitable attribute is related to the part thickness. Peak cavity pressure is more suitable for thin wall molding while area under curve is more applicable for thick wall. Although only thin wall is involved in the current hollow cap, area under curve is still an attribute worth investigating.
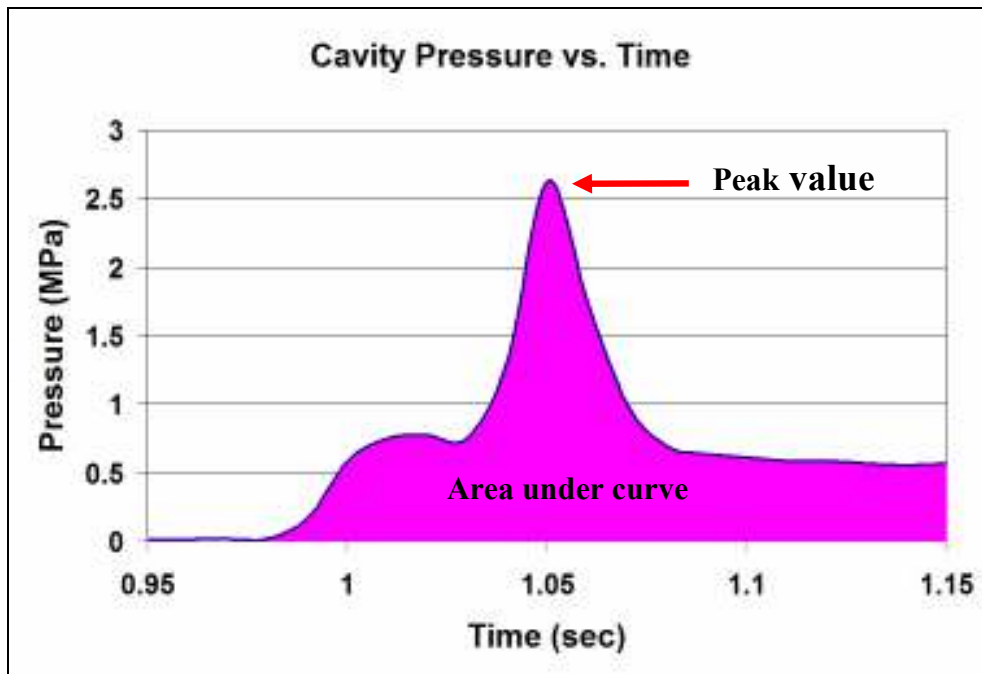
Figure 25: Graphical Representation of Peak Pressure and Area

Relationship between Peak Cavity Pressure, Part Weight, and Switchover Settings

The following discussion focuses on the relationship between peak cavity pressure, part weight, and switchover settings. As shown by the data in Figure 26 and Table 8, the peak cavity pressure and part weight increase when switchover occurs later in the cycle. This result corresponds with the initial prediction that later switchover allows the polymer melt to fill up more of the cavity and hence generated higher peak cavity pressure and part weight.

In Figure 26 pressure curves with switchover of 3.04mm, 2.84mm, and 2.64 mm have relatively low peak pressure value and small area under curve, this reflects the fact that very little polymer melt was able to fill up the cavity. For pressure curves with a later switchover of 2.24mm and 2.44mm, a sharp rise in pressure is observed. This indicates that the polymer melt has at least filled up the thin wall section. Given that there is no pack pressure during the molding process, polymer melt stops filling once the switchover takes place. As a result, later switchover allows injection to proceed longer and allows melt to flow further into the cavity before the injection phase ends.
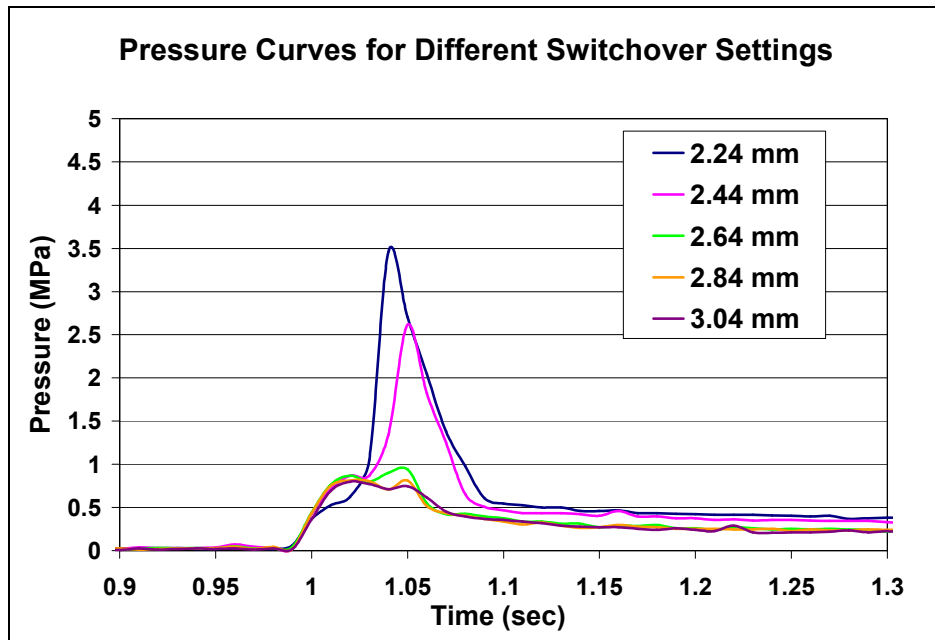
Figure 26: Cavity Pressure Curves for Different Switchover Settings

During molding, variation was observed among shots from the same trial. Therefore, average values for peak cavity pressure, area under curve, and part weight were calculated for each trial to correlate with switchover settings as shown in Table 8. Again, the values for the peak cavity pressure, area under curve, and part weight increase as switchover settings are decreased. By referring back to Figure 26, once the polymer melt fills up the thin wall section, a sudden spike in cavity pressure is observed. This results in the large change in peak cavity pressure from 1.77MPa in trial 4 to 3.22 MPa in trial 5. This finding shows that the parts are more completely filled or at least the thin wall section has been filled in trial 5 (Trial with 2.24mm).

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Table 8: Attribute Values and Part Weights for Different Switchover Settings

Trial	1	2	3	4	5
Switch Over (mm)	3.04	2.84	2.64	2.44	2.24
Average Part Weight (mg)	1.503	1.916	2.160	2.300	2.410
Average Cavity Pressure (MPa)	0.789	0.914	1.570	1.700	3.220
Average Area Under Curve	0.092	0.100	0.132	0.138	0.224

Part Quality

In terms of part quality, although weight is used as the quality indicator, normal visual inspection can also easily detect some obvious defects on the parts. Figure 27 shows how the different short phases of the hollow cap are divided into three distinct stages: stage 1 corresponds to fill of the thick cap/annular section, stage 2 corresponds to fill of the thin wall section, and stage 3 corresponds to fill of the small portion of flash at the end of the hollow cap. The flash as shown in the figure is due to machining error on the mold and is treated as a part feature; it is not the result of over packing. This feature happens to be the thinnest portion of the cavity and it is located the farthest away from the gate. Therefore, it then turns out to be the last portion for the melt to fill up. Due to this reason, the "flash" can be used to indicate a completely filled part.
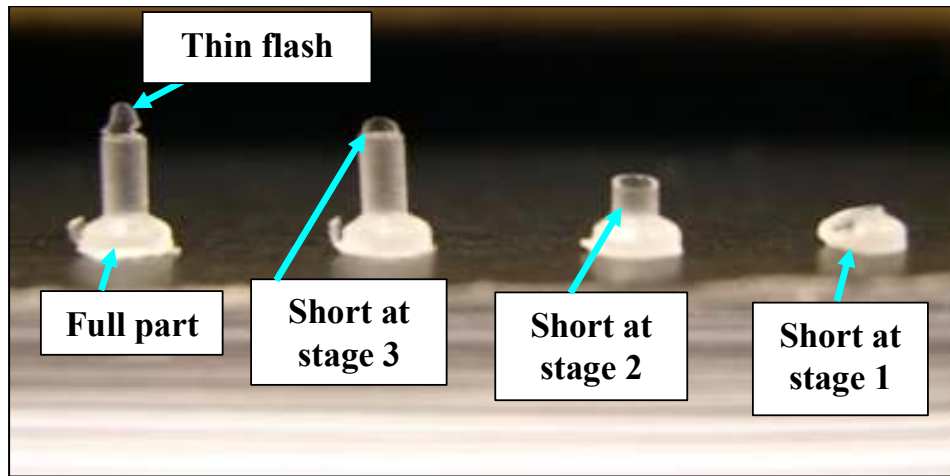
Figure 27: Different Stages of Short Defect

The different short stages can also be identified from cavity pressure curve as shown in Figure 28. The part that is short at stage 1 does not have two distinct steps in pressure curve. The pressure curve starts to decay once switchover happens and the melt failed to flow into the thin wall section. As a result, very low cavity pressure is generated by this type of short part. For part that is short at stage 2, since the melt has reached a portion of the thin wall, a slight change of slope may be observed from the pressure curve since higher pressure is needed to fill the thin wall section. Sometimes, a dip occurs in the pressure curve between these two stages. For the curve in Figure 28, such a dip can be observed on the green line (2.64 mm). Under the current process settings, whenever a dip is observed, the part happens to be short at stage 2. The formation of the dip will be discussed in detail in the next paragraph. As far as differences between being short at stage 3 and having a full part, the general shape of the curve alone does not indicate the differences between the two (blue line and pink line). However, when both curves are

compared, it is then obvious that differences do exist with the full part having a higher

peak cavity pressure.
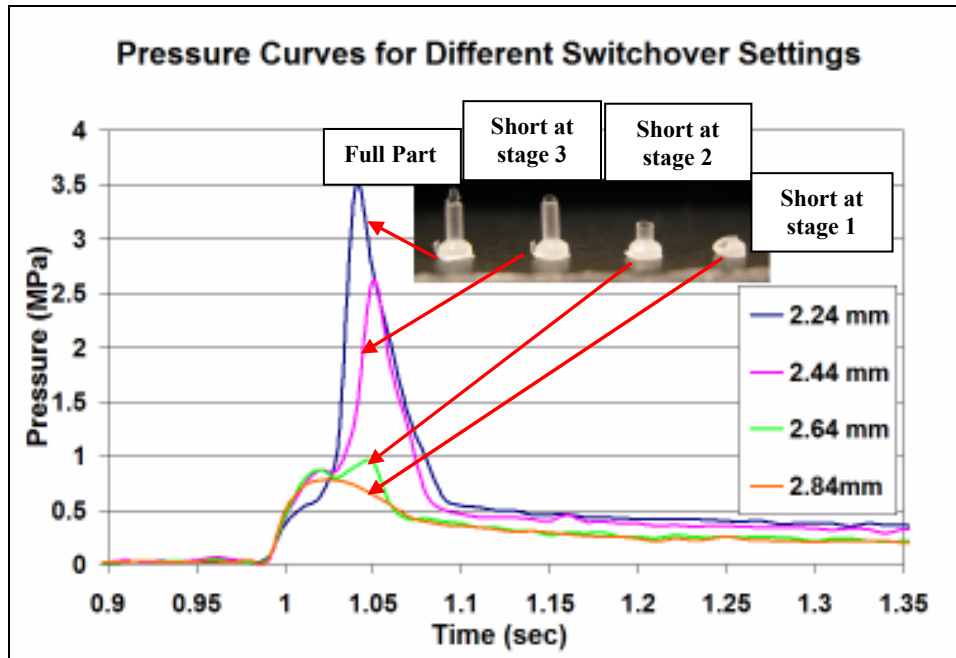
Figure 28: Cavity Pressure with Different Switchover Settings and Short Stages

As mentioned in the previous paragraph, one general observation about the

pressure curve is that whenever there is a dip in the filling stage, it indicates that the

polymer melt has already entered into the thin wall section – stage 2, but it is short either

at stage 2 or stage 3. Figure 29 shows an example of pressure curve that has a dip on it

that corresponds to a stage 2 short part.

When polymer melt enters the cavity, the melt tends to fill up the thick cap

section first due to hesitation effect. As pressure gradually increases during the filling

stage, the melt also build up pressure and energy. When the pressure is strong enough, it

breaks through the stagnant skin layer that is formed at the entrance of the thin wall. It is believed that the penetration of melt into the thin wall creates the decrease of cavity pressure or the dip as seen in Figure 29. As expected, once the melt starts filling the thin wall section, pressure increases immediately until switchover happens and the curve starts to decay. In short, the first peak before the dip is due to pressure build-up when the melt enters the cavity. The dip happens when the pressure immediately drops due to the break-through of the stagnant skin layer. The second peak after the dip is the pressure required to continue filling the thin wall.
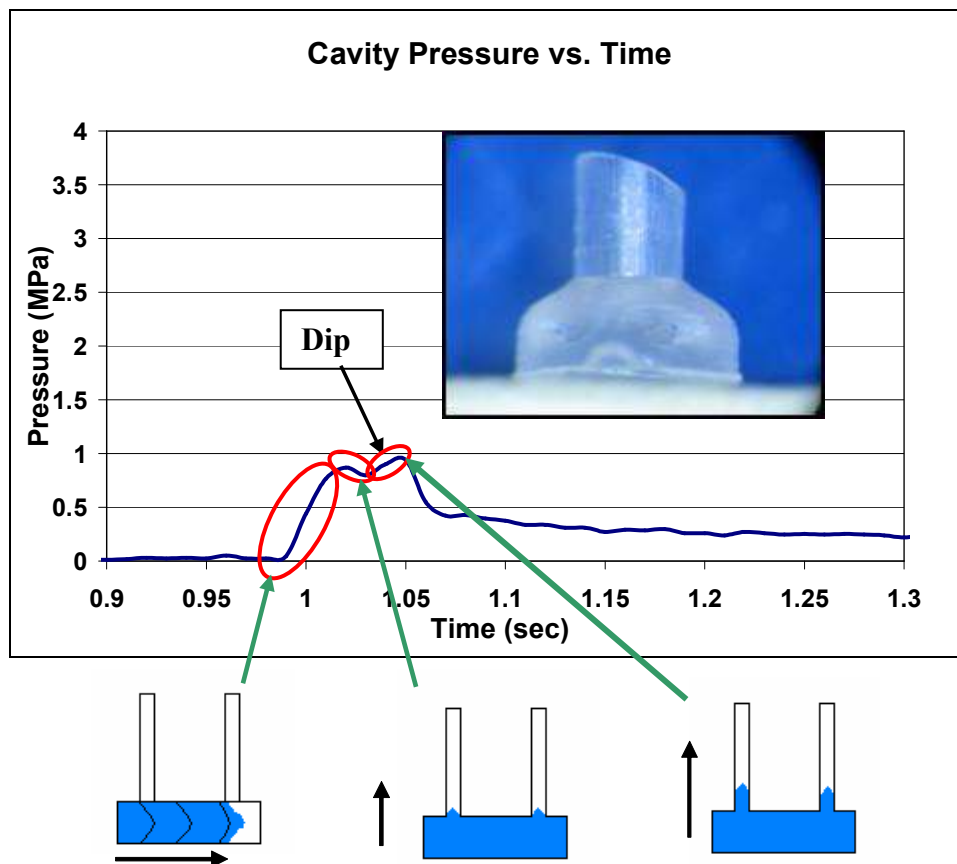
Figure 29: Formation of Dip on Cavity Pressure Curve

However, some inconsistencies have been observed in the processing behavior. Some parts were found to be short even though no dip was observed in the curve. With current parameters settings, whenever there is a stagnant skin layer formed at the entrance of the thin wall due to the hesitation effect, further injection of materials can penetrate the stagnant layer, but may not provide sufficient pressure to fill up the entire cavity. On the other hand, the polymer melt may still fail to fill up the entire cavity even though there is no dip or hesitation effect observed in the curve. Therefore, while a dip in pressure curve typically signifies a short part, not all the short parts could be identified solely by relying on the dip in pressure curve.

