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PROCESS MONITORING IN MICRO-INJECTION MOLDING

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ABSTRACT

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.

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 then can be used to manufacture thousands of micro-parts using the micro-injection molding process. Since the cost of polymeric materials is usually inexpensive and since only small amounts of materials are required to mold such small parts, this process has become an effective method of producing large volume inexpensive micro-parts [1]. Furthermore, the advantages of polymers such as easy mass processing, low cost, and tailorable 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, micro-injection molding, the newer of the two, requires further investigation for it to become a viable and effective option due to the unique challenges inherent in working at a size scale a few orders of magnitude smaller than typical injection molding.

Micro-injection process has a smaller processing window with the filling time and packing time normally being much shorter. This increases 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 moldability and freezing time arise when the process is reduced in size. Scaling down the process from conventional injection molding process also involves changes in molding process and mold designs. One example in terms of process changes are the application of higher melt temperature and higher injection velocity, and the introduction of variothermal process to prevent premature freezing issue due to the high L/T (length/thickness) ratio of micro-parts[2].

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 no flawed parts are overlooked. However, due to the micro-scale dimensions involved, it is difficult to inspect part quality without using costly microscopic observation 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[3-5]. 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 lead to different part quality of a hollow cap. In addition, correlation between different parameters are discussed and presented.

EXPERIMENTAL SETUP

The experimental work was conducted on a 17-ton Cincinnati/Milacron Fanuc Roboshot Si-B17. This machine is an electric servo-driven injection molding machine having a screw diameter of 18 mm. A hollow micro-cap (see Figure 1) 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. The final produced part weighs approximately 2.4 milligrams with aspect ratio of ~30 on the annular wall section. Figure 2 shows the size of two micro-molded caps relative to a U.S. dime.

Cavity melt pressure was measured using a Kistler 6183A melt pressure transducer. 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. The material used in this study was polypropylene – a semi crystalline material. Table 2 shows the properties for the polymer.

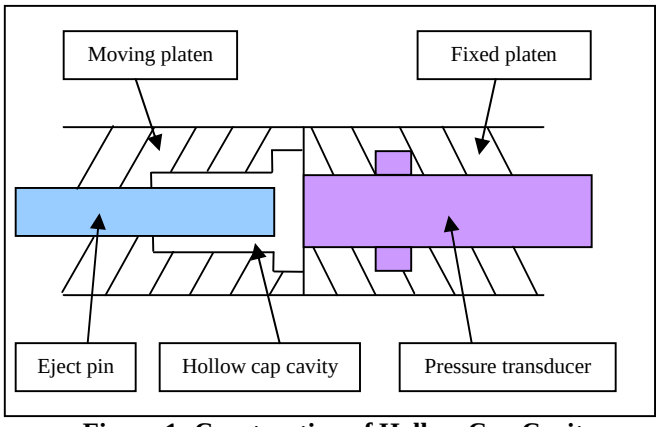

Figure 1: Construction of Hollow Cap Cavity

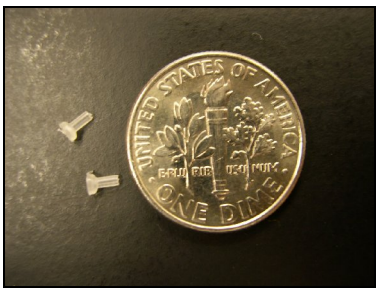

Figure 2: Molded Hollow Caps Relative to a U.S Dime

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 such as injection velocity, pack pressure, packing time, shot size, and barrel temperature remained unchanged as shown in Table 1. 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 desired 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, the closer the screw to the mold is, which also means that switchover happens later in the process. The switchover is denoted by the screw position (in 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 produces over pack or flash on the part. 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 0MPa pack pressure is set to prevent any influence of pack on cavity pressure and filling of the cavity.

