Response of a Sequential-Valve-Gate System Used for Thin-Wall Injection Molding

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ABSTRACT: Sequential injection molding using a valve-gate-controlled hot runner system has attracted attention for industrial applications in recent years. Because of the complexity of the operation mechanisms, a commercial valve gate usually delays for about 0.3–0.5 s once the valve-opening command is given. The signal-to-operation delay is acceptable for the conventional injection molding of large parts. However, this operation delay limits its application to thin-wall molded parts for computer, communication, and consumer electronics, for which the required filling time is very short. In this study, a gas-driven fast-response sequential-valve-gate system was developed for thin-wall injection molding by the adoption of valve-gate control performance. The characteristics and verifications of the valve-gate opening were monitored with a charge-coupled device (CCD) camera (nonmelt condition) and cavity pressure transducers and an accelerometer (melt-filled condition). The influence of the tolerance between the inner piston and cylinder and the gas pressure on the valve-gate opening was investigated in detail. Tensile bar parts 1 mm thick were used for the molding experiments. The delay time has been found to be intimately related to the response of the gas-pressure delivery controlling the valve-gate movement. In a nonmelt environment, the delay time of the valve-gate opening decreases with increasing driven gas slightly. In a melt-filled environment, the delay time is quite sensitive to the operating gas pressure because of the extra resistance between the shaft and the melt. A threshold pressure as high as 100 bar is required to keep the delay time below 15 ms. With the proper choice of the piston size and driven gas pressure, the delay time can be reduced to about 8 ms in a nonmelt environment and to about 12 ms in a melt-filled environment. Molding using this improved system for sequential valve opening can provide thin-wall injection parts without a weld line, and good cosmetic quality and better tensile strength require a lower injection pressure than molding using single-gate and concurrent-valve-gate opening. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 98: 1969–1977, 2005

Key words: injection molding; valve gate; delay time

INTRODUCTION

Along with high-technology development, many computer, communication, and consumer electronics (3C) are designed for weight reduction, thin walls, and minified size. Therefore, thin-wall injection molding[1–10] has become an important manufacturing technology for the 3C plastics industry in recent years. Generally, conventional injection molding (CIM) can be considered thin-wall molding when the part thickness becomes less than 1.5 mm and/or the ratio of the flow length to the part thickness is greater than 100. To overcome the melt flow resistance within the thin-wall mold cavity, a high injection pressure is required. In addition, to avoid the freezing of the melt due to fast cooling, thin-wall parts need to be molded at a 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 likely requires an accumulator capable of supplying instantaneous high boosting pressure. Also, a smaller screw should be used to reduce the melt residence time so that material 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 material properties. When a high-melt-index resin is chosen as a molding material, it provides better molding performance. However, its impact strength is usually not satisfied. With all these molding challenges, it is more difficult to obtain good product properties for thin-wall parts than for CIM parts. On the other hand, the requirements of 3C part properties, such as proper mechanical strength, good structure and drop-test performance, minimized warpage, and low residual stress, are increasing.

Basically, it is inevitable that under the condition of a single-gate design, insufficient filling will often oc-

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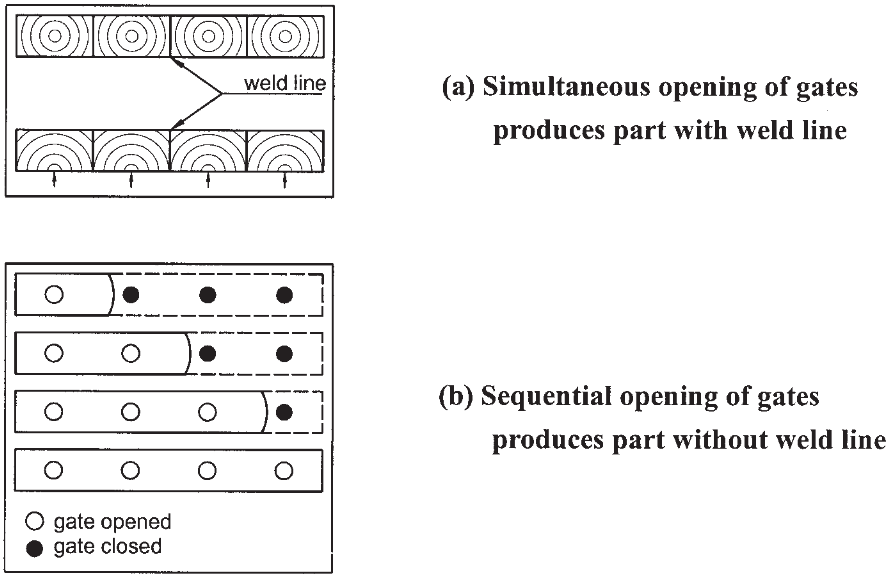