Relationship between Cavity Pressure and Part Weight

In terms of the relationship between cavity pressure and part weight, coefficient of determination (R^2 value) was calculated to determine how peak cavity pressure and area under curve correlate with the part weight. The coefficient of determination is a measure of the degree of correlation or dependence between the dependent and independent variables in a regression analysis. A high R^2 value indicates that the two variables are well correlated. Table 9 shows both the R^2 value for peak cavity pressure value and area under curve increase with the decrease of switchover setting (later switchover). The higher R^2 value shows that later switchover in injection molding process not only produces better quality part, but also produces a better correlation between part quality and cavity pressure (both peak value and area under curve). In other

words, correlation between part weight and cavity pressure increase as the percentage in cavity is filled increases.

Table 9 also shows the comparison between these peak cavity pressure and area under curve. The higher R^2 value in peak cavity pressure suggests that peak cavity pressure appears to have a better correlation with part weight than area under curve. In addition to cavity pressure, machine injection pressure is compared as well. Machine injection pressure is the pressure experienced by the molding machine during the injection phase. This pressure has been used in different investigations on its feasibility as the process and quality indicator in micro-injection molding. However, different results were obtained. Zhao et al. [45] shows that the machine injection pressure is closely related to the quality of the molded micro-gear. Conversely, Whitesite et al. [41] found that machine injection pressure lack the capability as a process indicator in micro-injection molding. In the current experiment, data shown in Table 9 shows that peak cavity pressure and area under curve surpass the R^2 value for machine injection pressure as switchover setting decreases from 3.04mm to 2.24mm. This finding suggests that cavity pressure appears to be a better indicator of part quality and process variation as opposed to machine injection pressure.

Table 9: Coefficient of Determination (R^2) for Different Switchover Settings

Trial	1	2	3	4	5
Switch over (mm)	3.04	2.84	2.64	2.44	2.24
R^2 Value - Machine Pressure vs. weight	0.6158	0.5124	0.7167	0.4243	0.7134
R^2 Value - Cavity Pressure vs. weight	0.2869	0.4989	0.6028	0.6099	0.8454
R^2 Value - Area Under Curve vs. weight	0.1267	0.4905	0.579	0.5662	0.7288

Peak Cavity Pressure vs. Area Under Curve For All Shots

Figure 30 and Figure 31 present peak cavity pressure and area under curve with respect to part weight for all the trials with different switch over settings. As seen from both figures, both plots share almost similar trend with the cavity pressure attributes (peak value and area under curve) are less responsive to the weight changes when the weight is low. However, both attribute response significantly to the weight differences when the weight reaches about 2.36 mg. Hollow caps with low weights (less than 2.36 mg) are parts that are short at stage 1 and 2. When the melt fills up the part to at least stage 2, part weight and cavity pressure increase and good correlation is observed as shown in both figures. Although correlation is weak when parts are short at stage 1 and 2, those parts can still be easily screened out as shown in the same figures. The lack of good correlation for obvious gross defects is of no great concern because these defects can be easily detected by means of visual inspection. Furthermore, those parts are easily distinguished by referring to cavity pressure curve as shown in Figure 28.
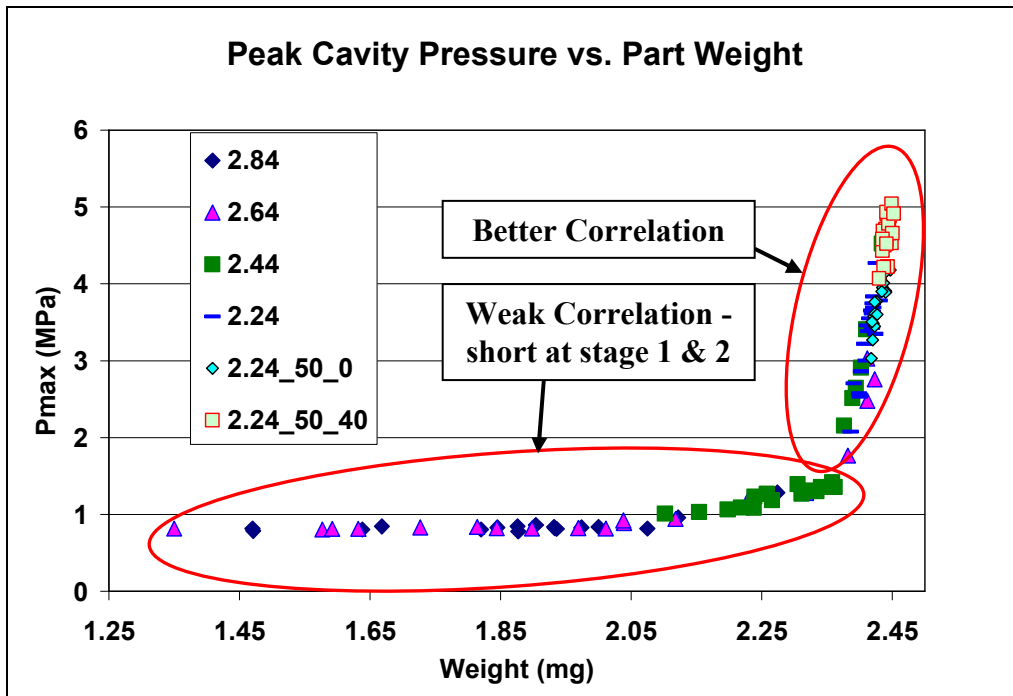
Figure 30: Peak Cavity Pressure vs. Part Weight for all Trials
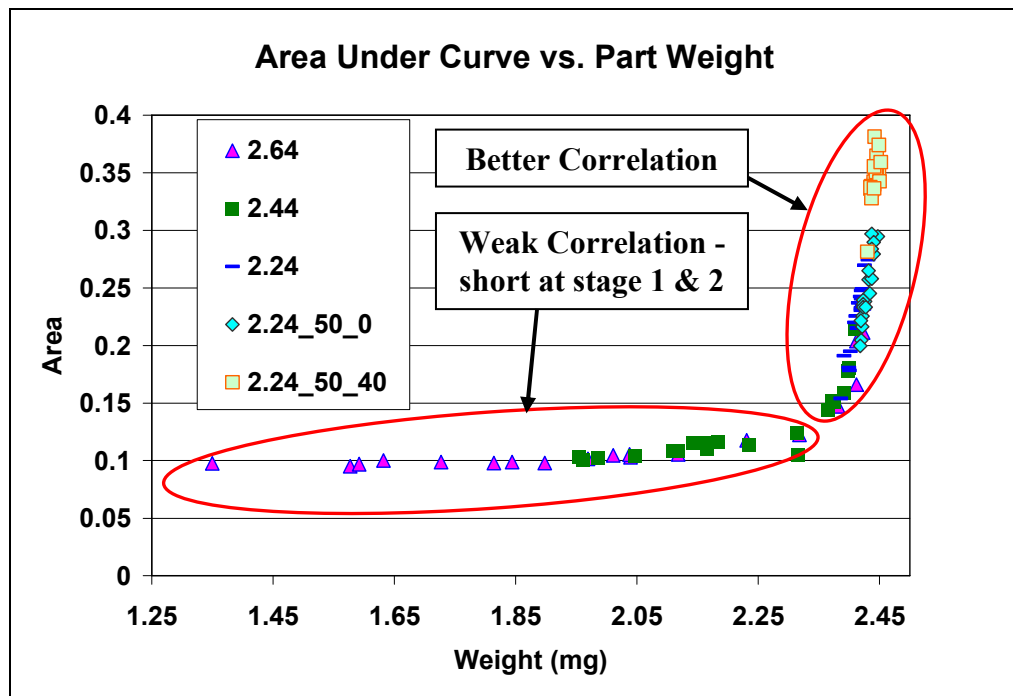
Figure 31: Area Under Curve vs. Part Weight for all Trials

Additional Trials with Heated Mold and Pack Pressure

Figure 30 and Figure 31 also include two additional trials - 2.24_50_40 and 2.24_50_0 with the first item in the notation represents the switchover value, follow by mold temperature, and pack pressure. Both trials have a heated mold with 50 ºC. Trial 2.24_50_40 has a pack pressure of 40 MPa and the other does not. For trials with a heated mold, the peak pressure values and area are greater than others. This is because the heated mold surface allows better flowabilty as the viscosity of the polymer melt remains low since the melt is still hot. At the same time, the hot mold delays the melt freezing and extends the processing window. This results in more material flowing in the cavity, extended packing, and generating higher cavity pressure and greater part weights. One trial (2.24_50_40) is supplied with pack pressure for the purpose of investigating the capability of cavity pressure in sensing the differences. The effect of pack pressure can be found in Figure 30, Figure 31, and Figure 32. As expected, the effect of the pressure can be seen from the trial 2.24_50_40 where heavier parts and higher cavity pressure were produced.
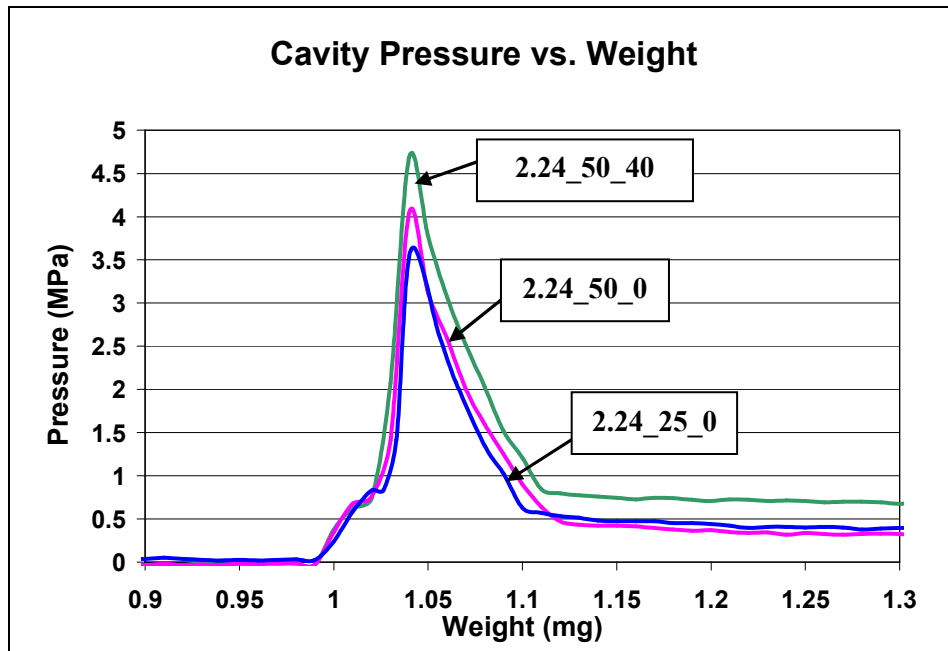
Figure 32: Cavity Pressure curve for Trial 2.24 with Different Pack Pressure and Mold Temperature Settings

Correlation: Full and short at stage 3 parts

Since producing quality parts is always the main objective in manufacturing processes, the next discussion will focus on parts that have filled at least up to stage 2. These are the parts that have shown better correlation between cavity pressure and part weight as illustrated in Figure 30 and Figure 31. Figure 33 shows the correlation of peak cavity pressure and area under curve of those parts with respect to part weight. As shown, both attributes have similar trends in the figure with peak cavity pressure having a higher R^2 value of 0.9139. This again suggests that peak cavity pressure appears to be a better quality indicator than area under curve in micro-molding of the hollow cap. Trial using both a heated mold and pack pressure (2.24_50_40) stands out from others by exhibiting higher peak cavity pressure and area under curve values. This trial is indicated

on both figures as a cluster of shots groups together at the upper right corner of the plot (circled in the plot).
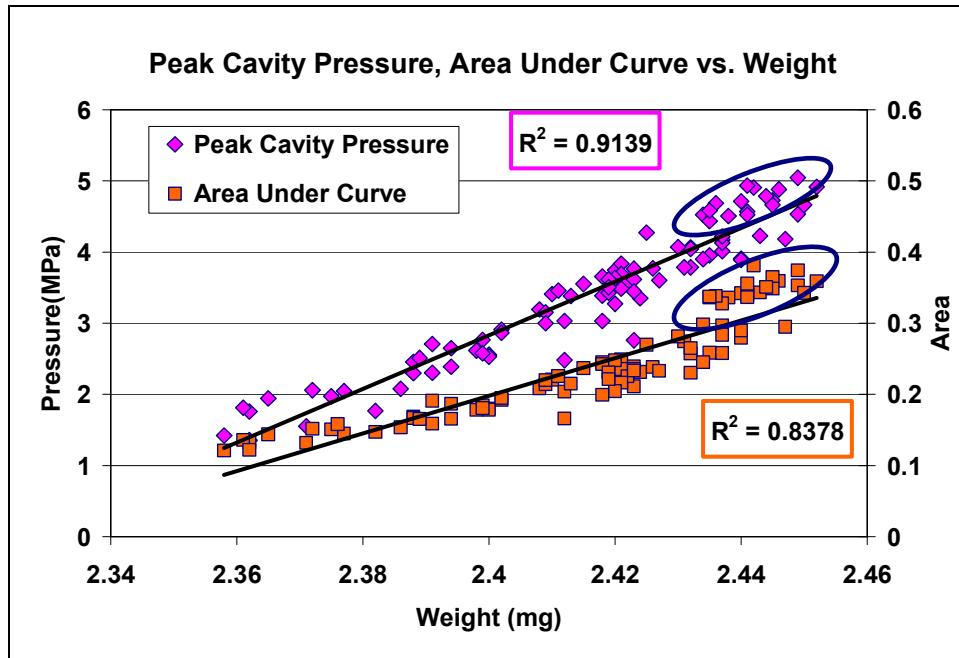
Figure 33: Peak Cavity Pressure and Area Under Curve with respect to Part Weight

With the high correlation between peak cavity pressure and part weight, parts can be sorted based on the pressure value recorded with minimum or no actual inspection of the parts. Figure 34 is the repetitive plot of Figure 33 which shows peak cavity pressure only. This figure serves as a useful chart where certain range of acceptable part weights are known, and the corresponding pressure range is used as the filtering criteria. For example, for a part where the acceptable weight ranges from 2.39 mg to 2.40 mg, the corresponding pressure value can be found to ranging from 2.2 MPa to 3.0 MPa. With this pressure value, an automatic sorting system can be installed and used to segregate

good and reject parts based on the real-time peak cavity pressure recorded during the molding process.

Peak Cavity Pressure vs. Weight

$R^2 = 0.9139$
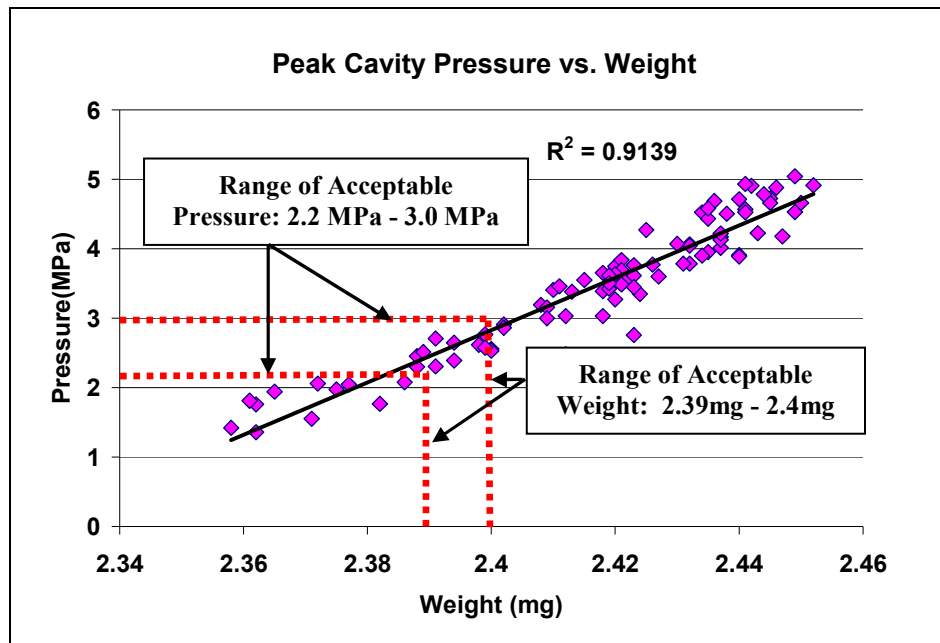
Figure 34: Example of Acceptable Part Weight and Cavity Pressure Range

II. Shot to Shot Variation

Part Weight and Peak cavity Pressure

The previous section has shown that peak cavity pressure appears to be a better process indicator than area under curve. Thus, the following discussion only focuses on peak cavity pressure. In each trial, shot to shot variation was observed although the process settings were the same. In this section, discussion of differences among shots in the trial with switchover setting of 2.24mm (which produced best quality parts) will be presented. Figure 35 shows 5 typical (out of 20) pressure curves from the same trial. The

shots presented in the figure have at least filled up stage 1 and 2, some of them even filled up stage 3. The differences in pressure curves indicate that each shot was different in filling rate, percentage of cavity filled, and part quality. Despite the differences, a general trend is found among those curves. Pressure slowly develops as polymer melt enters the cavity, the pressure increases significantly when it finished filling the cavity, and then the pressure drops during the cooling phase.