Table 1: Molding Parameters

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

Before the actual samples were taken in each trial, numerous shots were produced to stabilize the machine. This was conducted by running the machine and observing there was no drifting trend occurred on the data recorded. After that, 20 shots were conducted and samples were collected. All the samples were weighed using appropriate balances: Sartorius M2P for weighing hollow cap, and Sartorius BP 210S for weighing runner. In the present study, the part weight is considered as the quality indicator since weight is a parameter that is easier to measure.

Table 2: Materials Properties of Polypropylene

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

RESULTS AND DISCUSSION

Results and data obtained from all the trials were investigated and compared among the trials. Within each trial, different data among different shots of the same trial were studied as well. Therefore, the following discussion is separated to two portions: (1) Comparison among all the trials, and (2) Comparison among all the shots in one particular trial.

I. COMPARISON AMONG FIVE TRIALS

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 3. It starts with filling of thick cap section, and then the pressure rises again when the polymer melts enter the thin wall section. The pressure continues to rise with higher rate when the part is full and start packing. After that, the curve starts to decay when solidifying of the melts happens. As noticed from the same figure, the entire process takes less than 0.2 second.

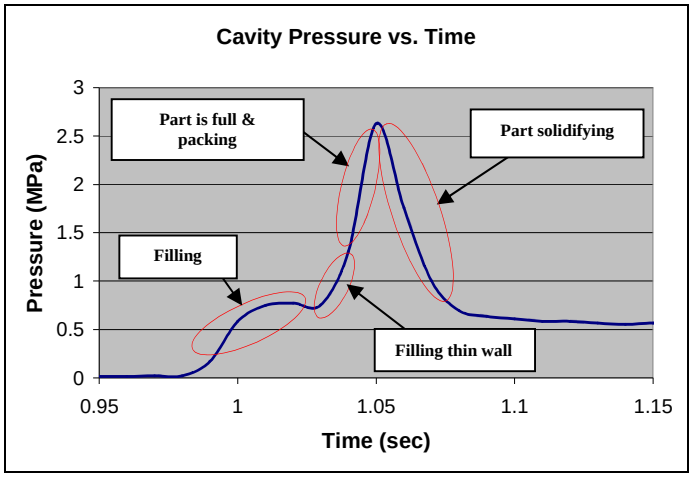

Figure 3: Cavity Pressure Curve for Hollow Cap

The average cavity pressure and weight increase as switchover settings reduce in each different trial. This result matches the initial prediction that later switchover allows polymer melt to fill up more of the cavity and hence generated higher cavity pressure. Figure 4 and Figure 5 confirm this finding. Figure 4 shows different pressure curves for different switchover position while Figure 5 shows the average part weight and average peak cavity pressure with respect to different switchover setting.

In Figure 4, pressure curves with switchover of 3.04mm, 2.84mm, and 2.64 mm have very low peak pressure point, this shows that very little polymer melt were able to fill the cavity. For pressure curves with switchover of 2.24mm and 2.44mm, a sharp rise of pressure is observed; this indicates that 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 phase to proceed longer and allows melt to flow further into the cavity before the injection phase ends.

