Study on the response of sequential valve gate system used for thin-wall injection molding

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Abstract

Sequential injection molding using valve-gate controlled hot runner system has attracted attentions. Commercial valve gate usually delays for about 0.3~0.5 sec when the command is given. This delay limits its application to 3C molded parts where the required filling time is very short. In this study, a gas-driven fast-response sequential valve gates system was developed by adopting valve gate control performance. Characteristics and verifications of valve-gate opening were monitored using CCD camera and cavity pressure transducers and accelerometer, respectively. It was found that the delay time is intimately related to the response of gas pressure delivery controlling valve gate movement. The delay time of valve-gate opening decreases with increased driven gas slightly and is quite sensitive to the operating gas pressure for non-melt and melt-filled environment, respectively. Under proper choice of piston size and driven gas pressure, the delay time can be reduced to about 8 and 12 ms in non-melt and melt-filled environment, corresponding. The molding using improved system can provide thin wall injection parts without weld line and good cosmetic quality as well as better tensile strength.

Keyword：Valve gate, Sequential injection molding, Delay time of opening

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熱澆道時序閥澆口控制系統應用於薄殼射出成型製程特性與機械性質之研究

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摘要

近來利用熱澆道時序閥控制用於射出成型已吸引很多注意。然而傳統閥澆口當控制系統下命令時會延遲約 0.3~0.5 秒，這將會限制其在 3C 成品成型上之應用，因為其所需之充填時間非常之短 。在本研究中，建立一氣體驅動快速反應時序閥澆口系統以提高閥澆口之控制性能，並分別利用 CCD、模穴壓力感測器和加速規等監控閥澆口打開之特性。研究中發現，延遲時間與氣體壓力令控制閥澆口移動反應有極大的關係。閥澆口打開之延遲時間不論於有融膠或無熔膠之情況下皆對操作壓力非常敏感。在適當之活塞尺寸與驅動氣體壓力選擇之下，延遲時間於有融膠或無熔膠之情況下可分別降低至約 8 和 12 ms。利用研究中建立之熱澆道時序閥澆口控制系統可在無縫合線、好的表面品質與更佳之抗拉強度下用於薄殼射出成型元件之射出成型。

關鍵詞：閥澆口, 時序射出成型,開啟延遲時間

1. Introduction

Thin-wall injection molding becomes an important manufacturing technology for 3C plastics industry in recent years. Generally speaking, conventional injection molding (CIM) can be considered as thin-wall molding when part thickness becomes smaller than 1.5 mm and/or the flow length to part thickness ratio is greater than 100. In order to overcome the melt flow resistance within the thin-wall mold cavity, high injection pressure is required. In addition, to avoid melt frozen due to the fast cooling, thin-wall parts need to be molded at relatively high injection speed during the filling stage. These molding requirements result in specialized injection molding machine performance. To reach a high injection speed and to provide high injection pressure, the molding machine most probably requires an accumulator capable of supplying instantaneous high boosting pressure. Also, smaller-size screw should be used to reduce melt residence time so that materials degradation can be minimized. As a result, the associated controllability of the hydraulic system becomes critical. Besides, the fast injection induces high viscous melt shear heating and may degrade the melt and the associated materials properties. When high melt-index resin is chosen as molding materials, it provides better molding performance. However, its impact strength is usually not satisfied. Facing all these molding challenges, it is more difficult to obtain good product properties for thin-wall parts than those of conventional injection molding parts. On the other hand, requirements in 3C part properties such as proper mechanical strength, good structure and drop-test performance, minimized warpage and low residual stress, etc. are increasing.

Basically, it is inevitable that under the condition of single-gate design insufficient filling may often occur or relatively high injection pressure is required for molding thin-wall parts. Cosma and Tantakom *et al.* pointed out that the moldability of thin-wall injection molding can be increased by using multi-gate design to reduce the flow length. However, the weld lines will arise due to the combination of the melt flow fronts. Weld lines can be considered as a crack initiated on the surface of the molded part. These crack-like features are often visible to the naked eye, and as a result, are esthetically unacceptable for commercial applications. Moreover, the local mechanical strength in the area of the weld line can be significantly reduced. The presence of weld lines is one of the most significant problems associated with designing plastic parts for structural applications since the potential for failure in the weld line area, particularly in the thin-wall injection molded parts, is quite high.