Figure 1 (a) Simultaneous and (b) sequential valve-gate openings producing parts with and without a weld line, respectively.

cur or a relatively high injection pressure will be required for molding thin-wall parts. Cosmar[11] and Tantakom[12] pointed out that the moldability of thin-wall injection molding can be increased with a multigate design to reduce the flow length. However, weld lines will arise because of the combination of the melt flow fronts. Weld lines can be considered cracks initiated on the surface of a molded part. These cracklike 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 because the potential for failure in the weld-line area, particularly in thin-wall injection-molded parts,[10] is quite high.

To solve the requirement of a high molding pressure, the hot runner system has become more popular for thin-wall injection-molding applications. The hot runner basically can be considered an extension of the injection unit into the mold. Generally, hot runners offer several advantages in comparison with conventional cold runner systems when used for thin-wall injection molding. The advantages include the following:

1. The high melt temperature enables the use of a longer flow path in the cavity.
2. The injection pressure required for filling the cavity is reduced.
3. Material that is lost in cold runners is saved without further finishing work.
4. Special gate designs are necessary for thin-wall injection-molded parts; conventional runner systems cannot do the job.
5. A hot runner system makes sequential injection molding[13,14] possible and easily implemented.

For the purpose of reducing the injection pressure and eliminating weld lines simultaneously to promote the quality of molded parts, sequential injection molding using a valve-gate system has attracted attention in recent years.[15–19] A schematic of sequential injection is shown in Figure 1. Typical applications for sequential injection molding include large-dimension parts such as bumpers and television front housing. The major advantages of sequential injection molding include (1) reducing molding pressure and associated residual stress, (2) reducing cycle times, (3) eliminating weld lines, (4) distributing packing pressure more uniformly, and (5) balancing melt flows within family mold. Despite these advantages, the process becomes more complicated and thus hinders applications in the plastics industry. New applications for 3C products are being seriously considered, such as multiple-cavity cellular-phone housing and compact disks. For CIM parts, a typical filling time ranges from 2 to 8 s. The opening and closing of a valve gate usually involves about a 0.3–0.5-s response time in a pneumatic-based control system. The delay in valve-gate actuation can be tolerated in the molding of large CIM parts. However, for thin-wall parts requiring less than a 0.3-s filling time, sequential injection molding using a valve gate meets this new challenge. A commercial valve-gate system does not provide the necessary information for actual applications. Therefore, it seems necessary and important to investigate characteristics of the valve-gate opening response so that it can be better used for molding thin-wall parts.

In this study, a gas-driven valve-gate control system with a human–machine interface using Labview soft-