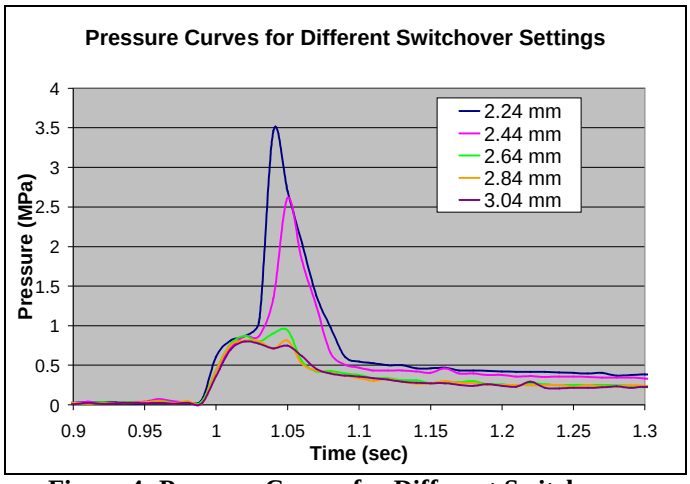

Figure 4: Pressure Curves for Different Switchover

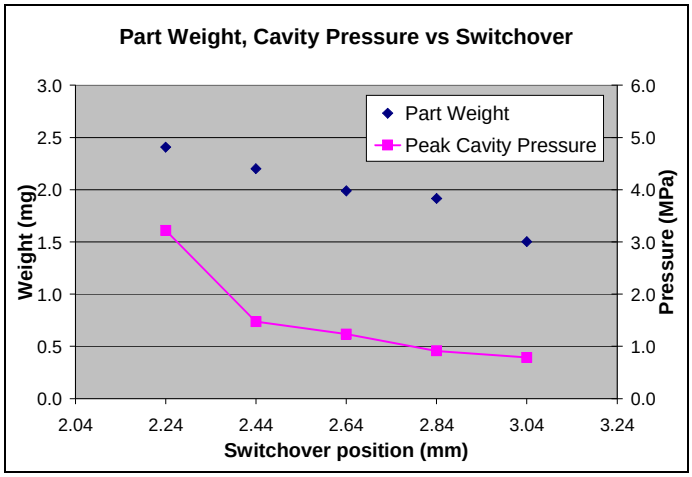

Figure 5: Part Weight, Cavity Pressure vs. Switchover

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 6 shows how the filling stage of the hollow cap is divided into 3 stages: stage 1 is the thick cap/annular section, stage 2 is the thin wall section, and stage 3 is 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, it is not the result of materials over packed. In the present investigation, we consider the error on the mold as an additional feature of the hollow cap. This feature happens to be the thinnest portion of the cavity and it is located the farthest away from the gate. Therefore, it turns out to be the last portion for the melt to fill up. Due to this reason, the flash is utilized as the full part indicator.

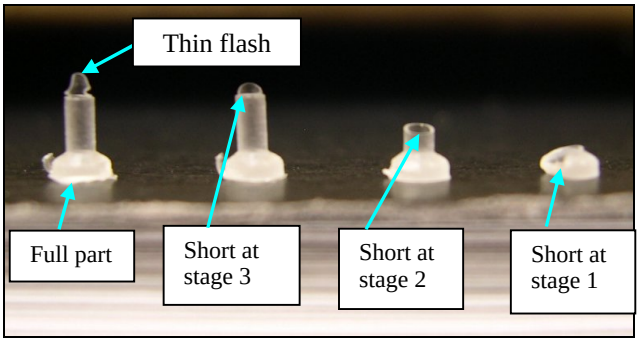

Figure 6: Types of Defects of Hollow Cap

One general observation about the pressure curve is that whenever there is a dip in the filling stage, this 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 7 shows examples of pressure curve that correspond to part that is short at stage 2. When polymer melts enter the cavity, the melts tend to fill up the thick cap section first due to hesitation effect. As pressure gradually increases during the filling stage, the melts build up enough energy to burst through the stagnant layer that is formed at the entrance of the thin wall. It is believed that the penetration of melts into the thin wall creates the decrease of cavity pressure or the dip as seen in cavity pressure curve in Figure 7. As expected, once the melts start filling the thin wall section, pressure increases immediately until switchover happens and the curve starts to decay.

However, not all the short parts have the pressure curve that behaves the same way. Some parts were found short even though no dip was observed in the curve. With current parameters settings, when there is a stagnant layers formed at the entrance of the thin wall due to hesitation effect, further injection of materials can penetrate the stagnant layer, but does not provide sufficient momentum to fill up the entire cavity.

On the other hand, polymer melt may still fail to fill up the entire cavity even though there is no pressure dip or hesitation effect observed in the curve. As a result, a dip in pressure curve signifies a short part, but not all the short parts could be identified by relying to the dip in pressure curve.