To solve high molding pressure requirement, the hot runner system becomes more popular for thin-wall injection molding application. The hot runner basically can be considered as an extension of the injection unit into the mold. Generally speaking, hot runners can offer several advantages as compared with conventional cold runners system when used for thin-wall injection molding.

For the purpose of reduce injection pressure and eliminate weld line simultaneously to promote the quality of molded parts, sequential injection molding using valve gate system has been attracted attentions in recent years. Schematic of sequential injection is shown in Figure. 1. For conventional injection molded (CIM) parts, typical filling time ranges from 2 to 8 seconds. The opening and closing of valve gate usually takes about 0.3 to 0.5 seconds' response time in the pneumatic based control system. The delay in valve gate actuation can be tolerated in molding large CIM parts. However, for thin-wall parts requiring less than 0.3 seconds' filling time, sequential injection molding using valve gate meets new challenge. Commercial valve gate system does not provide the necessary information for actual applications. Therefore, it seems necessary and is important to investigate characteristics of the valve-gate opening response so that it can be better used for molding thin-wall parts.

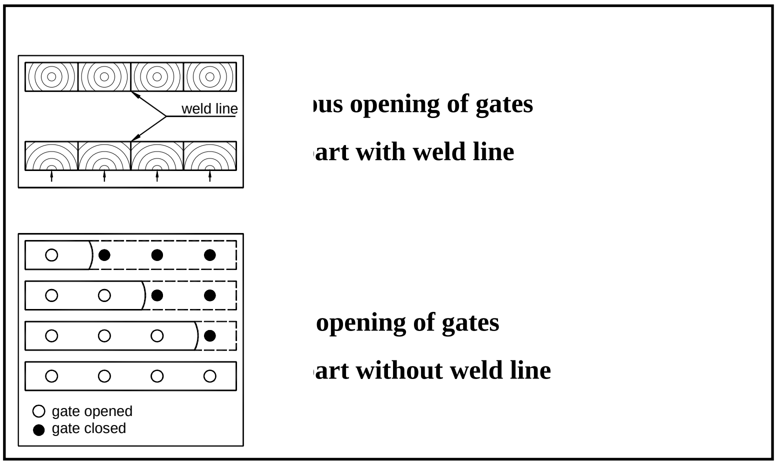

Figure 1 Simultaneous and sequential valve gate openings resulting with and without weld line

In the present study, a gas-driven valve gate control system with human-machine interface using Labview software was established. Then monitoring system for valve-gate opening was also built using shock accelerometer. System response was analyzed based on the tracing of triggered solenoid valve signal and shock accelerometer signal. The results can be also verified by using a high-resolution CCD camera under non melt-filled environment and cavity pressure transducers in melt-filled condition. The factors that influence gas-driven valve response characteristics as well as the associated delay including tolerance between inner piston and cylinder, gas pressure, etc., were investigated in details. Hopefully, one can reduce the delay time to less than 0.1 seconds so that the vale-gate sequential injection molding can be more suitably applied for molding thin-wall parts. To illustrate the applicability of the improved valve gate system, thin-wall parts of 1 mm thickness were also molded with a filling time of 0.41 seconds under three different kinds of gate designs including conventional single-gate, sequential opening of two valve gates and concurrent opening of valve gates, respectively. The maximum pressure of mold cavity and the maximum pressure of oil hydraulic cylinder were also measured simultaneously. The tensile tests following the methods of American Society for Testing and

Materials (ASTM) were also conducted. The effect of different gate design on molding pressure and part tensile strength were analyzed and discussed.