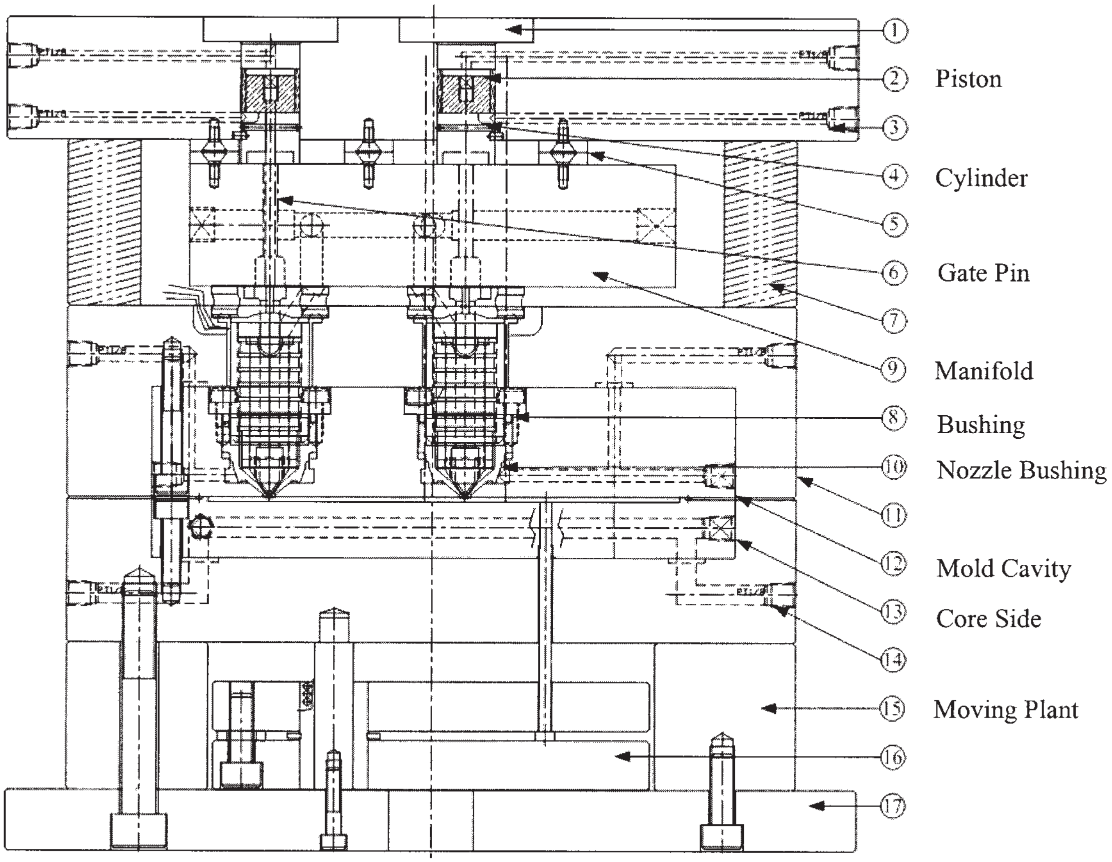

Figure 2 Two-valve-gate system for a plate mold.

ware (National Instruments Co., Austin, TX) was established. Then, a monitoring system for valve-gate opening was also built with a shock accelerometer. The system response was analyzed on the basis of the tracing of the triggered solenoid valve signal and shock accelerometer signal. The results were also verified with a high-resolution CCD camera under a nonmelt-filled environment and with cavity pressure transducers in a melt-filled condition. The factors that influence the gas-driven valve response characteristics as well as the associated delay, including tolerance between the inner piston and cylinder and the gas pressure, were investigated in detail. It is hoped that we can reduce the delay time to less than 0.1 s so that valve-gate sequential injection molding can be more suitably applied to molding thin-wall parts. To illustrate the applicability of the improved valve-gate system, thin-wall parts 1 mm thick were also molded with a filling time of 0.41 s with three different kinds of gate designs: a conventional single gate, a sequential opening of two valve gates, and a concurrent opening of valve gates. The maximum pressure of the mold cavity and the maximum pressure of the oil hydraulic cylinder were also measured simultaneously. Tensile tests following the methods of the American Society for Testing and Materials (ASTM)[20] were also conducted. The effects of the different gate designs on the molding pressure and part tensile strength were analyzed and discussed.