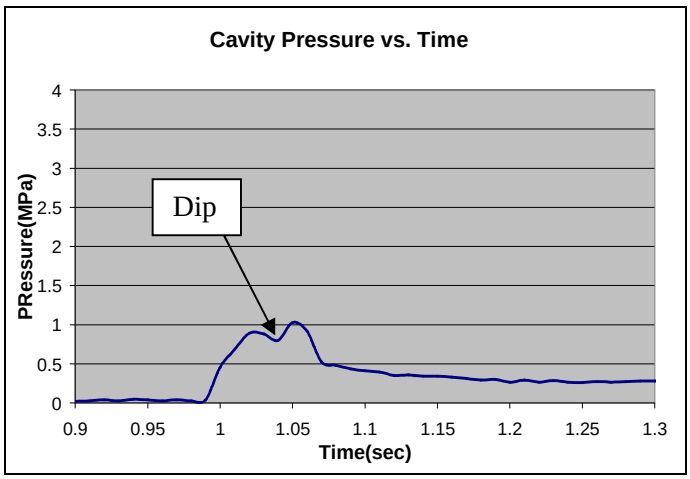

Figure 7: Cavity Pressure Curve for Short Part

In terms of the relationship between cavity pressure and part weight, coefficient of determination (R^2 value) is applied to show how peak cavity pressure correlates with the part weight. It is a measure of the correlation between the dependent and independent variables in a regression analysis. A high R^2 value indicates that the two variables are well correlated. Table 3 shows the R^2 value increases with the decrease of switchover setting. The higher R^2 value proves 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. This shows that as the % of cavity is filled by the melt increases, the better the correlation between part weight and cavity pressure. Also, the R^2 value for cavity pressure surpasses the R^2 value for injection pressure as switchover setting decreases from 3.04mm to 2.24mm. This suggests that cavity pressure appears to be a better indicator of part quality and process variation as opposed to injection pressure.

Table 3:R2-value Obtained 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	0.5115	0.7796	0.5727	0.7134
R^2 Value - Cavity Pressure vs. weight	0.2869	0.4989	0.5538	0.6741	0.8454

II. INDIVIDUAL TRIAL

In each trial, different shot to shot variation was observed although the settings were the same. In this section, discussion of differences among shots in the trial with switchover setting of 2.24mm will be presented. Figure 8 shows 5 out of 20 pressure curves of 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 show that each shot was different in filling rate, % 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 when the cooling phase starts.

A shot that has higher peak pressure normally produces part with better quality. In this case, shot 12 has the greatest amount of weight while shot 20 has the least amount of weight. Shot 20 also failed to fill up stage 3 of the cavity.

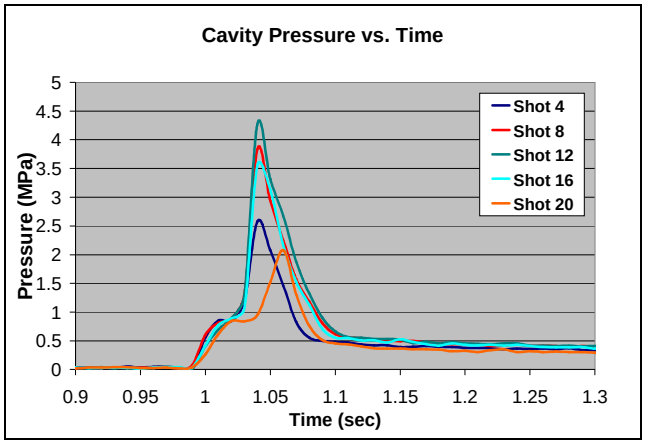

Figure 8: Pressure Curves for Trial with Swicthover of 2.24mm

Different pressure curves bring along different peak cavity pressure. Figure 9 shows the peak cavity pressure distribution for all the shots in the same trial. Pressure for each shot varies from 2.077MPa to 4.271MPa. The statistical information such as average, standard deviation, and correlation of variation are shown in the same figure. After visually inspecting of all the parts, it is found that all the shots are good shots except shots number 1, 4, 14, 19, and 20 (circled in Figure 9) 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. As polymer melt enters the cavity, pressure slowly develops and it is sensed by the pressure transducer. The greater the amount of material flows into the cavity is, the higher the generated pressure is.