2. Establishment of valve-gate control and monitoring system

A two-valve gate hot runner system for a rectangular plate mold as shown in Figure. 2 was designed and built for the study. Gas pressure regulation system developed for gas injection was modified as the pneumatic actuator for valve-gate motion. Control schematic is illustrated in Figure 3. In addition, there was a gas buffer tank built on the top of the pneumatic-driven system. The buffer was pre-charged to operation pressure prior to gate opening so that the target gas pressure can be delivered as quickly as possible minimizing the pressure loss alone gas pipe and thus decreasing the response time. This concept follows the fast response gas injection unit designed for gas-assisted thin-wall injection molding. Linear variable displacement transducer (LVDT) is used to monitor screw location and send signal to actuate gas pressure valve and the associated piston linked to the top of the needle valves. Man-machine interface developed using @Labview provides operator an easily way to input the process parameters. Two valve gates can be opened and closed independently at the desired time during the molding process. Within core side, two pressure transducers (Kisler, type 6159A) were also flush mounted near by each valve gate (Figure 4). Hot manifold system was also carefully designed with the help of Kun Wu Company having twenty years' experience in hot runner system. Temperature control system (Hanyuong, MX4) provides six channels for melt temperature control for six different locations of hot runners.

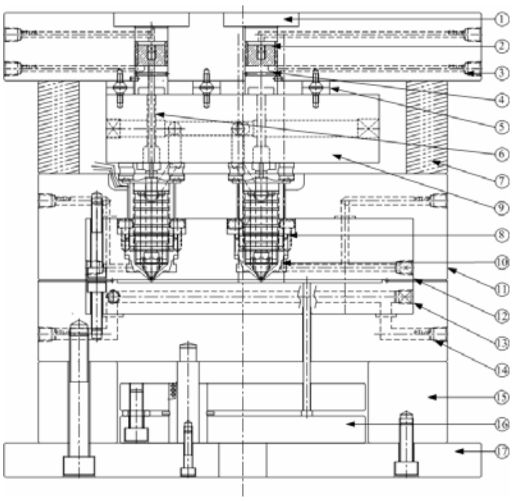

Figure 2 A two-valve gate system for plate mold.

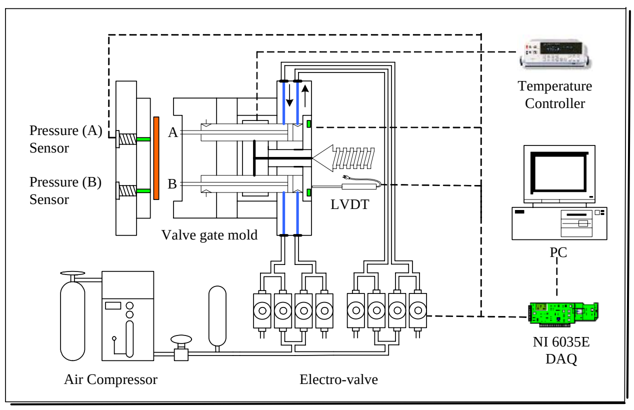

Figure 3 Schematic of valve gate control system.

Before mold is fully assembled, valve gate operation was also monitored and verified by a high resolution CCD camera (Figure 5). This video system enables us to measure the delay time once signal was sent to actuate the gas and the needle valve movement. Since the recording speed of CCD is 60 frames per second. The exact opening time of valve gate may lie between two consequent frames. That is, a frame which records the complete opening of valve gate and one frame before this frame. As a result, we took the maximum and minimum opening time of valve gate as the times when these two consequent frames taking pictures. When the gate pin driven by the gas and go to the end, it will touch the topper of the mold and the accelerometer will be drive to send the signal to the computer. It can help us to measure the delay time of the valve gate system. However, one of the key factors for the opening delay can be contributed to the dimension tolerance between piston and the cylinder. For a small tolerance, piston may be difficult to move due to a larger friction force existing between piston and inner surface of cylinder. For a lager tolerance, there may be a gas leakage leading to a smaller pressure difference in gas inlet and outlet sides. It is expected that there should be an optimized tolerance for each operation gas pressure. We have designed four different sizes for piston diameters corresponding to different tolerances. The inner diameter and the length of cylinder are fixed at 19.985 mm and 18 mm, respectively. In addition, the length of piston is 15 mm, and the outer diameters are 19.980 mm, 19.975 mm, 19.970 mm and 19.965 mm, respectively. Gas pressure also varies form 25 bars to about 175 bars. Then, the delay times for different piston diameters and gas pressures were recorded and analyzed. After finding the optimized condition for valve gate opening/closing, mold was assembled for molding test.