ESTABLISHMENT OF A 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 this study. A gas-pressure regulation system developed for gas injection[21,22] was modified as the pneumatic actuator for valve-gate motion. A control schematic is illustrated in Figure 3. Moreover, Figure 4 is a schematic of a valve gate opening and closing by cylinder actuation. The pneumatic-driven system for the valve gate was set up on top of the hot manifold and is shown in Figure 5. In addition, there was a gas buffer tank built on top of the pneumatic-driven system. The buffer was precharged to the operation pressure before the gate opening so that the target gas pressure could be delivered as quickly as possible; this minimized the pressure loss along the gas pipe and thus decreased the response time. This concept follows the fast-response gas-injection unit designed for gas-assisted thin-wall injection molding.[23] A linear variable displacement transducer (LVDT) was used to

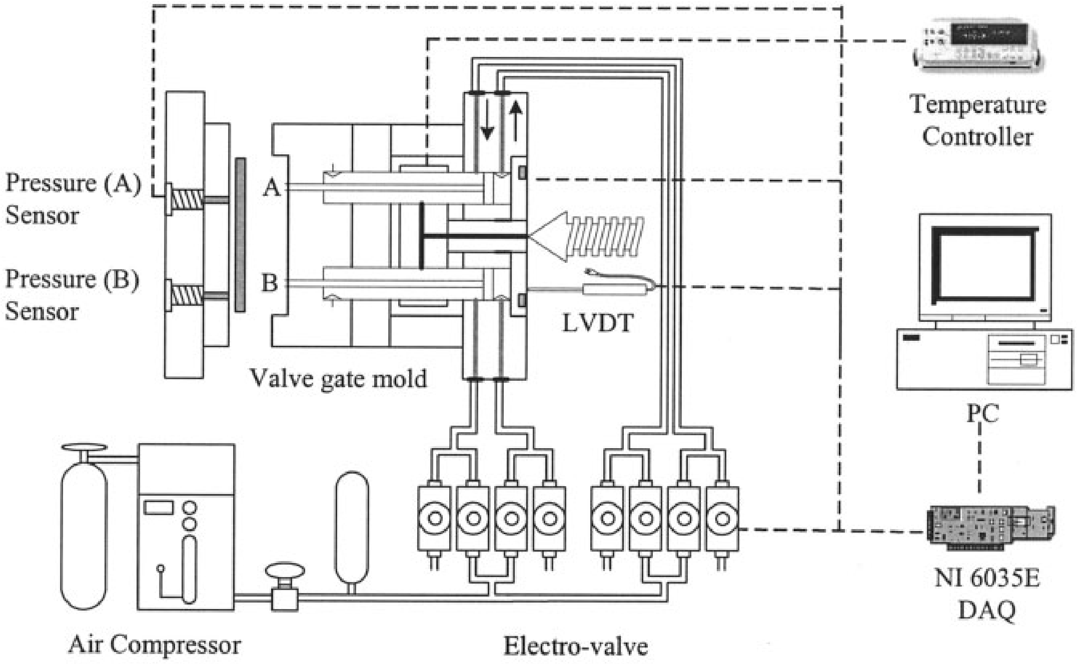

Figure 3 Schematic of a valve-gate control system.

monitor the screw location and send a signal to actuate the gas-pressure valve and the associated piston linked to the top of the needle valves. A man–machine interface developed with Labview provided the operator an easy way to input the process parameters. Two valve gates could be opened and closed independently at the desired time during the molding process. Within the core side, two Kisler type 6159A pressure transducers (InterTechnology, Inc., Don Mills, Ontario, Canada) were also flush-mounted near each