A shot that has a higher peak pressure normally produces part with higher weight. In this case, shot 12 has the highest weight while shot 20 has the lowest amount weight. In term of filling stages, shot 12 is completely filled while shot 20 is short at stage 3 as shown in Figure 36.
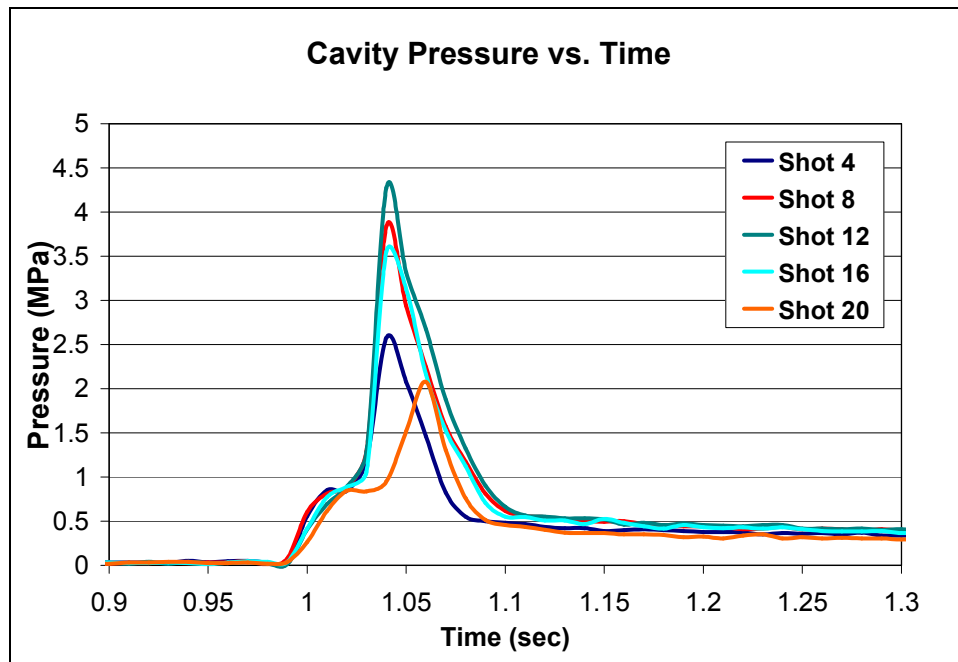
Figure 35: Pressure Curves for Trial with Switchover of 2.24mm
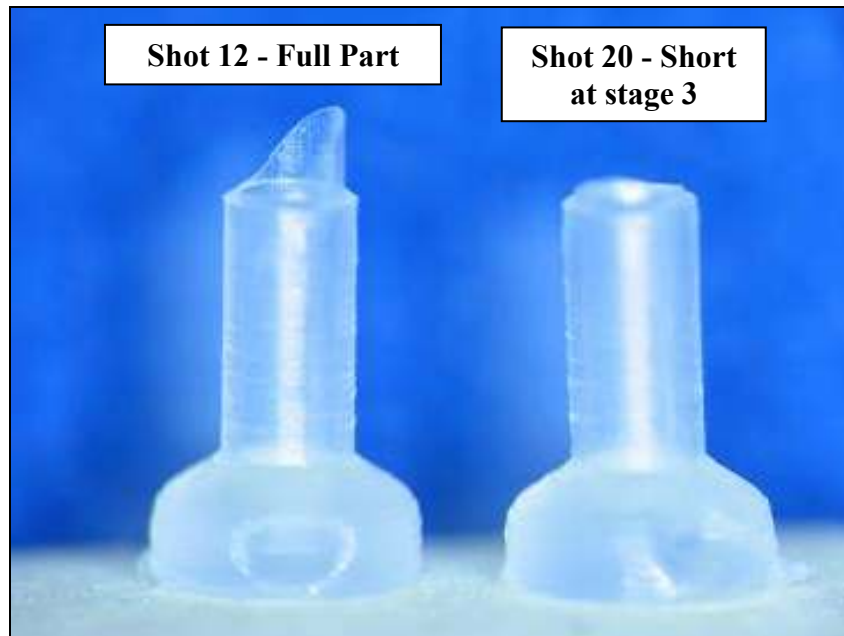
Figure 36: Shot 12 and Shot 20

Figure 37 shows the peak cavity pressure distribution for all the shots from trial 2.24. The pressure varies from a minimum of 2.077MPa to a maximum of 4.271MPa. After visually inspecting of all the parts, it was found that all the shots produced good parts except for shots number 1, 4, 14, 19, and 20 (circled in Figure 37) which are short at stage 3. Those shots also produce lighter parts than the rest of the good shots as presented in the same figure. Statistical information such as average, standard deviation, and coefficient of variation are shown in the figure too. The standard deviation measures the spread of the data about the average value. Coefficient of variation is a measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation to the average.
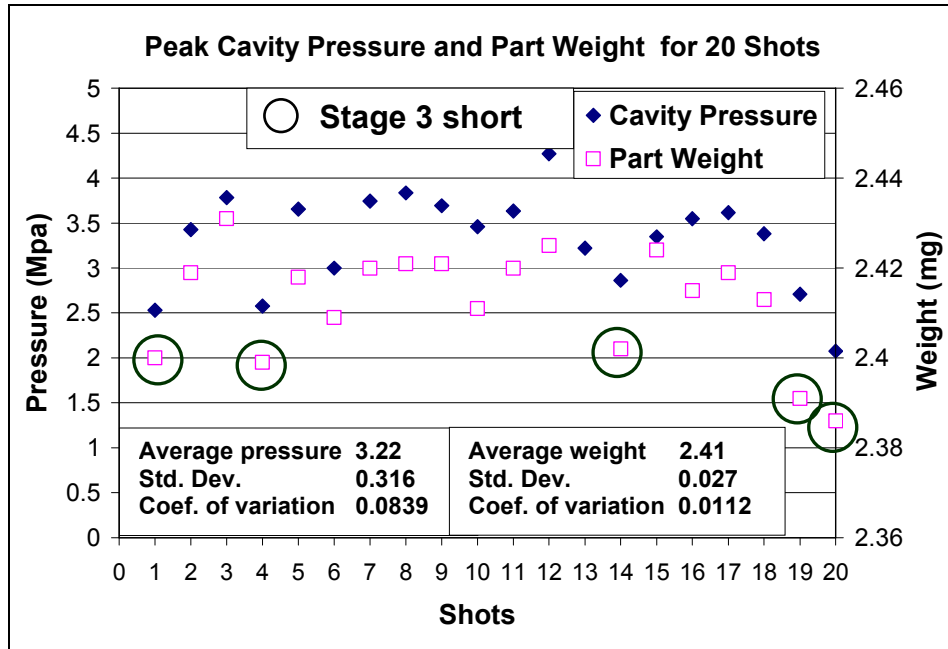
Figure 37: Peak Cavity and Part Weight Distribution for 20 Shots with Same Settings

To further investigate the relationship between part weight and cavity pressure, a plot between peak cavity pressure and part weight is presented. Figure 38 shows the correlation between peak cavity pressure and part weight. As can be seen from this figure, cavity pressure responds almost linearly with part weight with a correlation coefficient (R^2) value of 0.8454. In addition to cavity pressure, machine injection pressure was also found to have correlation with part weight as shown in the same figure. However, the R^2 value is only 0.7134, which is lower than the one with cavity pressure as discussed earlier. This indicates that cavity pressure is a better indicator of part quality than injection pressure.
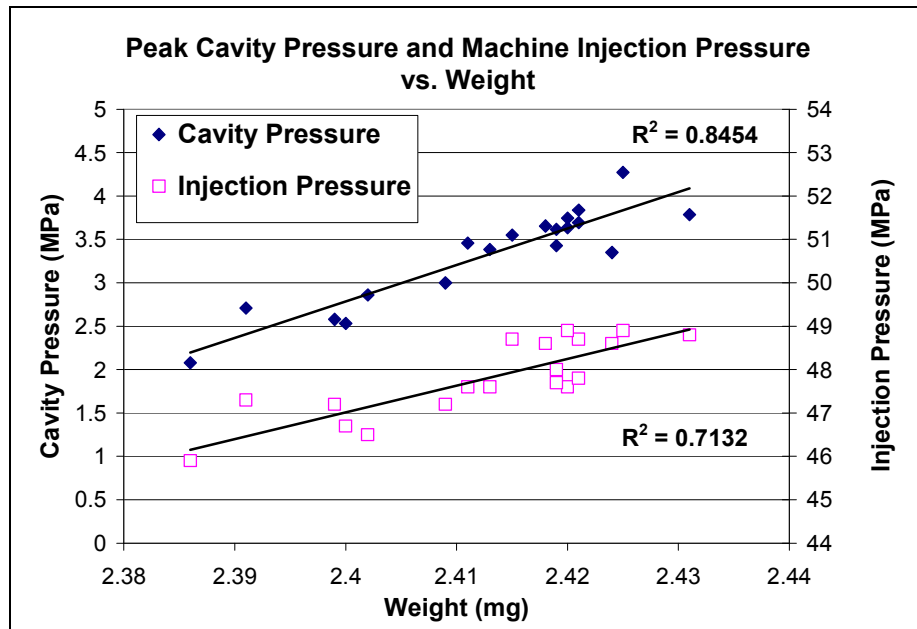
Figure 38: Cavity Pressure and Injection Pressure with respect to Part Weight

Machine Data

In an attempt to explain the inconsistency of cavity pressure and part weight obtained in a same trial, machine data was analyzed. Machine injection pressure and nozzle temperature were recorded throughout the process. Figure 39 shows the peak machine injection pressure for all the shots of the same trial, the pressure values range from 45.9MPa to 48.9MPa, and the coefficient of variation is 0.0197. The inconsistency of injection pressure is expected due to the fact that the injection phase is control under velocity. During the injection phase, the screw movement is based on the set velocity regardless of the pressure. Due to the viscosity changes in the polymer melt from shot to shot, different injection pressure is experienced although the identical injection velocity is applied.
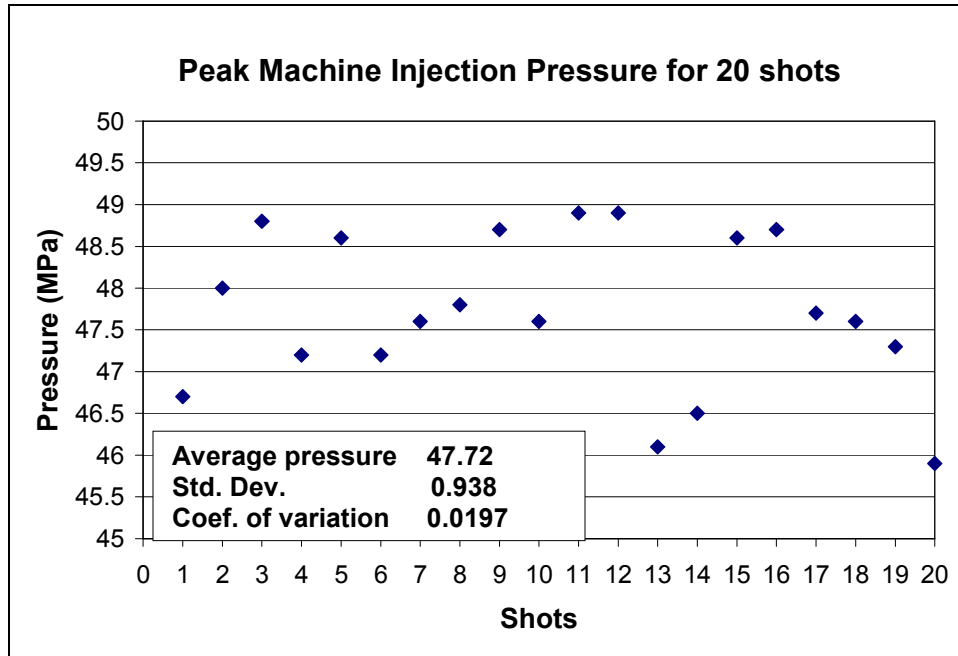
Figure 39: Injection Pressure Distribution for 20 Shots

This inconsistency in machine injection pressure is believed to have an impact on cavity pressure. The pressure transducer in the cavity experiences the injection pressure from the machine through the polymer melt. Figure 11 shows the relationship between cavity pressure and injection pressure. Although the relationship shown does not have a very high degree of correlation, it is strong enough to affect the value generated in cavity pressure.
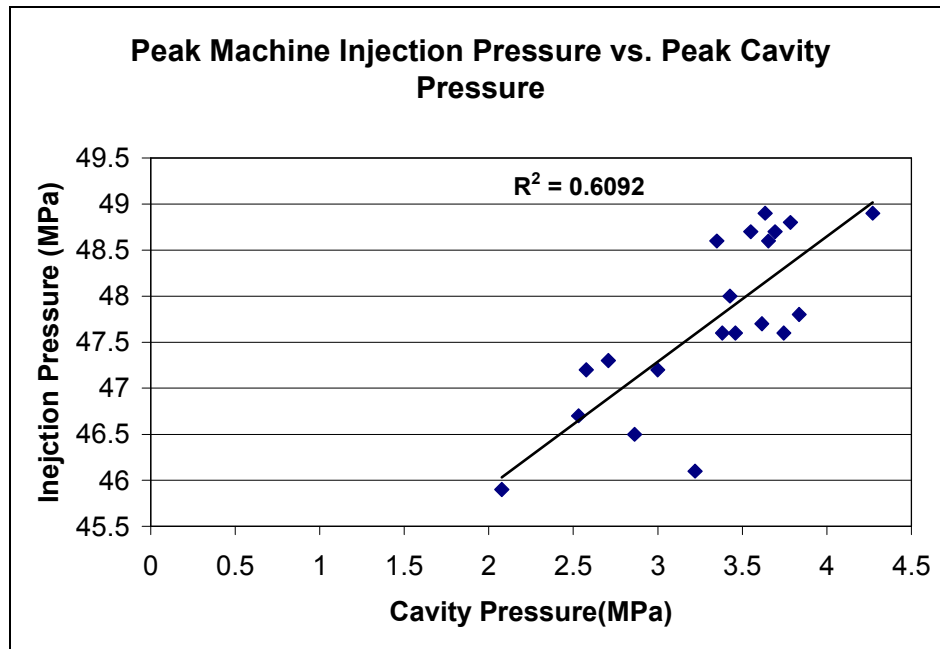
Figure 40: Peak Injection Pressure vs. Peak Cavity Pressure for the Same Trial