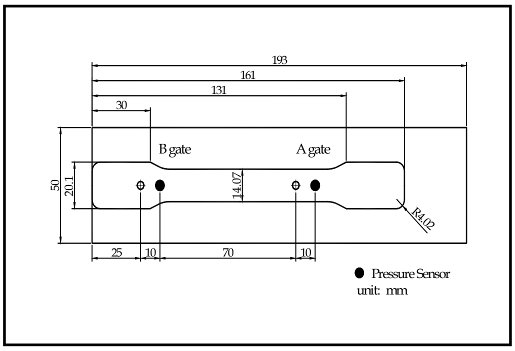

Figure 4 Schematic of cavity dimension and two pressure-sensor

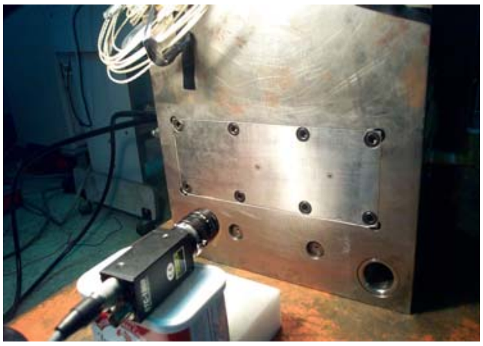

Figure 5 Monitoring of valve gate opening using CCD camera.

3. EXPERIMENTAL

Melt temperature within hot runner was controlled by separate heating equipment linked to heaters within manifold. Victor injection molding machine was used for the molding experiments. A rectangular plate mold with dimension of 193mm (length) x 50 mm (width) × 1 mm (thickness) was used. The geometry of the plate mold is shown in Figure 4. Transparent polystyrene (Chi-Mei, PG33) was utilized as the materials. The melt temperature was fixed at 230 ℃ and the mold temperature at 50 ℃. Since both A and B pressure transducers are in equal distance to valve gate, from measured pressure profiles one can also characterize the delay time and the performance of both valve gates. Under melt-filled environment, valve gate opening is to subject to additional resistance. The opening delay is expected to increase. For purpose of investigation the influence of valve gate system design on injection pressure and mechanical property. The molding experiments include conventional single-gate design, sequential gate opening and concurrent valve gate opening for melt filling process. At the same time, the maximum pressure of mold cavity and oil hydraulic cylinder was also measured. The tensile test specimens were prepared according to D638 of the ASTM testing method by cutting from plate parts carefully, as shown in Figure 6. The tensile tests were conducted on a MTS machine, which had full loads of 500 kgf. For each test, ten molded samples under the same molding conditions were used. The average value from these ten tests was used for analysis and correlation.

4. RESULTS AND DISCUSSIONS

The delay time of valve gate opening using accelerometer can be defined to be the interval between when the signal was sent by man-machine interface to actuate the gas, driving needle movement and when the needle valve move to the final position where piston shaft will touch the installed accelerometer. The delay time of valve gate opening was then evaluated from the two detected signals. Another way of tracing valve gate opening can be evaluated indirectly from the cavity pressure transducers. Once the signal is sent to valve gate, the timer counting begins. Assume the melt starts to fill mold cavity once valve gate is completely open. The pressure sensor starts to act once melt arrived. The best design is to install the pressure transducers directly beneath the valve gate, i.e., on the opposite mold side (core side) of valve gate. This design has the opportunity to destroy the pressure transducers. Therefore, we decide to offset the pressure sensors by 10 mm. By doing so, we are still able to evaluate the valve gate opening time once melt flow velocity can be calculated exactly. The monitoring of screw location and associated screw velocity has been reported. The melt flow rate as well as melt front velocity can be precisely predicted. By correction of this melt traveling time from valve gate to the transducer, one can obtain the valve gate opening delay time (i.e. the interval time of 0-1 in Figure 6). Figure 6 shows the pressure profile measured from the pressure transducer from which the delay times of valve opening at different gas pressures are estimated and listed in Figure 7.