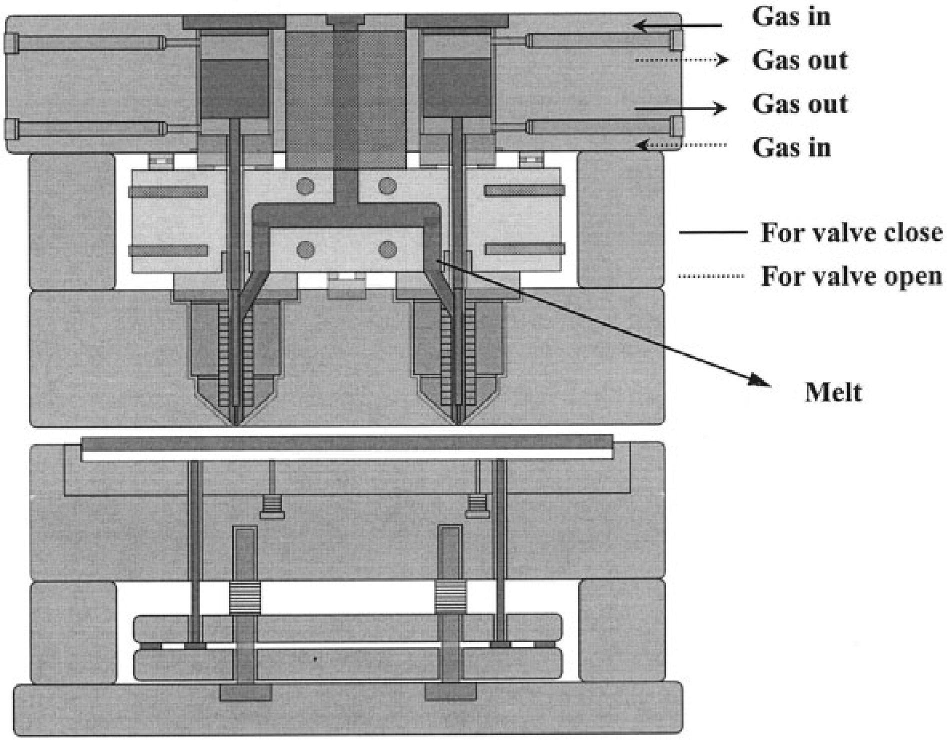

Figure 4 Schematic of a valve gate opening and closing by cylinder actuation.

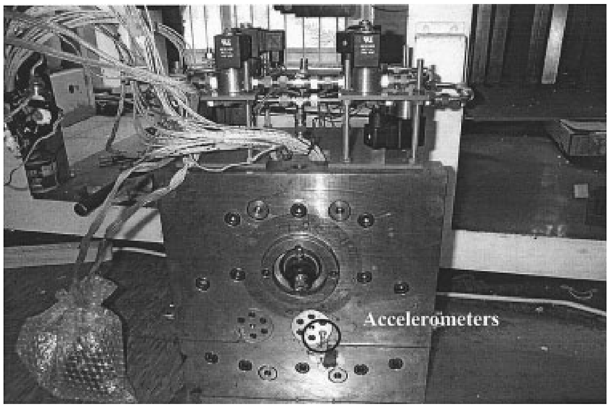

Figure 5 Pneumatic-driven system for a valve gate. The installation of the accelerometer is also identified.

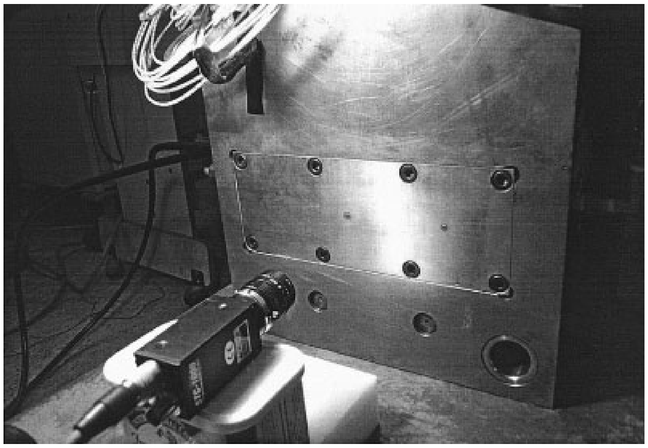

Figure 7 Monitoring of a valve gate opening with a CCD camera.

valve gate (Fig. 6). A hot manifold system was also carefully designed with the help of Kun Wu Co. (Tayuan, Taiwan), which has 20 years of experience in hot runner systems. A Hanyuong MX4 temperature control system (Hanyoung Electric Co., Hanyoung, Korea) provided six channels for melt temperature control for six different locations of hot runners.