Figure 41 shows a snapshot obtained from machine display screen for one of the trials with 0 MPa pack pressure. The screen shot clearly shows how the process parameters react during the molding process. During the injection phase, injection velocity is maintained while pressure varies (increasing). Once switchover occurs, the screw movement is based on the pressure setting (pack pressure). In this stage, the velocity of the screw varies in order to achieve the required pack pressure setting. In the present study, since pack pressure is always set to 0 MPa, the screw actually backs up when the switchover occurs and the pressure is reduced to 0 MPa. Since the pressure is increasing during the filling phase, it takes a small amount of time to reduce to 0 MPa. As a result, the pressure "overshoots" a bit before settling down to 0 MPa.
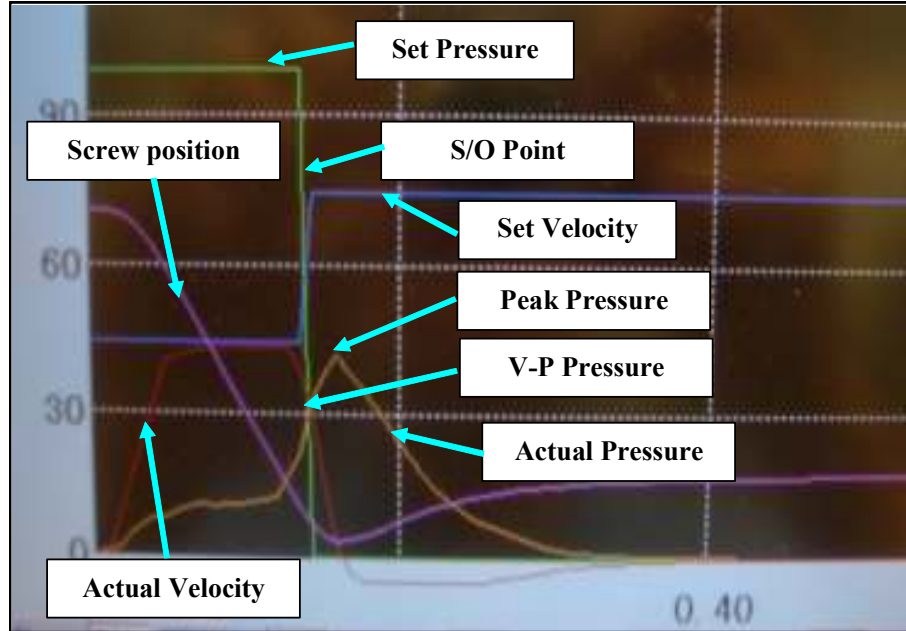
Figure 41: Curves Obtained from Machine

Another interesting finding is the relationship between peak injection pressure and V-P pressure. V-P pressure is the pressure at the point where switchover happens; it is a part of the rising path that eventually reaches the peak point. As shown from Figure 41, peak pressure is closely depended on V-P pressure. A plot to illustrate the correlation between peak pressure and V-P pressure is shown in Figure 42; it shows high degree of correlation with R^2 value of 0.9755. The inconsistency of V-P pressure is suspected to be due to the viscosity of the polymer in the barrel. Due to the fluctuation of viscosity, a different injection pressure has to be applied in order to maintain the same injection velocity.
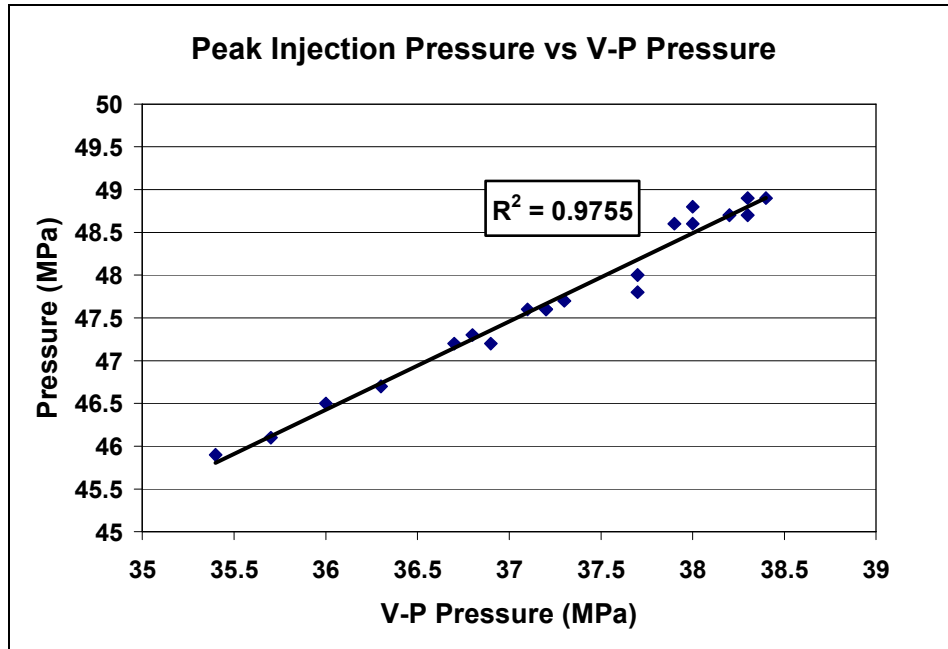
Figure 42: Peak Injection Pressure vs. V-P Pressure

In addition to pressure data, the nozzle temperature distribution for every shot has also been recorded. Figure 43 shows the nozzle temperature for every shot. As expected, the temperature fluctuates in a cyclic form from shot to shot. This happens as the barrel heaters cycle on and off automatically throughout the experiment to maintain the set temperature of 210 °C. Although the actual melt temperature can only be determined by using probe-style pyrometer [46], the nozzle temperature obtained earlier is adequate since our purpose is only to determine whether there is any fluctuation in terms of melt temperature.
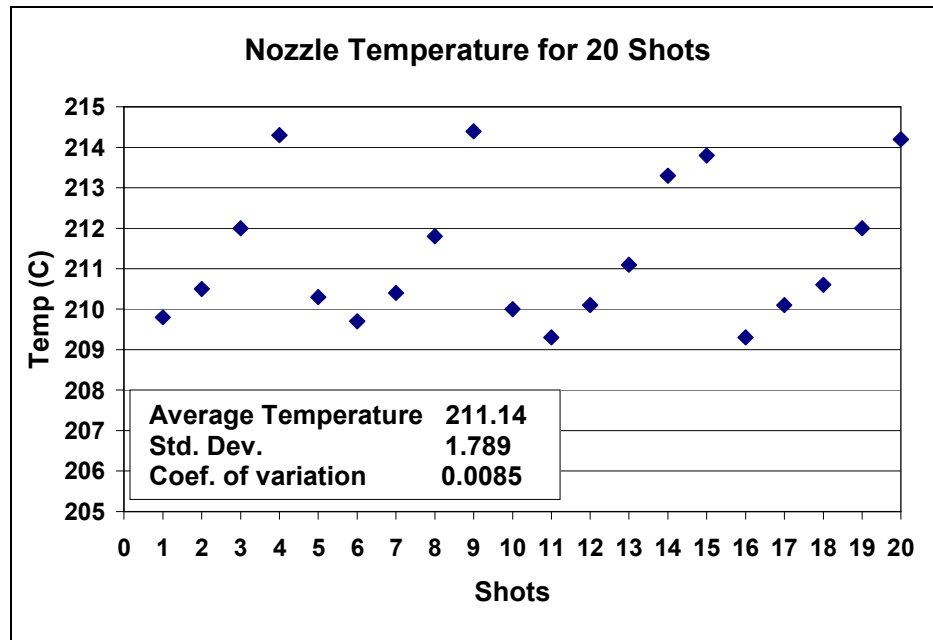
Figure 43: Fluctuation of Nozzle Temperature

The fluctuation of temperature is believed to affect the viscosity of polymer melt. Investigation is carried out to check how temperature affects the part quality due to the change of viscosity. However, the R^2 value for part weight and nozzle temperature calculated is only 0.0013. This suggests that there is no direct relationship observed between the two parameters. However, further investigation on this finding is needed because the current measured melt temperature is based on the nozzle temperature. It may not reflect the exact melt front temperature which is located at the front tip of the nozzle.

Relationship between part weight and runner weight

Figure 44 presents the relationship between part weight and runner weight. As shown, part weight and runner weight has little to no relationship between them. This

differs from the finding of Zhao et al.[45], where part weight is linearly related to runner weight until certain metering size is reached. A logical explanation to this dissimilarity is the pack pressure setting. When pack pressure is involved in injection molding process, at the switchover point, the screw will continue to move forward for certain distance and speed (depending on pack pressure setting) to attain the required pack pressure. In the current experiment, no pack pressure is involved in the process. As a result, at the end of the injection phase, the screw is backed up in order to reach the 0 MPa of pack pressure. This backing up is believed to have "sucked" back some of the polymer in sprue and runner system, and hence causes the loss of the relationship between runner weight and other parameters such as injection pressure, cavity pressure, and part weight.
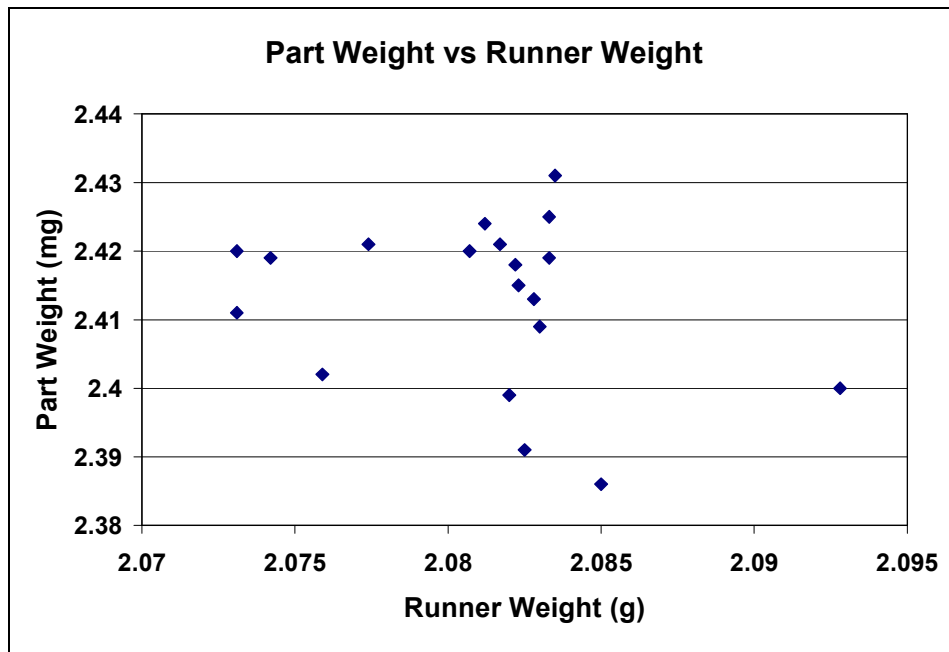
Figure 44: Part Weight vs. Runner Weight

Conclusion

Consistency in micro injection molding is difficult to achieve since variations that are negligible in molding of macro-scale parts are much more significant when molding micro-scale parts. This makes it even more critical to have an accurate and reliable process monitoring system to detect and segregate defective parts. Cavity pressure has been shown to respond linearly to part weight and provide an indication of process variation. In addition, peak cavity pressure has a higher degree of correlation with part weight than area under cavity pressure curve. These findings signify the potential of cavity pressure to be utilized as an indicator of part quality and process variation. Although nozzle temperature fluctuated throughout the experiment, it appears to have had no impact on the part weight.

CHAPTER 6

QUALITY AND PROCESS MONITORING IN THE MICRO INJECTION MOLDING PROCESS

Introduction

Due to the tendency of miniaturization in technical products, the market for MEMS/MST (Micro-Electro-Mechanical Systems/Micro-System Technology) has grown rapidly over the last decade. The market volume is estimated to reach $24 billion by 2009, lead by IT peripherals, consumer electronics, and automotive industries as the three primary application area [47]. Examples of micro-parts include the micro-rotors, locking wheel, and micro-latches commonly used in the watch industry; micro-parts for medical applications; and the micro-pumps, micro-gears, pressure sensors, and ink-jet printer heads found in various other industries. Figure 45 shows example of some of the micro-parts.
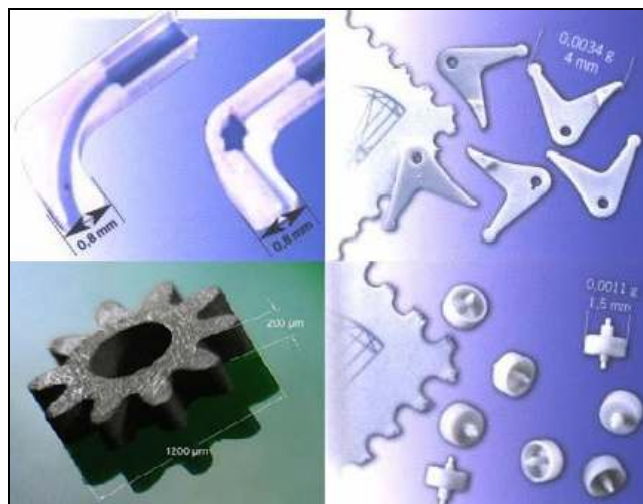
Figure 45: Examples of Micro-Parts: (clockwise from top left) Hearing Aid Component, Micro-Latch, Micro-Rotor, Micro-Gear [8, 28]

In order to meet the market demand in micro-parts, there have been lots of research efforts focusing in developing new fabrication method for micro-parts or improving existing techniques. One such attempt is to manufacture micro-part using injection molding method, i.e. micro-injection molding. This process offers short production time and low manufacturing cost; it is regarded as a suitable method to mass-produce micro-parts in the industry [20]. Although the overall principal is the same for both molding processes, due to the unique challenges inherent in working at a size scale a few orders of magnitude smaller than typical injection molding, micro-injection molding requires further research and development for it to become a viable and effective option.

The micro-injection molding process has a smaller processing window compared to traditional injection molding with the filling time and packing time normally being much shorter. This presents the difficulty in controlling and monitoring the entire molding process. The process is also more susceptible to slight changes in process parameters such as mold temperature, injection velocity, metering size, and packing pressure. Therefore, good process repeatability and a high-quality mold are essential in order to achieve consistently high quality micro-parts.

In general, micro-injection molding is still a relatively immature process where achieving a good process consistency and part quality remain challenges. As a result, quality inspection becomes crucial in order to ensure detection and segregation of defective parts. However, physically inspecting micro-parts is usually more difficult than inspecting conventionally molded parts primarily because of the difference in size [11]. Inspecting micro-parts requires extra attention because the part features and defects are

smaller and therefore more difficult to detect. To address this issue, a number of microscopic and surface evaluation measurement techniques including atomic force microscopy (AFM) and scanning electron microscopy, have been applied by manufacturers and researchers. These methods provide accurate inspection results, however they are time, labor, and capital intensive.

One possible method for reducing the cost of inspection while still guaranteeing quality in micro-injection molding is to use cavity pressure measurement for detection of part deviation. In the conventional injection molding process, it has been found that cavity pressure can provide early detection of process and part deviation [38, 42, 43]. Previous studies have also shown that cavity pressure has significant utility as an indicator of part quality and process variation. Specifically, the present study addresses how cavity pressure responds to different part quality and combination of molding conditions based on the approach of Design of Experiment. The objective is to cover a broader range of processing parameters to investigate the robustness of cavity pressure as a process and part quality indicator.

Experimental Setup

The experimental work was conducted on a 17-ton Cincinnati/Milacron Fanuc Roboshot Si-B17 as shown in Figure 46. This is an electric servo-driven injection molding machine having a screw diameter of 16 mm. A hollow micro-cap (see Figure 47) with a 1mm outer diameter, overall height of 3 mm and wall thickness of ~0.1 mm was molded for the study. The top portion of the part consists of a ~0.5 mm thick cap

with diameter of 2 mm. A 0.793 mm diameter eject pin was inserted on the moving platen through the 1mm diameter cavity hole to act as a core pin. On the stationary platen, a flush-mount pressure transducer is installed and acted as part of the cavity. Both cavities on moving and stationary platen were machined out of a 2.5 in. x 2.5 x 0.5 inch stainless steel insert which were then mounted in larger mold plates. The platen assemblies were fitted on MUD U-type mold frame. The final produced part weighs approximately 2.4 milligrams with aspect ratio of ~30 on the annular wall section. Figure 48 shows the size of two micro-molded caps relative to a U.S. dime.