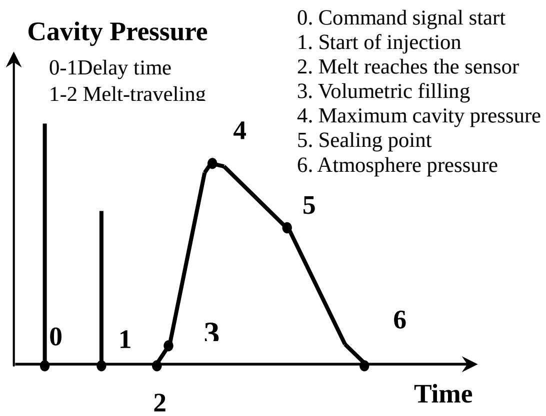

Figure 6 Pressure profiles from which valve gate delay time can be deduced.

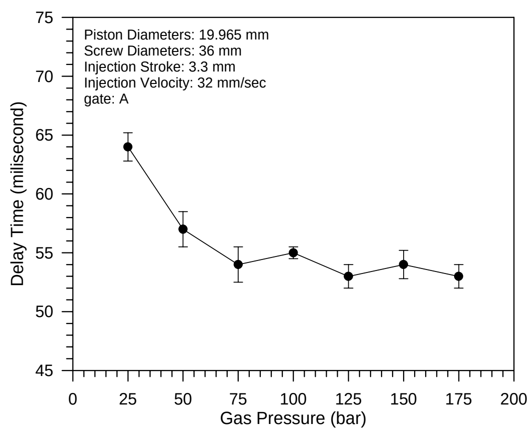

Figure 7 Delay time of valve gate opening in melt-filled environment.

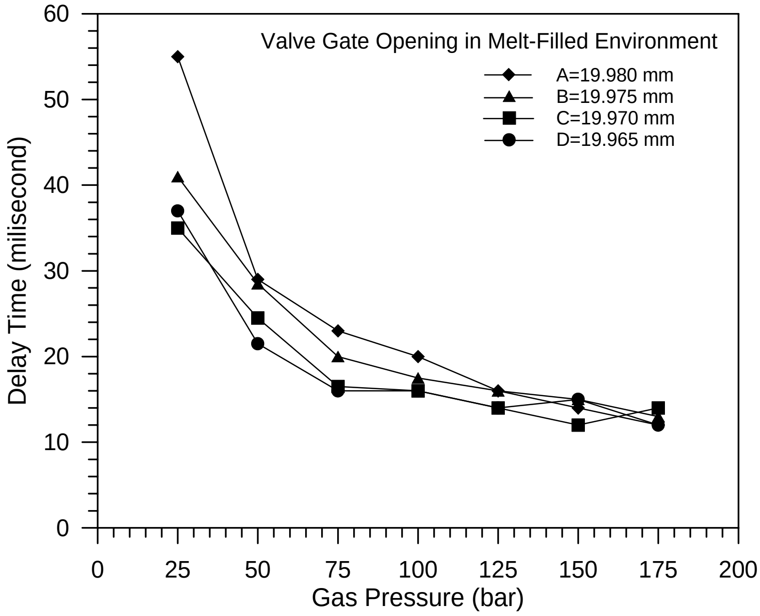

Figure 8 Variations of response time of valve gate opening in melt-filled environment with gas pressures under various piston sizes