Before the mold was fully assembled, the valve-gate operation was also monitored and verified by a high-resolution CCD camera (Fig. 7). This video system enabled us to measure the delay time once a signal was sent to actuate the gas and the needle-valve movement. Because the CCD recording speed was 60 frames per second, the exact opening time of the valve gate could lie between two consequent frames, that is, a frame recording the complete opening of the valve gate and one frame before this frame. As a result, we took the maximum and minimum opening times of the valve gate as the times at which these two consequent frames took pictures. Details have been reported elsewhere.[24] In addition, a PCB Piezotronics Co. model 352C22 accelerometer (Depew, NY) was used to monitor valve-gate opening, as illustrated in Figure 5. When the gate pin was driven by the gas and went to the end, it touched the topper of the mold, and the accelerometer was driven to send a signal to the computer. It helped us to measure the delay time of the valve-gate system. However, one of the key factors for the opening delay was the dimension tolerance between the piston and the cylinder. For a small tolerance, the piston could be difficult to move because of a larger friction force existing between the piston and inner surface of the cylinder. For a larger tolerance, there could be gas leakage leading to a smaller pressure difference in the gas-inlet and gas-outlet sides. An optimized tolerance was expected to exist for each operation gas pressure. We designed four different sizes for the piston diameters corresponding to different tolerances. The inner diameter and length of the cylinder were fixed at 19.985 and 18 mm, respectively. In addition, the length of the piston was 15 mm, and

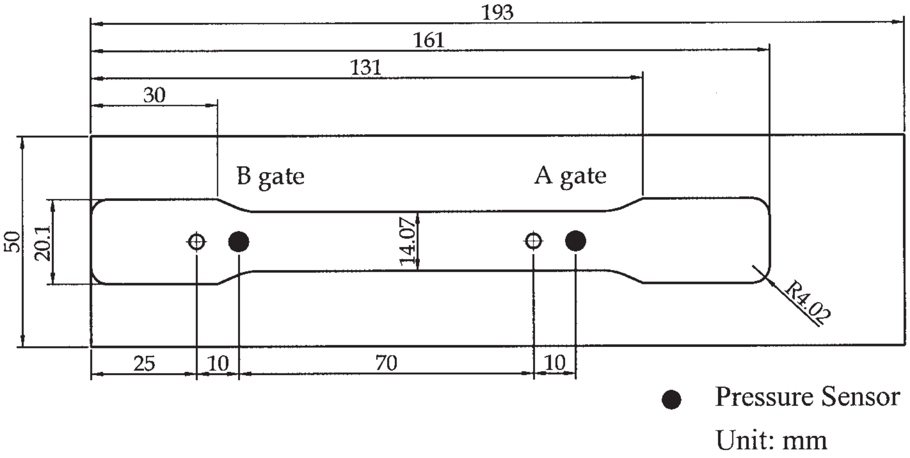

Figure 6 Schematic of the cavity dimensions and two pressure sensors flush-mounted near each valve gate. The shape and dimensions of the tensile test specimen are also identified.

the outer diameters were 19.980, 19.975, 19.970, and 19.965 mm. The gas pressure also varied form 25 to about 175 bars. Then, the delay times for different piston diameters and gas pressures were recorded and analyzed. After the optimized conditions were found for valve-gate opening and closing, a mold was assembled for the molding test.

EXPERIMENTAL

The melt temperature within the hot runner was controlled by separate heating equipment linked to heaters within the manifold. A Victor injection-molding machine (Taichung, Taiwan) was used for the molding experiments. A rectangular plate mold with dimensions of 193 mm (length) × 50 mm (width) × 1 mm (thickness) was used. The geometry of the plate mold is shown in Figure 6. Chi-Mei PG33 transparent polystyrene (Tainan, Taiwan) was used as the material. The melt temperature was fixed at 230°C, and the mold temperature was fixed at 50°C. Because pressure transducers A and B were of equal distance from the valve gate, from the measured pressure profiles we could also characterize the delay time and the performance of both valve gates. Under a melt-filled environment, the valve-gate opening was subject to additional resistance. The opening delay was expected to increase. For this investigation, the influence of the valve-gate-system design on the injection pressure and mechanical properties was studied. The molding experiments included a conventional single-gate design, sequential-gate opening, and concurrent-valve-gate opening for the melt-filling process. At the same time, the maximum pressure of the mold cavity and the oil hydraulic cylinder was also measured. The tensile test specimens were prepared according to the ASTM D 638 testing method[20] by slow cutting from plate parts, as shown in Figure 6. The tensile tests were conducted on a C-MTS machine (MTS Systems Co., Eden Prairie, MN), which had full loads of 500 kgf. For each test, 10 molded samples under the same molding conditions were used. The average value from these 10 tests was used for analysis and correlation.