Figure 46: Milacron Roboshot Si-B17
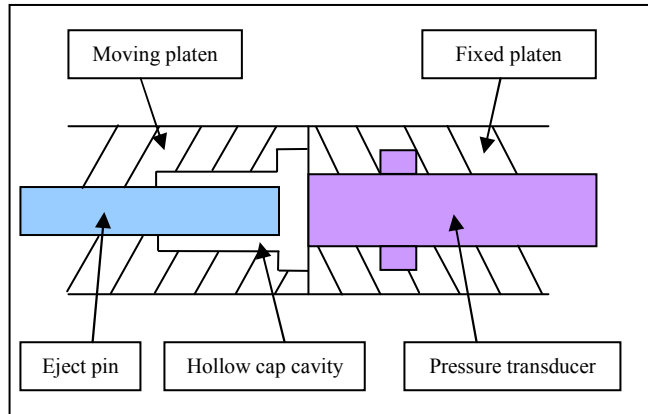
Figure 47: Construction of Hollow Cap Cavity

Figure 48: Molded Hollow Caps Relative to a U.S Dime

In terms of processing material, the type of material used in the present experiment is polypropylene - a crystalline material. The materials properties are shown in Table 10.

Table 10: Materials Properties for Polypropylene

Density (g/cc)	0.9 g/cc
Melt Flow (g/10 min)	11 g/10 min
Processing Temperature (ºC)	200 ºC - 232 ºC

Cavity melt pressure was measured using a 1 millimeter diameter Kistler 6183A piezoelectric pressure transducer as shown in Figure 49. The voltage signal was amplified by a Kistler 5122 charge amplifier, conditioned by a SCB-68 signal conditioning module, and then received by a NI PCI-6229 National Instrumentation data acquisition card. The resulting pressure data was then recorded by using National Instrument Lab View graphical programming software. Both pressure signals and elapsed time were recorded for each shot at a sampling frequency of 100 hertz. Figure 50 shows the overall experimental apparatus.
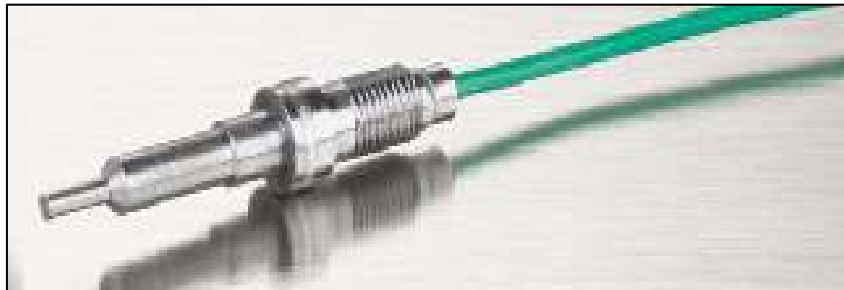
Figure 49: Kistler 6183A Pressure Transducer
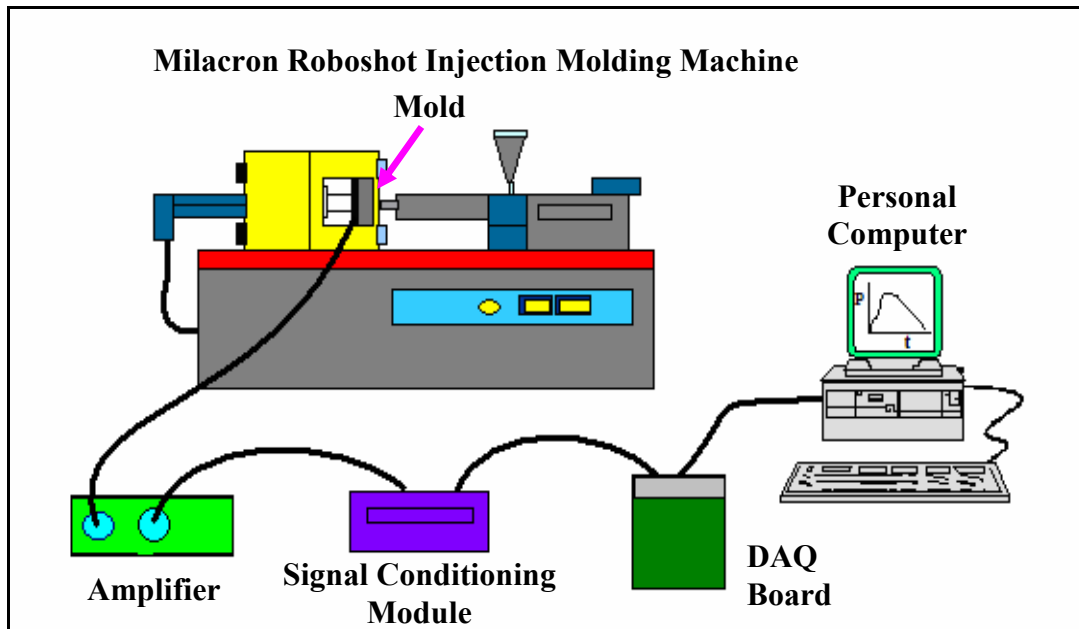
Figure 50: Connection of Experimental Apparatus

Experimental Trial

Three different processing parameters are varied to conduct a total of nine experiment trials to investigate the relationship between cavity pressure and part weight. These nine trials were conducted using a 3-parameter, 3-level orthogonal array as shown in Table 11. The three machine parameters chosen for this set of experimental trials were mold temperature, melt temperature, and pack pressure. In the micro-injection molding process, premature freezing is a common problem due to the high surface to volume area in the micro-part. To solve this problem, the mold is commonly heated up to delay the freezing. Realizing the impact of mold temperature to the filling of polymer melt, mold temperature is chosen as one of the parameters in this study to investigate the effect to the process. The next chosen parameter is the melt temperature. The fluctuation of melt

temperature during the molding process was discussed in the previous investigation. Melt temperature is believed to affect the melt and process behavior. Current study is to further investigate the effect of melt temperature on the process by having different melt temperature settings in the experiment. The third parameter is the pack pressure. In the injection molding process, pack pressure supplies additional pressure to provide extra polymer melt to compensate for material shrinkage. However, little is known about the effect of pack pressure since it was not included in the previous investigation. Therefore, this parameter is included in the current experiment to observe the impact to the process and part quality. Table 12 shows the settings of each parameter at different levels.

All of the nine trials were carried out in a random order to minimize the risk of bias in the results due to unknown or uncontrolled factors. Before the actual sample data was taken in each trial, the molding machine was stabilized by running the machine until there was no drift observed in the injection pressure and nozzle temperature. After that, thirty shots were produced and corresponding data was collected. All of the samples were weighed using appropriate balances: A Sartorius M2P for weighing the hollow cap, and a Sartorius BP 210S for weighing the runner. In the present study, the part weight is considered as the part quality indicator since it is a parameter that is quick and easy to measure.

Table 11: L9 Orthogonal Array

Trial	Parameter		
	Barrel Temperature	Mold Temperature	Pack Pressure
1	-1	-1	-1
2	-1	0	0
3	-1	+1	+1
4	0	-1	0
5	0	0	+1
6	0	1	-1
7	+1	-1	+1
8	+1	0	-1
9	+1	+1	0

Table 12: Parameter settings

Parameter	Level		
	-1 (low)	0 (mid)	+1 (high)
Barrel Temperature (ºC)	210	220	230
Mold Temperature (ºC)	30	40	50
Pack Pressure (Mpa)	25	40	55

The results obtained from the experiment cover different aspects that include the processing parameters, correlation of attributes to part weight, part quality, and process variations. Therefore, the following discussion is organized based on the different aspects mentioned.

(I) Main Effect Analysis on Processing Parameters

Main effect analysis is carried out to determine the effect of three different processing parameters on part weights. Table 13 shows the data obtained from the analysis. Coefficient of variation and standard error are relatively small among the processing parameters signifies the small variations among the shots. Figure 51 shows the plot of different processing parameters at different levels with respect to different settings level with the vertical lines on the data points represent the standard error. It is well illustrated from the figure that pack pressure has the most effect on part weight and they are proportionally related; average part weight increased from 2.365 mg to 2.373 and then to 2.409 as the level of pressure setting increases from low level to high level. Part weight decreases when mold temperature and nozzle temperature settings change from low level to mid level. However, the weight increases to a higher value when the mold and nozzle temperature change from mid level to high level.

Table 13: Average Part Weights from Different Settings

	Mold Temp		
Level	-1	0	1
Average Part Weight	2.383	2.371	2.395
Standard Deviation	0.031	0.009	0.024
Coefficient of Variation	0.013	0.004	0.010
Standard Error	0.004	0.001	0.003
	Nozzle Temp		
Level	-1	0	1
Average Part Weight	2.383	2.374	2.392
Standard Deviation	0.036	0.007	0.022
Coefficient of Variation	0.015	0.003	0.009
Standard Error	0.004	0.001	0.002
	Pack Pressure		
Level	-1	0	1
Average Part Weight	2.365	2.373	2.409
Standard Deviation	0.011	0.013	0.021
Coefficient of Variation	0.005	0.005	0.009
Standard Error	0.001	0.001	0.002
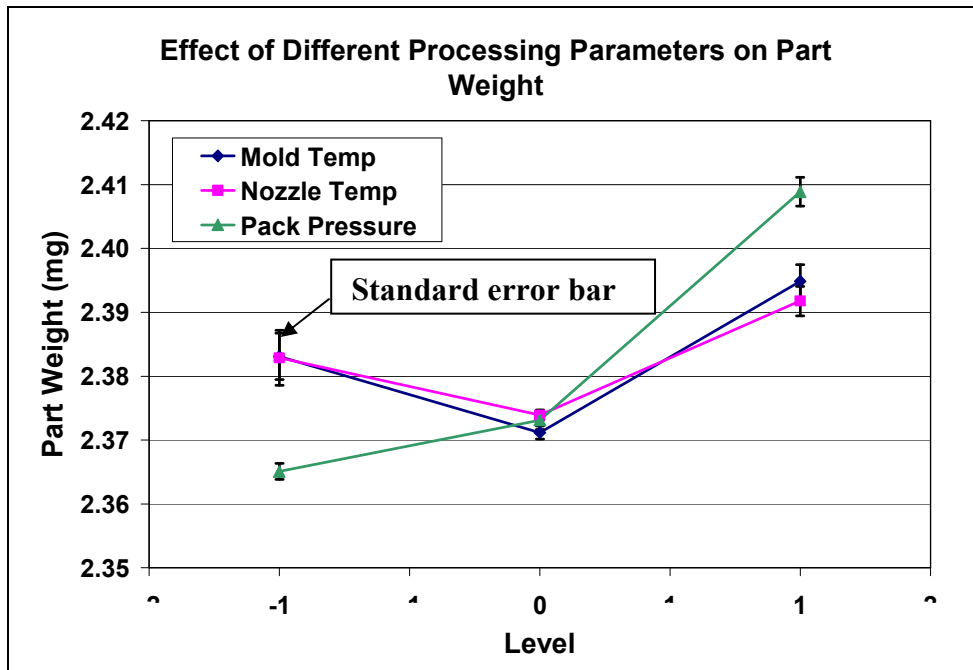
Figure 51: Main Effect Analysis of Different Parameters on Part Weight

Attributes and the Correlation with Part Weight

Two attributes obtained from the cavity pressure - peak cavity pressure and area under curve, are utilized to relate with the part weight. Figure 52 shows the average part weights and average value of area under curve for all the trials while Figure 53 shows the average weights and average peak cavity pressure. Both figures show that both attributes appear to have promising correlation with part weight as shown in the figures respectively: Higher part weight has higher value in both attributes. In terms of standard error of every trial for average part weight, average peak cavity pressure, and average area under curve, the error values are not presented in both Figure 52 and Figure 53 because they are relatively small and hardly noticeable from the plots. The small value of standard error signifies that the average value obtained has small scattering and deviation from the mean value.
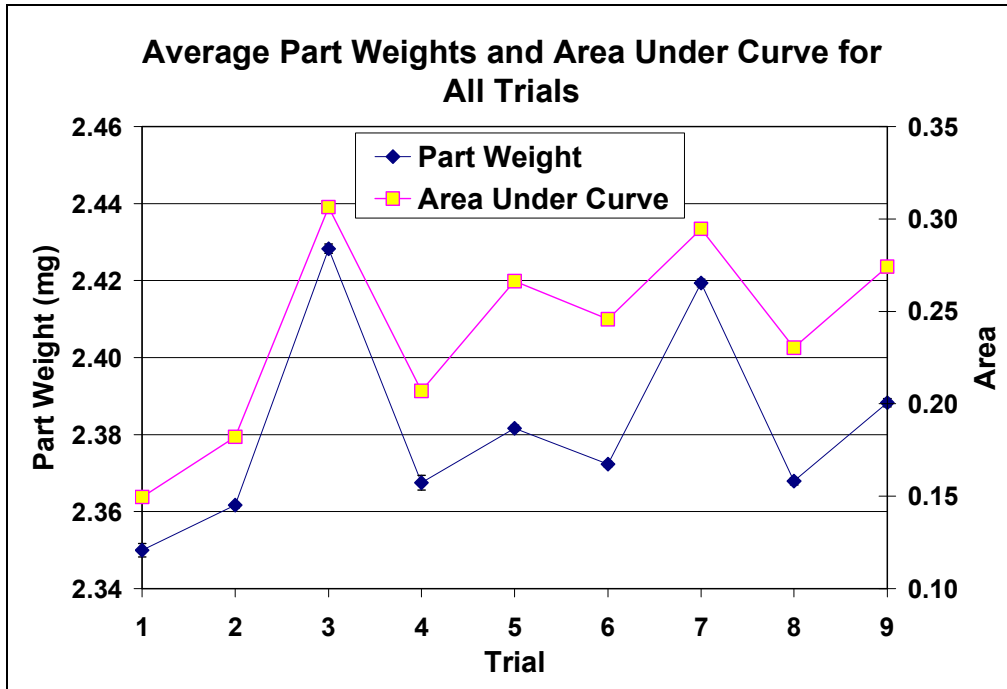
Figure 52: Average Part Weight and Area Under Curve for All of the Trials
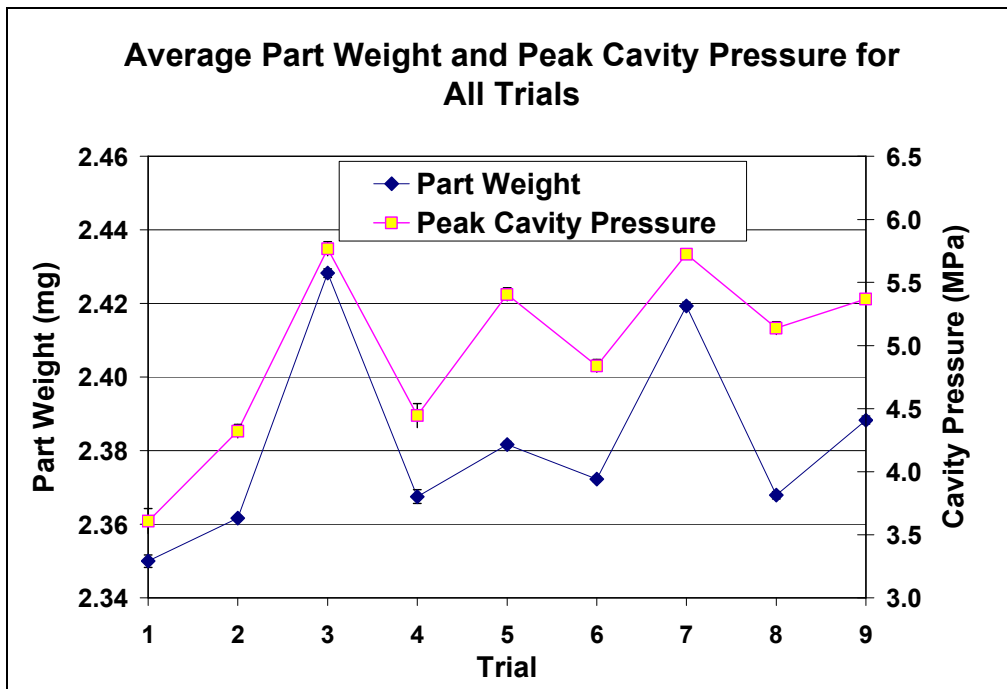
Figure 53: Average Part Weight and Peak Cavity Pressure for All of the Trials

Table 14 presents the statistical data such as the average, standard deviation, coefficient of variation, and standard error for all the trials conducted. The coefficient of variation for part weight is relatively small compare to cavity pressure and area under curve. From the table, Trial 1 is shown to have the largest value in coefficient of variance and standard error for part weight, peak cavity pressure, and area under curve. This shows that trial 1 produces the most variations among the shots.