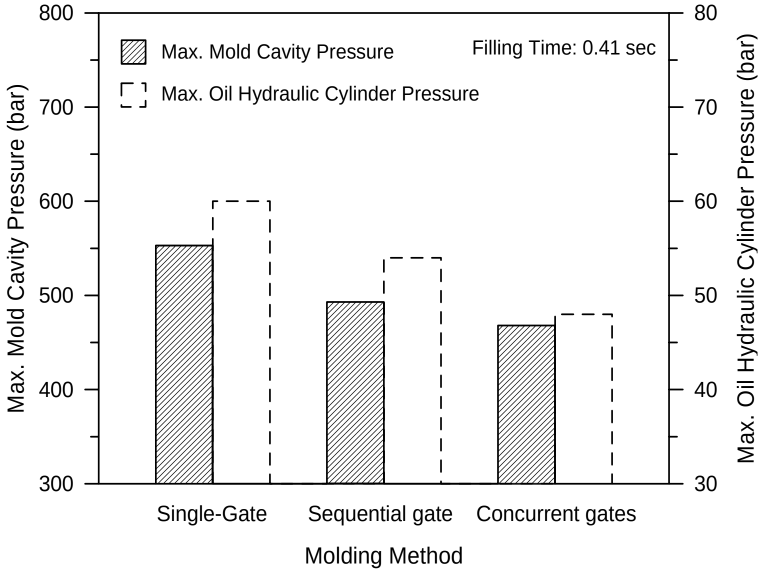

Figure 9 Delay time of valve gates A and B in melt-filled environment under specified piston sizes

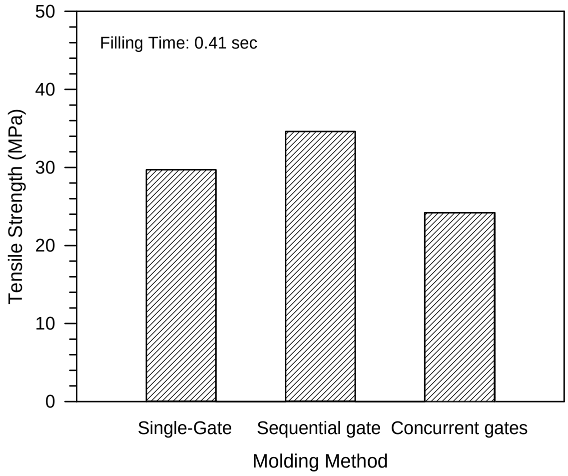

Figure 10 Maximum mold cavity pressure and maximum oil hydraulic cylinder pressure under the condition of three different gate design for molding

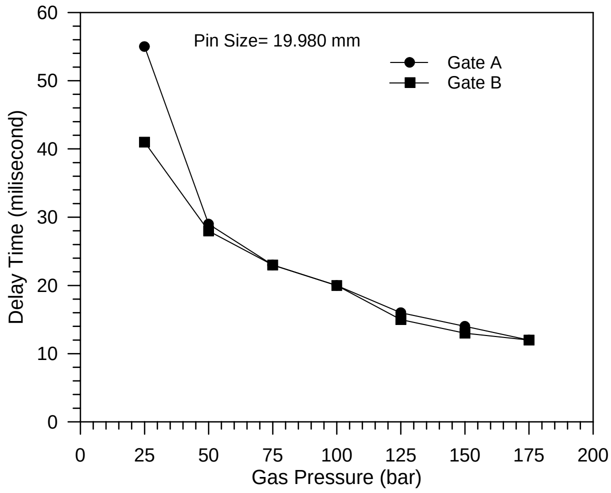

Figure 11 Maximum tensile strength under the condition of three different gate design for molding

For various diameters of piston (whose sizes are marked as A, B, C and D) linked to valve gate, the response time may be different under the same gas pressure due to the different friction between the exterior surface of piston and inner surface of driving cylinder. In addition, different gas pressure may also affect the friction and drive the piston at different speed. The delay times of valve gate opening versus gas pressure in non-melt and melt-filled for various piston sizes are given in Figures 8 and 9, respectively. From the experimental results, it can be found that high gas pressure may introduce small leakage leading to extra resistance for piston movement. For valve gate opening in non-melt condition, the delay times show less influence by size of piston and gas pressure than in melt-filled. As expected, the delay time of valve gate can be reduced to less than 15 milliseconds. As far as valve gate opening in melt-filled environment, it shows slightly higher delay time values than those in non-melt situation. In addition, it is highly sensitive to the size of piston, especially in the low gas pressure. However, the delay times of valve gate opening are less than 50 milliseconds still suitable for thin-wall molding. With regard to the effect of gas pressure on the response time of valve gate, it was found from Figures 10 that the delay time decreases with increasing gas pressure, especially in the condition of melt-filled environment. For valve gate A and piston diameter 19.970 mm as a example, the response time of 14 ms at 25 bar reduces to 8 ms at 175 bar in non-melt condition and reduces from 35 ms at 25 bar to 14 ms at 175 bar in melt-filled situation, respectively. At this point it is worthwhile to compare the measured delay time performance of valve gate opening in melt-filled environment using pressure transducer and accelerometer, respectively, under piston diameter 19.965 mm (Figures 7 and 8). The delay time measured by pressure transducers result in greater values. It is not easy to obtain the exact traveling time from beneath valve gate to the embedded pressure transducer. The monitoring of LVDT to estimate the screw location and the associate melt front velocity may introduce extra delay time. Using accelerometer for direct valve gate opening measurement shows an advantage over pressure transducer, particular in higher gas pressure situation, although both of them are suitable to monitor valve-gate opening. Figure 9 shows the delay time variation for valve gate A and B under different gas pressures with a piston size of 19.980 mm. On examining the data, it shows almost the same delay times for both gate A and B at high operating gas pressures. In summary, the delay time for vale-gate shaft movement in a non-melt environment can be reduced to about 8 mini-seconds whereas it increases to about 12 mini-seconds in a melt-filled environment by choosing proper design window. The developed system is now more appropriate for sequential thin-wall injection molding.