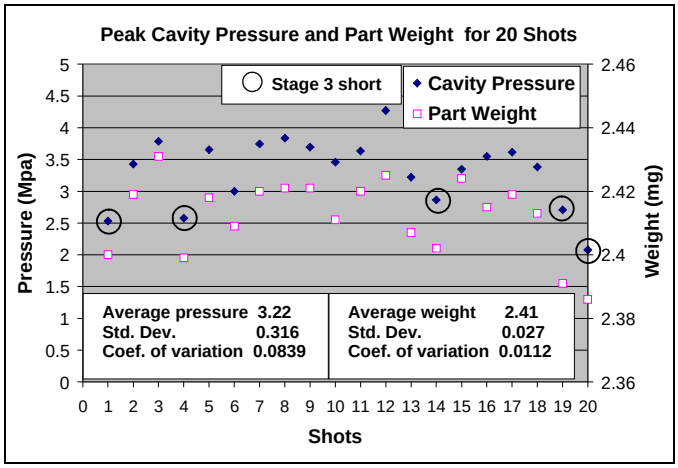

Figure 9: Peak Cavity and Part Weight Distribution for 20 Shots with Same Settings

To further investigate the relationship between part weight and cavity pressure, a plot between peak cavity pressure and part weight is presented. As can be seen from this figure, cavity pressure responds almost linearly with part weight with the R^2 value of 0.8454. In addition to cavity pressure, injection pressure was 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 again indicates that cavity pressure is a better indicator of part quality than injection pressure.

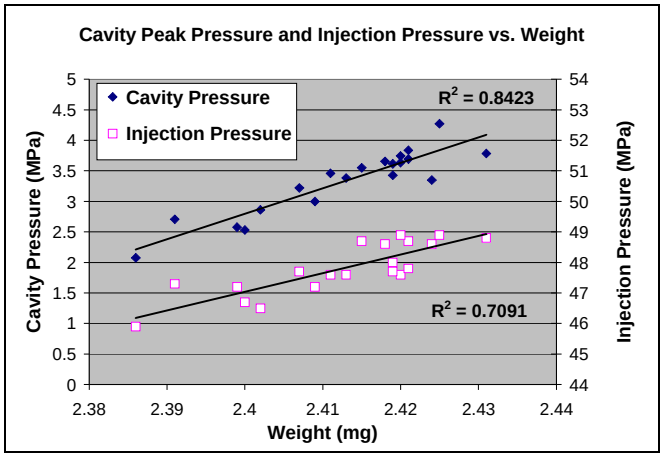

Figure 10: Cavity Pressure and Injection Pressure with respect to Part Weight

On the other hand, the inconsistency of cavity pressure and part weight obtained in a same trial leads to the observation of machine's data. Machine injection pressure and nozzle temperature were recorded throughout the process. Figure 11 shows the peak injection pressure for all the shots of the same trial, the pressure ranges from 45.9 MPa to 48.9

MPa, and the standard deviation is 0.938. The inconsistency of injection pressure is expected due to the fact that the velocity is fixed. Pressure is varied from shot to shot in order to achieve the set velocity. Ideally, since the velocity is the same for all the shots, the amount of materials at the same screw position for different shots is supposed to be the same as well. In other words, parts weight should not have any relationship with the changed of injection pressure. However, this does not match with the results obtained as shown previously in Table 3 where part weight has certain degree of correlation with injection pressure.

The inconsistency of 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 12 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.