Table 14: Data Obtained From DOE Trial

Trials	1	2	3	4	5	6	7	8	9
Average Part Weight	2.350	2.362	2.428	2.368	2.382	2.372	2.419	2.368	2.388
Standard deviation	0.010	0.004	0.006	0.010	0.004	0.004	0.006	0.005	0.006
Coefficient of variance	0.004	0.002	0.003	0.004	0.002	0.002	0.002	0.002	0.003
Standard error	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001
Average Peak Cavity Pressure	3.608	4.320	5.767	4.445	5.406	4.839	5.724	5.138	5.368
Standard deviation	0.540	0.293	0.304	0.523	0.283	0.277	0.185	0.277	0.208
Coefficient of variance	0.150	0.068	0.053	0.118	0.052	0.057	0.032	0.054	0.039
Standard error	0.099	0.053	0.055	0.096	0.052	0.051	0.034	0.051	0.038
Average Area Under Curve	0.149	0.182	0.306	0.207	0.266	0.246	0.295	0.230	0.274
Standard deviation	0.027	0.018	0.019	0.024	0.018	0.018	0.014	0.023	0.015
Coefficient of variance	0.178	0.099	0.062	0.117	0.068	0.072	0.047	0.099	0.055
Standard error	0.005	0.003	0.003	0.004	0.003	0.003	0.003	0.004	0.003

To further investigate the relationship between cavity pressure and part weight, coefficient of determination (R^2 value) was calculated to determine how well peak cavity pressure and area under curve correlate with the part weight. The coefficient of determination is a measure of the degree of correlation or dependence between the dependent and independent variables in a regression analysis. A high R^2 value indicates that the two variables are well correlated. A plot to show the correlation of average area under curve and peak cavity pressure with respect to part weight is presented in Figure 54. As shown in the figure, both attributes have good correlation with the part weight by having R^2 value above 0.92. Additional plot in Figure 55 shows the distribution of all the shots of both attributes in the current DOE trial with respect to part weight.
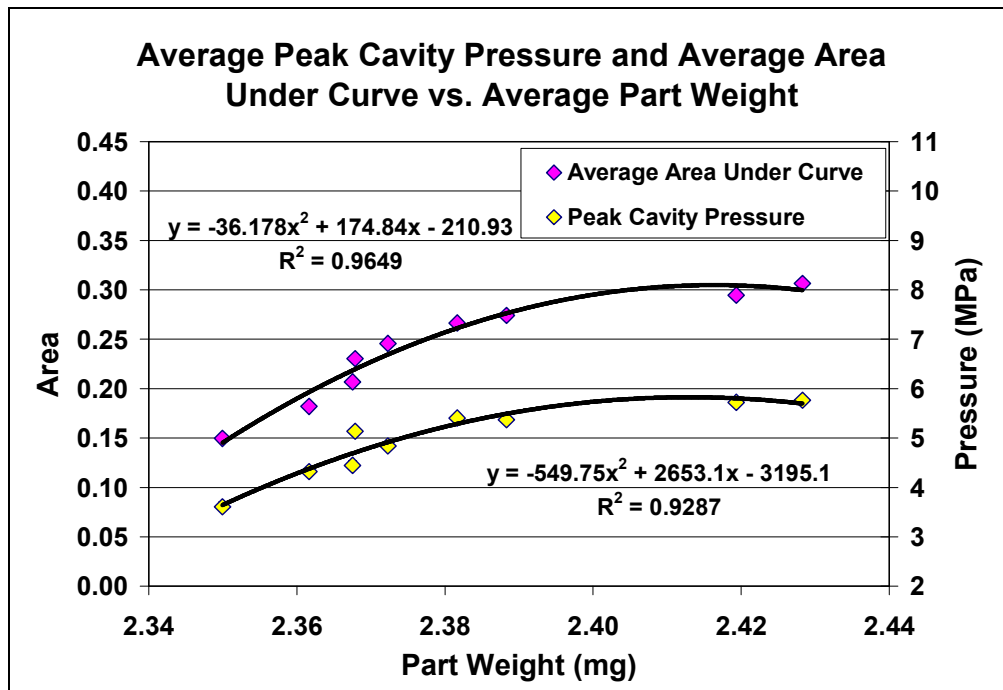
Figure 54: Average Area and Peak Cavity Pressure vs. Part Weight
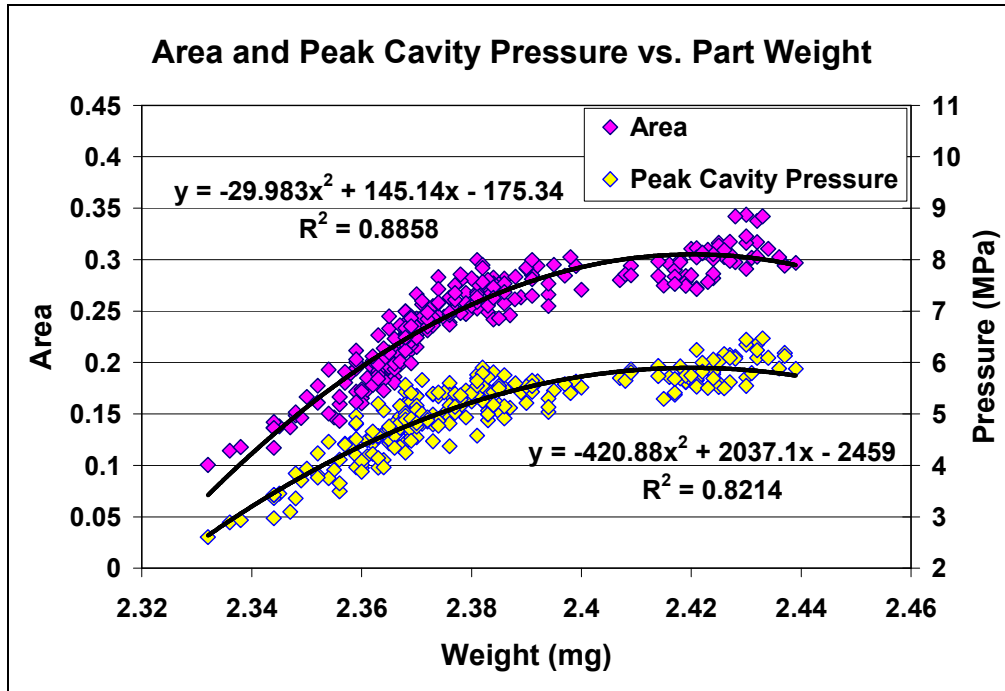
Figure 55: Area and Peak Cavity Pressure vs. Part Weight

Different types of relationship such as linear, logarithm, and different orders of polynomial were used to best fit the data distribution. Under current processing parameter range, both attributes are found to have a second order polynomial relationship with part weight as shown in both Figure 54 and Figure 55. The curves start to increase linearly at the beginning and then begin to flatten out at the pressure of 5 Mpa and area value of 0.25. By referring to Figure 56, that portion corresponds to trial 3, trial 7, and trial 9, which are the trials that have two processing parameters at high level settings. This combination of two high level settings appears to allow more materials to fill up the cavity at a less responsive pressure range. The hot mold and/or hot melt delay the gate freezing time and decrease the melt viscosity; meanwhile the pack pressure continues to pack in additional material which is low in viscosity. Therefore, the less viscous melt is

able to fill up the cavity thoroughly (including some hardly visible micro features) and even created some flash without causing significant increase in pressure. Due to the fact that more material is in the cavity, the parts produced are heavier and denser although cavity pressure does not increase much.

(II) Comparison between Attributes

In terms of the comparison between peak cavity pressure and area under curve, although both attributes respond to part weight in an almost similar manner, the R^2 values are different. Area under curve is found to have a higher R^2 value of 0.8858 compare to peak cavity pressure with the R^2 value of 0.8214, this signifies that area is a better quality indicator than peak cavity pressure. This finding contradicts with the result obtained in previous chapter where peak cavity pressure was found to be a better quality indicator in the molding of hollow micro-cap. A possible explanation to this difference is the significant effect of pack pressure. Pack pressure provides extra material to compensate for the part shrinkage in the cavity. However, this action is not well represented by the peak cavity pressure as it only indicates the maximum pressure at the moment the part is fully filled; anything that occurs after the part is filled is overlooked. On the other hand, area under curve covers entire processing window from the moment the melt enters the cavity to the time when the part solidifies. In the previous experiment, since pack pressure was set to 0 MPa, the polymer melts stopped flowing into the cavity at the end of the injection phase. Therefore, there was little effect on the part weight after the part is filled and the injection phase is over. As a result, peak cavity pressure alone was able to

correlate well to the part weight. In the current trials, pack pressure appears to have an important effect on the part weight, therefore area appears to be a better attribute to correlate to part quality.

One question may arise as to why one would not rely on area under curve for all experiments since it covers the entire processing window. According to an article published by Tat Ming Engineering Works Ltd.[31], the choice of the most suitable attribute is related to the part thickness. Peak cavity pressure is more suitable for thin wall molding while area under curve is more applicable for thick wall. Furthermore, from all the experiments conducted in the current research work, peak cavity pressure has always appeared to provide a better indication of part weight except on trials that include the effect of pack pressure. For example, in the previous chapter, peak cavity pressure has a better correlation with part weight compared to area under curve as shown in Table 8 and Figure 33. Only in the most recent investigation are mixed results obtained where the R^2 value of peak cavity pressure is no longer consistently higher than the R^2 value of area under curve. Table 15 shows the R^2 value of both attributes with respect to part weight from the current DOE trial. Note that trial 1, 4, 5, and 7 have a higher R^2 value in area under curve than peak cavity pressure.

Table 15: R^2 Value of DOE Trial

Trials	1	2	3	4	5	6	7	8	9
Mold Temperature (°C)	30	40	50	30	40	50	30	40	50
Nozzle Temperature (°C)	210	210	210	220	220	220	230	230	230
Pack Pressure (MPa)	25	40	55	40	55	25	55	25	40
R2 Value - Cav Pmax vs. weight	0.8155	0.5209	0.2567	0.5884	0.0127	0.528	0.0039	0.6499	0.3402
R2 Value - Area vs. weight	0.8588	0.5052	0.1223	0.7608	0.2805	0.3585	0.2298	0.5841	0.3055

(III) Breakdown of DOE Trials

The next discussion focuses on the breakdown of the data in Figure 55 to individual trial as presented in Figure 56. Here, only area under curve will be presented since it has a higher R^2 value as discussed earlier. In general, the result obtained from the Figure 56 is expected since trials with low level settings such as trial 1 and trial 2 produced lighter parts and lower attribute values while trials with higher level settings such as trial 3 and trial 7 produced heavier parts and greater area under curve. As shown in the figure, two distinct clusters are observed from in the data with most of the parts weighing from ~2.33mg to ~2.40mg and a second group falling in the range from ~2.41mg to ~2.44 mg. This second group consists of trial 3 and trial 7. Both of these trials were conducted at high level settings in two of the three processing parameters. The separation of the trials suggests the possibility of having an excessive gap between each level for the pack pressure setting. Despite the disjointed data, the results obtained match the previous finding from Figure 51 which shows that pack pressure has the greatest effect on part weight.
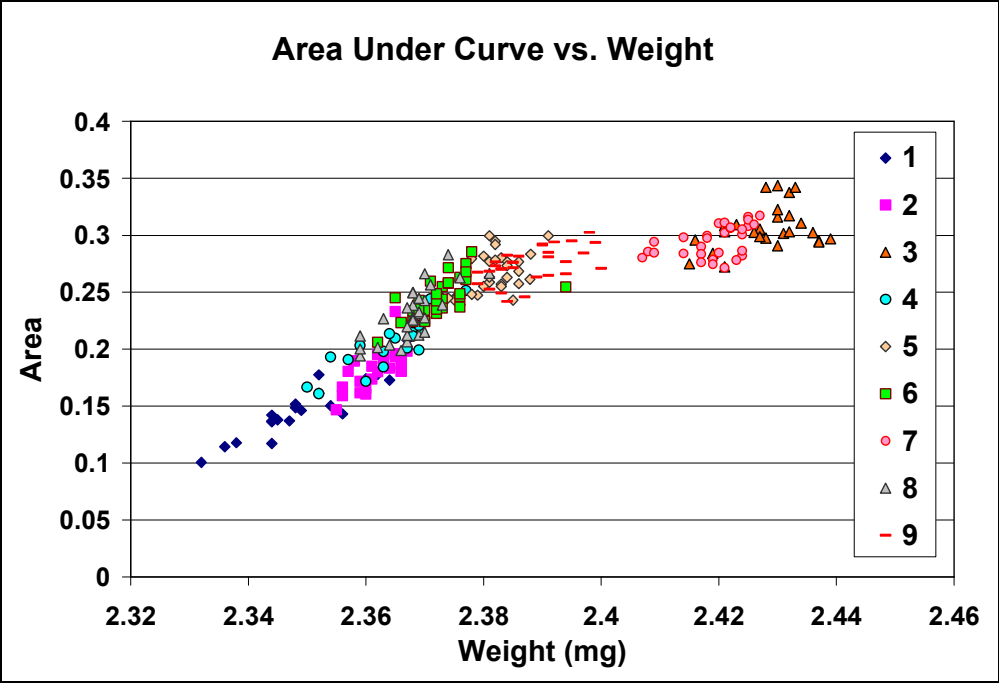
Figure 56: Break Down of DOE Trial

(IV) Part Quality

In terms of part quality, although weight is used as the quality indicator, normal visual inspection can also easily detect some obvious defects on the parts. The common defects detected in the present experiment are short at stage 3, flash, and air trap. For the filling stages of the hollow cap, they are divided into three distinct stages: stage 1 corresponds to fill of the thick cap/annular section, stage 2 corresponds to fill of the thin wall section, and stage 3 corresponds to fill of the small portion of flash at the end of the hollow cap. Therefore, stage 3 shortage is also the shortage at the thin flash feature located at the end of the thin wall. This flash as shown in the figure is due to machining error on the mold and is treated as a part feature; it is not the result of over packing. This feature happens to be the thinnest portion of the cavity and it is located the farthest away

from the gate. Therefore, it then turns out to be the last portion for the melt to fill up.
Due to this reason, the "flash" can be used to indicate a completely filled part.
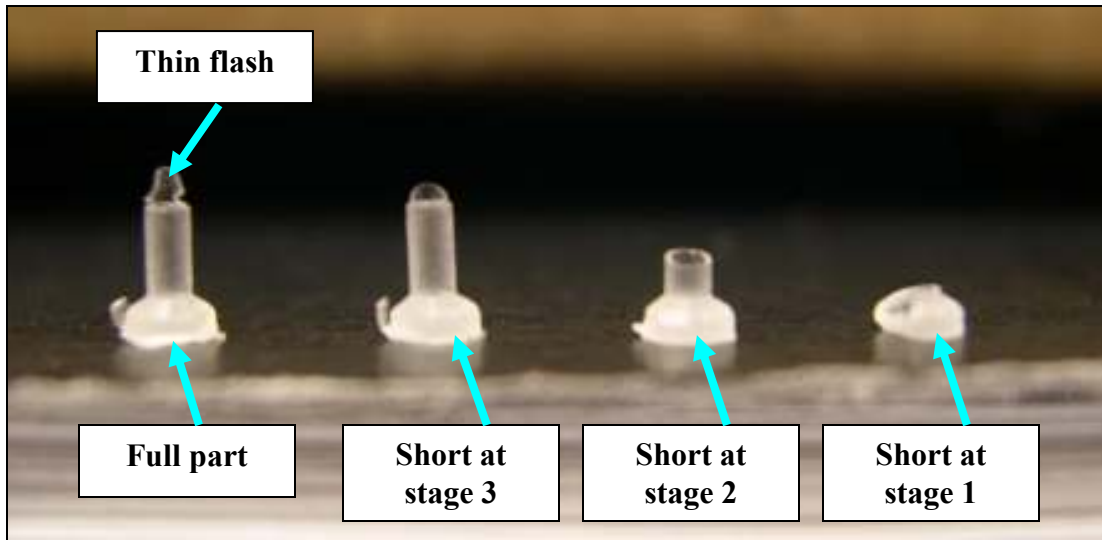
Figure 57: Full Part and Short Part

In the present investigation, all the parts produced have at least filled up stage 2. Only short at stage 3 is detected from some of the parts from low level setting trials. Short part happens because of a few reasons: low melt and mold temperature speed up the freezing process, and the insufficient of pack pressure to supply additional materials to fill up the cavity. Figure 58 shows the comparison between a good part and a short at stage 3 part obtained from the current DOE trial.