For further verification of the developed system, molding experiments were conducted at the same injection filling time whereas different gate operation methods were implemented including single-gate, sequential gate opening and concurrent gate opening for melt filling process. The associated molding pressures within the mold cavity and the oil hydraulic cylinder were measured. Graphical displays of maximum mold cavity pressure and maximum oil hydraulic cylinder pressure under the condition of filling time 0.41 seconds can be found in Figure 10. It can be seen that the maximum mold cavity pressures are 553 bar, 493 bar and 468 bar for single-gate, sequential valve gate and concurrent double valve gate, respectively. And the maximum pressures of oil hydraulic cylinder are 60 bar, 55 bar and 48 bar, correspondingly. From the measured results, it was found that single-gate molding not only needs higher machine injection pressure but also the higher mold cavity pressure. Both of the concurrent valve gates and sequential valve gate require lower molding pressure. The reason can be attributed to the flow length. The flow length ratio (ratio of maximum flow length to thickness) are 105, 80 and 55 for single-gate, sequential gate and concurrent valve gates, respectively. Consequently, sequential gate reduces molding pressure more efficiently as compared to that of concurrent valve gate if both have the same flow length. Finally, it is worthwhile to check part performance such as the mechanical strength. The presence of weld line in the concurrent valve gates results in weaker tensile strength (24.2 MPa), lower than 29.7 MPa of single-gate molding and 34.6 MPa of sequential gate (Figure 11). Molding using sequential gate has the both advantages of single-gate (i.e. without weld line) and concurrent valve gates (i.e. lower flow length ratio). In summary, as would be expected, the developing of fast-response sequential valve gate system for thin-wall injection molding results in thin-wall injection molded parts without weldline and good cosmetic quality as well as better tensile strength requiring lower injection filling pressure.

5. CONCLUSIONS

Based on the experimental results, the following conclusions were found:

(1) The pneumatic control and monitoring systems for characterization of valve gate opening in both non-melt and melt-filled environments have been successfully established. Using accelerometer provides a direct measurement of valve gate opening under all conditions and seems to be the most reliable for delay time measurement.

(2) In non-melt environment, the delay time of valve gate opening show less influence from driving gas pressure and the tolerance between the driving piston and the inner cylinder surface than in melt-filled environment. Under melt-filled environment, the delay time of valve-gate increases significantly and becomes more sensitive to the variation of driving gas pressure and piston tolerance.

(3) The delay time decreases significantly with increased gas pressure until the gas pressure reaches about 100 bar especially in the melt-filled condition.

(4) The delay time for vale-gate shaft movement in a non-melt environment can be reduced to about 8 mini-seconds whereas it increases to about 12 mini-seconds in a melt-filled environment by choosing proper piston size and driving gas pressure. The developed valve gate system is now more appropriate for sequential thin-wall injection molding.

(5) The application of the fast-response sequential valve gate system for thin-wall injection molding results in molded parts without weld line and good cosmetic quality as well as better tensile strength and lower molding pressure.

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