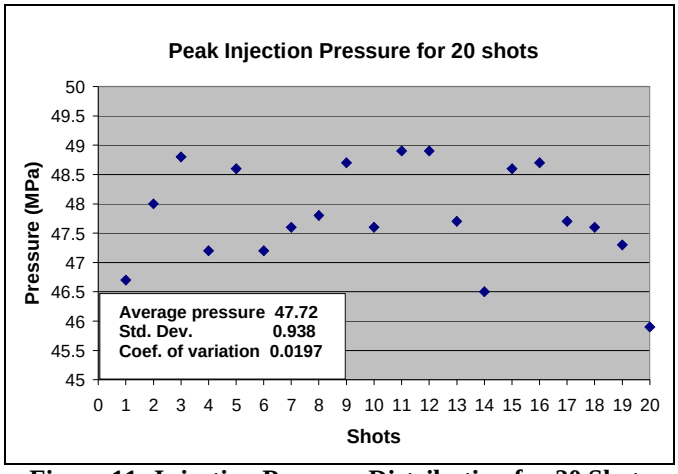

Figure 11: Injection Pressure Distribution for 20 Shots

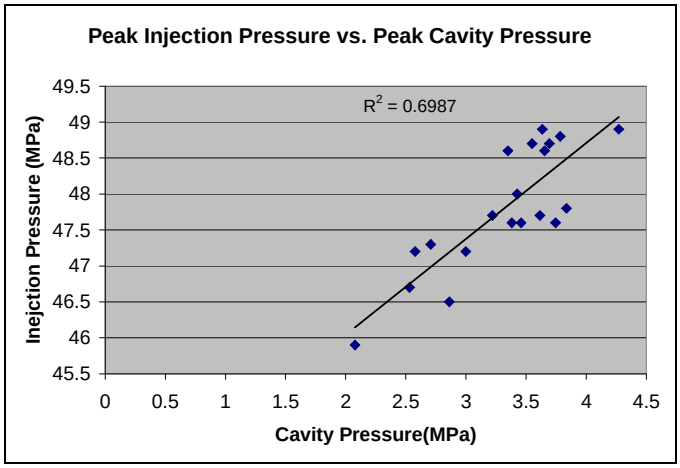

Figure 12: Peak Injection Pressure vs. Peak Cavity Pressure for the Same Trial

The next machine data recorded is the nozzle temperature distribution for every shot. Figure 13 shows the nozzle temperature for every shot. As expected, the temperature fluctuates in a cyclic form from shot to shot. This happens because the heater was constantly on and off automatically throughout the experiment to maintain the set temperature of 210 °C.

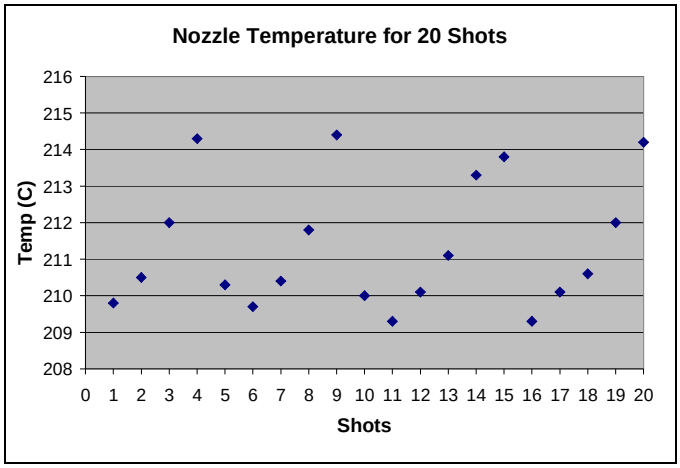

Figure 13: Fluctuation of Nozzle Temperature

Temperature is believed to affect 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 clearly shows that there is no direct relationship observed between the two parameters.

The next discussion is focused on at which point cavity pressure starts to respond linearly to part weight. Initial trial with early switchover setting of 3.04mm that did not produce any good quality part has generated a weak relationship between part weight and cavity pressure. However, as switchover setting is adjusted to smaller value, better quality parts are produced and the relationship between part weight and cavity pressure starts to emerge. In a trial with switchover setting of 2.64mm, parts with various degree of quality are produced. Parts that are short at stage 1 and 2 have little correlation to the cavity pressure, however, when the melt filled up to stage 2, part weight and cavity pressure increase and good correlation is observed as shown in Figure 14. Although correlation is weak when part is short at stage 1 and 2, those parts can still be easily noticed and screened out as shown in the same figure.