Figure 58: Short Part and Good Part from identical Settings

The next defect found among some of the hollow caps is flash. Flash happens at the thick cap section where the two mold platens meet. During the micro-injection molding process, the high level setting forced more polymer melt into the cavity that eventually flowed out into the parting plane and forms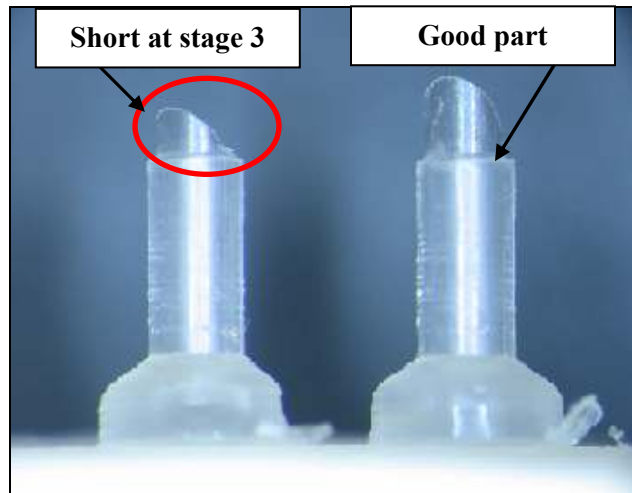 the flash. High mold and melt temperature delayed the freezing of the melt and allow extra material into the cavity. Furthermore, the high temperature in the mold and melt lowered the viscosity of the polymer and hence provided a better flowability to the polymer melt. Besides temperature, high pack pressure injected additional material into the cavity. Therefore, with the combination of high level settings in the processing parameters, the parts are heavier due to the extra materials being injected. The weights among the flash parts vary as the size of the flash varies from shot to shot. Figure 60 shows an example of a flash part.
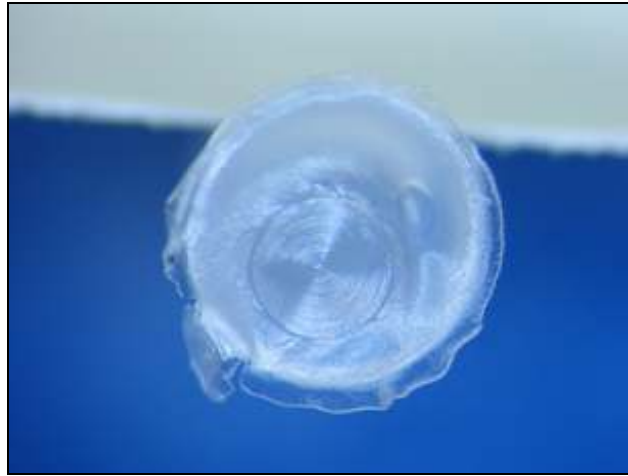
Figure 59: Flash Part

The last defect found from the parts is air trap. Almost all of the parts contain this flaw. There are three common locations on the thick cap where air traps are often spotted. The two common ones are the points next to the gate, and another point is at the point opposite of the gate. The amount and size of air trap varies from part to part, but most of them have two air traps next to the gate. Figure 60 shows the location of the air traps and Figure 61 shows the two commons air trap found near the gate. Air trap is formed because air could not escape as there was no air vent available in the current cavity design. Furthermore, prior evacuation before the injection phase was not performed. Although some researchers mentioned that air trap could jeopardize the quality of the part by producing burn mark due to the Diesel effect[48], in the present experiment, we did not encounter this issue that causes serious part defect due to air trap.
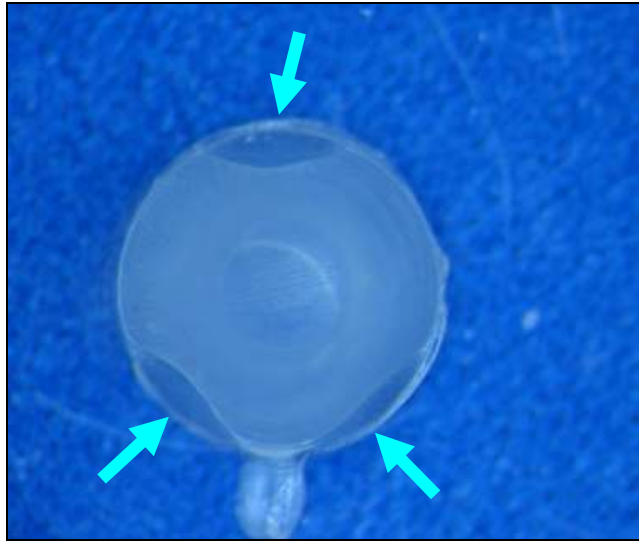
Figure 60: Location of Air Trap
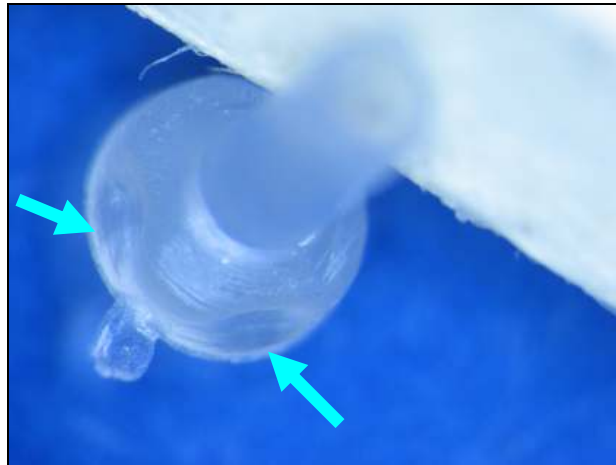
Figure 61: Common Location of Air Trap - Beside the Gate

After comparing the defects parts to Figure 56, two of the three defects presented earlier can be distinguished in the plot as shown in Figure 62. Parts with short at stage 3 are found in low level settings trial such as trial 1, 2, and 4, as circled in the Figure 62. Although those parts are short at stage 3, they still show good correlation in the graph, this matches with the result obtained in the previous chapter where cavity pressure starts

to respond well to part weight once stage 2 or the thin wall section is filled. Besides short parts, flash parts are also found in trial 3, 7 and 9 as identified in the same figure. On the other hand, parts with air trap cannot be identified from the same figure. Because of the existence of air trap, the pressure sensed by the pressure transducer may not solely related to the amount of material in the cavity. Therefore, the correlation between the weight and the cavity pressure is affected.

Figure 62: Defects Parts Identified from Area Chart

(V) Process Variation

The last discussion will be on the variation of part quality and results obtained. In a single trial, parts with different quality are produced. For example, in a same trial with same settings, parts with different qualities are found; some with shortage at stage 3, and
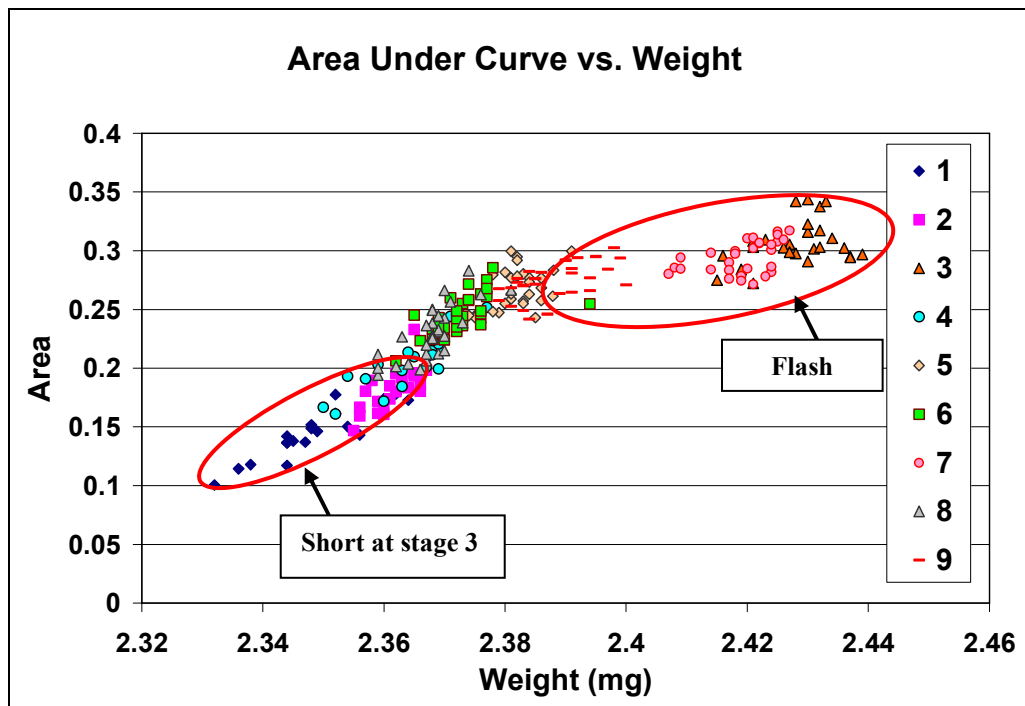
some are full (see Figure 58). Furthermore, the size of the small piece of materials left on the gate varies too as shown in Figure 63. Although de-gating is done when the part is ejected by the ejector pin, occasionally the part still stuck with the runner and have to be removed manually. In terms of air trap, size and numbers vary from part to part too. However, it has less variation within a single trial. Even so, the formation of air trap in the current study is believed to sway the correlation between cavity pressure and part weight. It is believed that the presence of air trap causes the pressure sensed by the transducer may not entirely due to the filling of the polymer melt but also due to the influence of air trapped. Moreover, the inconsistencies in the results are further affected by the variation in the number and the size of the air trap found in the samples. Figure 64 shows the variation of air trap number found in two samples.
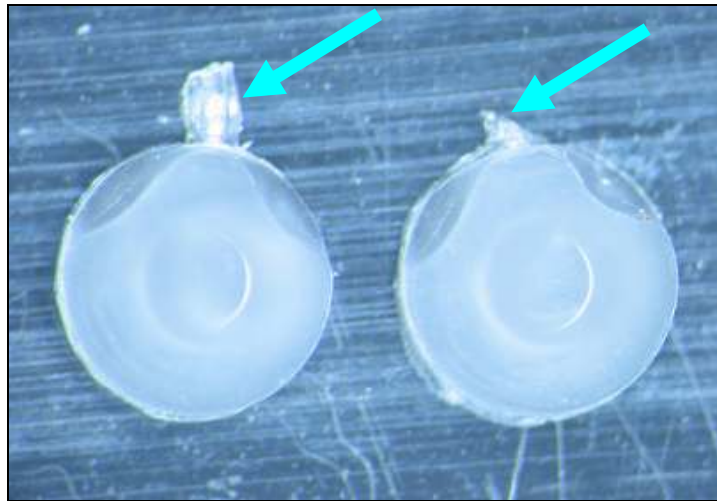
Figure 63: Different Sizes of Gate Piece
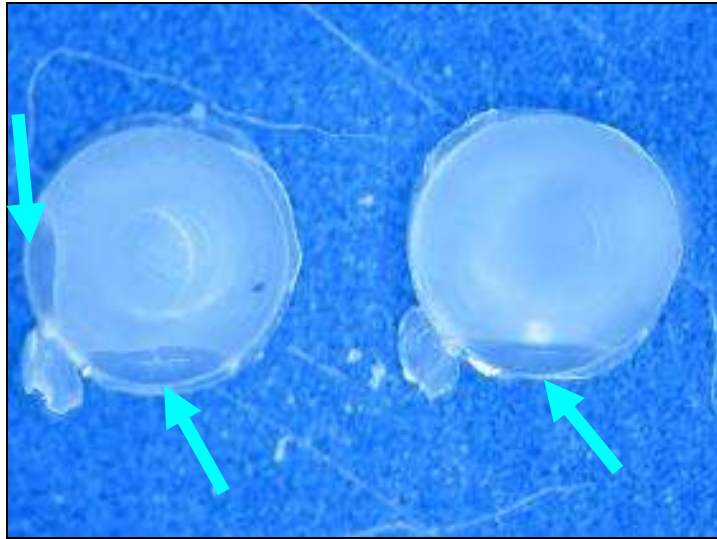
Figure 64: Number of Air Trap Varies

Another factor that causes inconsistencies in the part quality is process variation caused by fluctuation of melt temperature, mold temperature, and cycle time. As presented in the previous chapter, nozzle temperature fluctuates in a cyclic form in order to reach the required temperature as shown in Figure 65. The fluctuation of the temperature causes the affects the melt viscosity which then affects the flow of the material in the cavity.
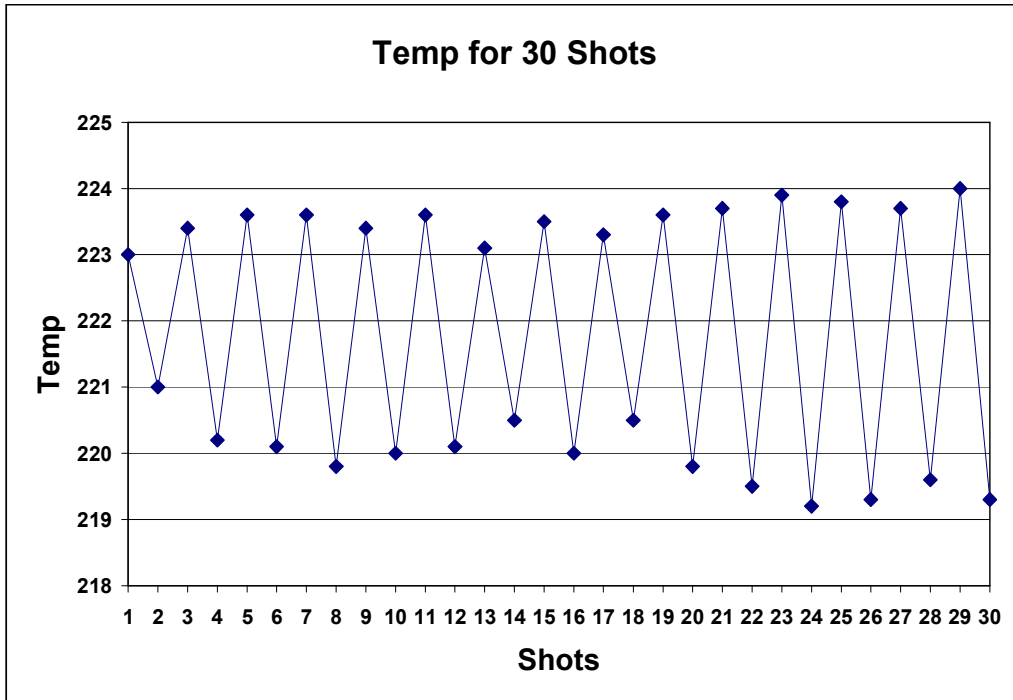
Figure 65: Fluctuation of Temperature

Besides melt temperature, mold temperature is believed to fluctuate as well since there is constant movement in the moving platen during the process. In addition, the variation is further affected by the repetition of closing and opening the machine cover for part removal. As mentioned earlier in the experimental trial section, the molding process is performed semi-automatically, therefore cycle time from shot to shot varies. Although there is effort to maintain a constant cycle time for every shot, it is impossible to achieve 100% consistency throughout the entire process. Hence, the difference is unavoidable and it affects the melt temperature as every shot has different residence time in the barrel.

Conclusion

Different processing parameters were varied and it was found that pack pressure appears to have the greatest effect on part weight at the current processing range. In the present study, peak cavity pressure and area under curve are the two attributes utilized in investigating the correlation between cavity pressure and part weight. Both attributes are found to respond to part weight in a promising manner. The attributes have a second order polynomial relationship with part weight with area under curve having a higher R^2. The type of applicable attributes in an experiment depends on several factors such as part geometry and processing parameters.

In terms of part quality, three types of defects were detected from the parts: short shots, flash, and air trap. Both short shots and flash are observable from the plot of area under curve vs. weight. However, air trap is not noticeable from the plot. The formation of air trap and the variation in size and numbers of air trap introduces some inconsistency to the results obtained. In addition to that, the results are further affected by process variation that is caused by fluctuation in melt temperature, mold temperature, and cycle time.

CHAPTER 7

CONCLUSION

Response of Cavity Pressure Curve to Different Molding Conditions

The research work started with the investigation on how cavity pressure curves respond to different processing parameters such as injection velocity and pack pressure. Different types of materials (semicrystalline and amorphous) were employed in this study too. The general shape of the curves of different trials were observed and compared. The following items summarize the major finding of this experiment:

- Although the processing window was much smaller in micro-injection molding process, the cavity pressure curve was still able to illustrate the progression of the molding cycle inside the cavity.

- Rapid cooling was observed from the steep slope of cavity pressure curve.

- Trial with higher settings in the processing parameters generated higher peak cavity pressure and greater processing time.

- Cavity was filled faster with higher settings.

- There was no significant difference in the pressure curves generated by different types of materials.

Response of Cavity Pressure Curve to Different Part Quality

In this set of experiments, the effect of switchover point was investigated using zero pack pressure. Different types of shortage parts were produced based on the different switchover settings. In terms of the relationship between cavity pressure and part weight, peak cavity pressure and area under the curve were the two attributes that were used to correlate to part quality. The following items summarize the major finding of this experiment:

- Later switchover allowed injection to proceed longer and produce heavier parts.

- By comparing different cavity pressure curve, the general shapes of the curves were able to indicate different types of shortage produced.

- Coefficient of determination (R^2 value) for part weight and area under curve were 0.9139 and 0.8378 respectively. This showed that peak cavity pressure appeared to be a better process and quality indicator than area under curve.

- Inconsistency in the process was noticeable. There were variations among the shots in the same trial although the process settings were identical.

- Part quality, peak cavity pressure, machine injection pressure, and nozzle temperature were not consistent throughout the experiment trial

Design of Experiment Approach

Three different processing parameters were varied to conduct a total of nine experiment trials to investigate the relationship between cavity pressure and part weight in a broader processing range. These nine trials were conducted using a 3-parameter, 3-level orthogonal array. The three different processing parameters chosen were pack pressure, melt temperature, and mold temperature. In the mean time, main effect analysis was carried out to determine the effect of three different processing parameters on the part weight. Again, the coefficient of determination, peak cavity pressure, and area under curve were used to determine the relationship between cavity pressure and part weight. The following items summarize the major finding of this experiment:

- In the current processing range, pack pressure was found to have the greatest effect on the part weight.

- The combination of two high levels settings produced heavier parts with less response in peak pressure value.

- The disjointed data in the trial suggests the possibility of a great gap between the processing parameter levels for pack pressure. Despite that, expected results were obtained with high level settings in pack pressure, melt temperature, and mold temperature produced higher weight while low level settings trial produced lighter part.

- Both attributes in the current trial were found to have a polynomial relationship with the part weight. R^2 value for area under curve (0.8858) is higher than peak cavity pressure (0.8214).

- With the effect of pack pressure, area under curve appeared to be a better process and quality indicator than peak cavity pressure. It can be concluded that the choice of the most suitable attributes depend on different combination of molding conditions.

- Short parts, flash part, and air trap were the defects found from the parts. Both short parts and flash parts were detectable by comparing the area under curve value. On the other hand, because air trap influenced the pressure value sensed by the pressure transducer, it affected the correlation between the cavity pressure and part weight.

- The results were further affected by the variation in the number and the size of the air trap found in the samples. Therefore, the current monitoring method may not provide reliable indication on parts with air trap.

- The variation in gate size due to improper de-molding contributes to weight variation among the parts.

- The fluctuation of mold and melt temperature is believed to have melt viscosity.

- The variation of cycle time between each shot affected the residence time of the polymer melts in the barrel. This led to the variation of melt temperature between shots.

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CHAPTER 8

FUTURE WORK

Future research should continue to investigate the polynomial relationship between the attributes and the part weight. A better understanding of the factors causing the relationship is needed to further develop a reliable and robust model for monitoring the micro-injection molding process.

The next focus should be on the formation of air trap. Since air trap introduces inconsistencies to the results obtained, future work should find ways to eliminate this defect. Besides affecting the result, air trap also forms the threat of causing serious defect to the molded part due to diesel effect.

Inconsistencies in the process need to be minimized. Future trials should be conducted in an automatic mode with minimum human interaction during the process. At the same time, degating method should be improved to reduce the variations in gate size. In order to minimize the inconsistencies induced by the machine, a better understanding on machine behavior is required as well. Fluctuation of nozzle temperature and inconsistencies in the machine injection pressure are the two aspects that required further investigation.

A cavity with different geometry and micro-feature should be constructed to investigate the robustness of cavity pressure as process indicator. At the same time, additional micro-feature can be added to the part. The replication of the micro-feature can be considered as another condition for quality besides part weight. In terms of the overall

mold construction, new cavity with shorter runner and sprue system should be constructed to better replicate the current practice in the industry's micro-injection molding process. Doing so also shortens the travel of polymer melt which helps to eliminate unnecessary heat and momentum lost.

REFERENCES

[1]   D. V. Rosato and M. G. Rosato., "Injection molding handbook," 3rd ed. Boston: Kluwer Academic Publishers, 2000.

[2]   J. A. Schey, "Introduction To Manufacturing Processes," Second Edition ed. New York: McGraw-Hill Book Company, 1987.

[3]   S. Kalpakjian and S. R. Schmid, *Manufacturing Processes for Engineering Materials*, 4th ed. Upper Saddle River: Prentice Hall, 2003.

[4]   L. E. Doyle, C. A. Keyser, J. L. Leach, G. F. Schrader, and M. B. Singer, *Manufacturing Processes and Materials*, Third ed. Englewood Cliifs, New Jersey: Prentice-Hall, 1985.

[5]   B. H. Amstead, P. F. Ostald, and M. L. Begeman, *Manufacturing Processes*, Eighth ed. New York: John Wiley & Sons, 1986.

[6]   A. K. Angelov and J. P. Coulter, "Micromolding Product Manufacture - A Progress Report," presented at ANTEC 2004, Chicago, IL., United States, 2004.

[7]   L. Weber and W. Ehrfeld, "Micro-moulding - processes, moulds, applications," *Kunststoffe Plast Europe*, vol. 88, pp. 60-63, 1998.

[8]   "MicroMoulding - Precision in Small Plastic Components," 2005.

[9]   W.Michaeli, A. Spennemann, and R. Gartner, "New Plastification Concepts for Micro Injection Moulding," *Microsystem Technologies*, vol. 8, pp. 55-57, 2002.

[10]   A. M. Tom and J. P. Coulter, "Advancements in micro-molding for small-scale product fabrication," presented at 2002 ASME International Mechanical Engineering Congress and Exposition, New Orleans, LO, United States, 2002.

[11]   D. M. Bibber, "Micro Molding Challenges," presented at ANTEC 2004 Chicago, IL., United States, 2004.

[12]   J. Zhao, R. H. Mayes, G. Chen, H. Xie, and P. S. Chan, "Effects of Process Parameters on the Micro Molding Process," *Polymer Engineering and Science*, vol. 43, pp. 1542-1554, 2003.

[13]   B. R. Whiteside, M. T. Martyn, P. D. Coates, P. S. Allan, P. R. Hornsby, and G. Greenway, "Micromoulding: Process characteristics and product properties," *Plastics, Rubber and Composites* vol. 32, pp. 231-239, 2003.

[14]   W. Leventon, "Part Making on a Very Small Scale: Micromolding for Medical Devices " in *Medical Device & Diagnostic Industry* 2002, pp. 60.

[15]   Medical Murray, "NanoMolding Machine." http://www.medicalmurray.com

[16]   R. Wimberger-Friedl, "Injection Molding of Sub-μm Grating Optical Elements," *Journal of Injection Molding Technology*, vol. 4, pp. 78-83, 2000.

[17]   L. E. Weber, Wolfgang; Freimuth, Herbert; Lacher, Manfred; Lehr, Heinz; Pech, Bernhard "Micromolding: a powerful tool for large-scale production of precise microstructures," presented at Micromachining and Microfabrication Process Technology II, Austin, TX, USA, 1996

[18]   V. Piotter, T. Benzler, T. Hanemann, H. Woellmer, R. Ruprecht, and J. Hausselt, "Innovative molding technologies for the fabrication of components for microsystems," presented at Proceedings of the 1999 Design, Test, and Microfabrication of MEMS and MOEMS, Paris, 1999.

[19]   R. Ruprecht, T. Gietzelt, K. Muller, V. Piotter, and J. Hausselt, "Injection molding of microstructured components from plastics, metals and ceramics," *Microsystem Technologies*, vol. 8, pp. 351-358, 2002.

[20]   M. Heckele and W. K. Schomburg, "Review on micro molding of thermoplastic polymers," *Journal of Micromechanics and Microengineering*, vol. 14, pp. R1-R14, 2004.

[21]   M. Knights, "Micro Molds Make Micro Parts," Plastic Technology.

[22]   S. Yuan, N. P. Hung, B. K. A. Ngoi, and M. Y. Ali, "Development of Microreplication Process - Micromolding," *Materials and Manufacturing Processes*, vol. 18, pp. 731-751, 2003.

[23]   O. Kemmann, C. Schaumburg, and L. Weber, "Micro Moulding Behaviour of Engineering Plastics," *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 3680, pp. 464-471, 1999.

[24]   M. S. Despa, K. W. Kelly, and J. R. Collier, "Injection molding using high aspect ratio microstructures mold inserts produced by LIGA technique," presented at Conference on Materials and Device Characterization in Micromachining, Santa Clara, CA, USA, 1998.

[25]   B. Kim and D. Yao, "Method for rapid mold heating and cooling," vol. 6846445. United States, 2005.

[26]   J. A. Chang, S. C. Chen, and J. C. Cin, "Rapid mold temperature control on micro injection molded parts with high aspect ratio micro-features," presented at ANTEC, Charlotte, NC, United States, 2006.

[27]   C.-M. Cheng and M.-S. Ho, "Applications of a novel microheater in micromolding," *Japanese Journal of Applied Physics*, vol. 43, pp. 5218-5220, 2004.

[28]   J. A. Chang, S. C. Chen, and J. C. Cin, "Rapid mold temperature control on micro injection molded parts with high aspect ratio micro-features," presented at ANTEC, Charlotte, NC, United States, 2006.

[29]   D. Yao and B. Kim, "Development of rapid heating and cooling systems for injection molding applications," *Polymer Engineering and Science*, vol. 42, pp. 2471-2481, 2002.

[30]   D. Yao and B. Kim, "Injection molding high aspect ratio microfeatures," *Journal of Injection Molding Technology*, vol. 6, pp. 11-17, 2002.

[31]   Tat Ming Engineering Works Ltd., "Quality Injection Moulding." Hong Kong, 1997, www.tatmingtechnology.com

[32]   H. T. Plant and R. T. Maher, "A Preliminary Analysis of The Injection Molding Process and Factors Effecting Part Size Control," presented at ANTEC, Atlanta, 1975.

[33]   N. Golden, N. Schott, and R. Youngsaye, "An Experimemtal Evaluation of a Peak Cavity Pressure Controller in Injection Molding," presented at 33rd ANTEC, Atlanta, GA, 1975.

[34]   D. A. Fara, W. I. Patterson, and M. R. Kamal, "Cavity Pressure Control in Injection Molding During Filling, Packing, and Holding," presented at ANTEC, 1987.

[35]   F. Gao, "Cavity Pressure Control During the Cooling Stage in Termoplastic Injection Molding," *Polymer Engineering and Science*, vol. 36, pp. 2467-2476, 1996.

[36]   F. Gao, W. I. Patterson, and M. R. Kamal, "Adaptive Control of Cavity Pressure During Filling," presented at ANTEC, 1993.

[37]   F. Gao, W. I. Patterson, and M. R. Kamal, "Cavity Pressure Dynamics and Self-Turning Control for Filling and Packing Phases of Thermoplastics Injection Molding," *Polymer Engineering and Science*, vol. 36, pp. 1272-1285, 1996.

[38]   D. C. Angstadt and J. P. Coulter, "Cavity pressure and part quality in the injection molding process," presented at The ASME International Mechanical Engineering Congress and Exposition, Nashville, TN, USA, 1999.

[39]   B. H. Min, "A Study on Quality Monitoring of Injection-Molded Parts," *Journal of Materials Processing Technology*, vol. 136, 2003.

[40]   C. Payne, B. Baylis, D. W. Panek, A. Plumb, and J. W. Bozzelli, "Application of in-mold pressure sensing to large scale production of injection molded parts: What are the benefits?," presented at ANTEC, Indianapolis, IN, 1996.

[41]   B. Whiteside, M. T. Martyn, and P. D. Coates, "Micromoulding: Process evaluation," presented at ANTEC 2004, Chicago, IL., United States, 2004.

[42]   C. Collins, "Monitoring Cavity Pressure Perfects Injection Molding," *Assembly Automation*, vol. 19, pp. 197-202, 1999.

[43]   S. Macfarlane and R. Dubay, "The Effect of Varying Injection Molding Conditions on Cavity Pressure," presented at SPE ANTEC, Orlando, Florida, 2000.

[44]   D. C. Angstadt, "The Development of Geometry and Polymer Independent Product Quality Moldels Based on Injection Molding Cavity Pressure," in *Mechanical Engineering and Mechanics*, vol. Master of Science. Bethlehem: Lehigh University, 2000, pp. 161.

[45]   J. Zhao, G.Chen, and Y. K. Juay, "Development of Process Monitoring Technologies for Polymer Micro Moulding Process," Singapore Institute of Manufacturing Technology, 2003.

[46]   D. M. Bryce, *Plastic Injection Molding...manufacturing process fundamentals*, vol. 1. Dearbon: Society of Manufacturing Engineers, 1996.

[47]   H. Wicht and J. Bouchaud, "Nexus Market Analysis for MEMS and Microsystems III 2005-2009," 2005, pp. 33-34.

[48]   O. Kemmann, C. Schaumburg, and L. Weber, "Micro Moulding Behaviour of Engineering Plastics," *Proceedings of SPIE - The International Society for Optical Engineering*, vol. 3680, pp. 464-471, 1999.