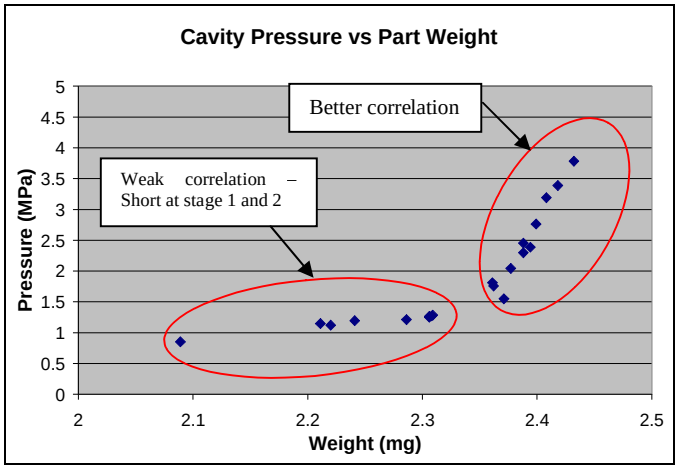

Figure 14: Correlation between Cavity Pressure and Part Weight

Figure 15 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 at al.*[6], 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, screw will continue to move forward for certain distance and speed (depending on pack pressure setting) to attain the required pack pressure. In 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 lost of the relationship between runner weight and other parameters such as injection pressure, cavity pressure, and part weight.

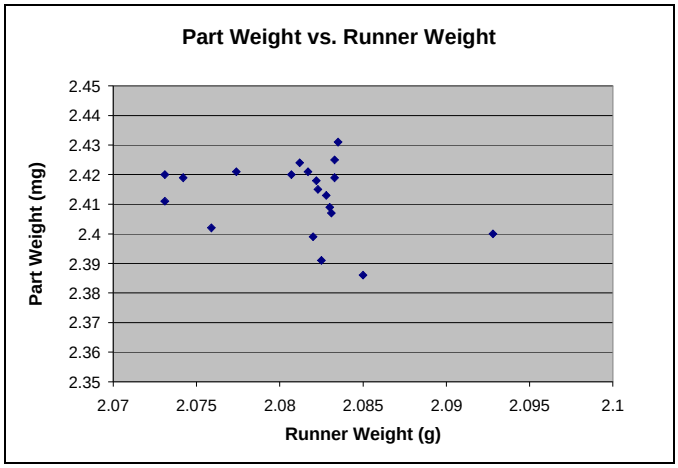

Figure 15: Part Weight vs. Runner Weight

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 indication of process variation. In addition, cavity pressure has a higher degree of correlation with part weight than does machine injection pressure. 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.

For future work, experiments will be focused on producing parts that have minor defect such as air trap, flash, and short at stage 3 in order to investigate the capability of cavity pressure in sensing more minor part defects. Investigation on the inconsistency of part quality due to fluctuation in injection pressure will also be conducted. Future trials will also use a heated mold to maintain the consistency of the mold temperature from shot to shot.

REFERENCES

[1] Weber, L., and Ehrfeld, W., 1998, "Micro-moulding - processes, moulds, applications," Kunststoffe Plast Europe, **88** (10), pp. 60-63.

[2] Ruprecht, R., Gietzelt, T., Muller, K., Piotter, V, and Haubelt, J., 2002, "Injection molding of microstructured components from plastics, metals and ceramics," Microsystem Technologies, **8**, pp. 321-358.

[3] Angstadt, D.C, and Coulter, J.P., 1999, "Cavity pressure and part quality in the injection molding process," The Science, Automation, and Control of Material Processes involving Coupled Transport and Rheology Changes - 1999 (The ASME International Mechanical Engineering Congress and Exposition), 89, pp. 7-17

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

[5] Macfarlane, S, and Dubay, R., 2000, "The Effect of Varying Injection Molding Conditions on Cavity Pressure," 58th SPE ANTEC Conference Proceedings, pp. 653-657

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