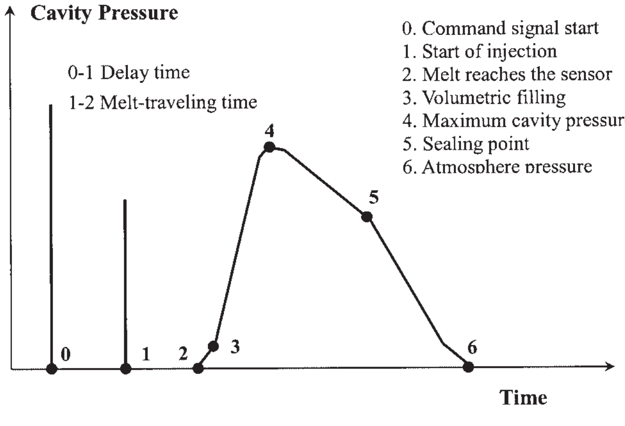

Figure 8 Pressure profiles from which a valve-gate delay time can be deduced.

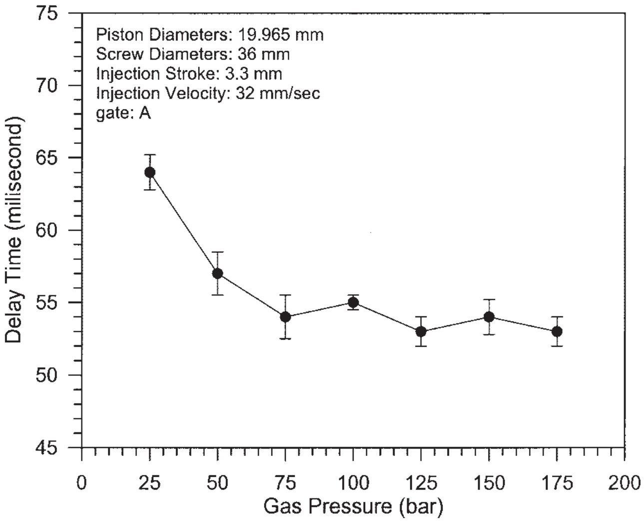

Figure 9 Delay time of a valve gate opening in a melt-filled environment.

RESULTS AND DISCUSSION

The delay time of valve-gate opening with an accelerometer can be defined as the interval between the times when the signal is sent by the man–machine interface to actuate the gas driving needle movement and when the needle valve moves to the final position at which the piston shaft touches the installed accelerometer. The delay time of the valve-gate opening is then evaluated from the two detected signals. Another way of tracing valve-gate opening is indirect evaluation from cavity pressure transducers. Once the signal is sent to the valve gate, the timer counting begins. It is assumed that the melt starts to fill the mold cavity once the valve gate is completely open. The pressure sensor starts to act once the melt has arrived. The best design has the pressure transducers installed directly beneath the valve gate, that is, on the opposite mold side (core side) of the valve gate. This design has the opportunity to destroy the pressure transducers. Therefore, we decided to offset the pressure sensors by 10 mm. By doing so, we were still able to evaluate the valve-gate-opening time once the melt flow velocity could be calculated exactly. The monitoring of the screw location and associated screw velocity has been reported.[24] The melt flow rate as well as the melt front velocity can be precisely predicted. By the correction of this melt traveling time from the valve gate to the transducer, we can obtain the valve-gate-opening delay time (i.e., the interval time of 0–1 in Fig. 8). Figure 8 shows the pressure profile measured from the pres-

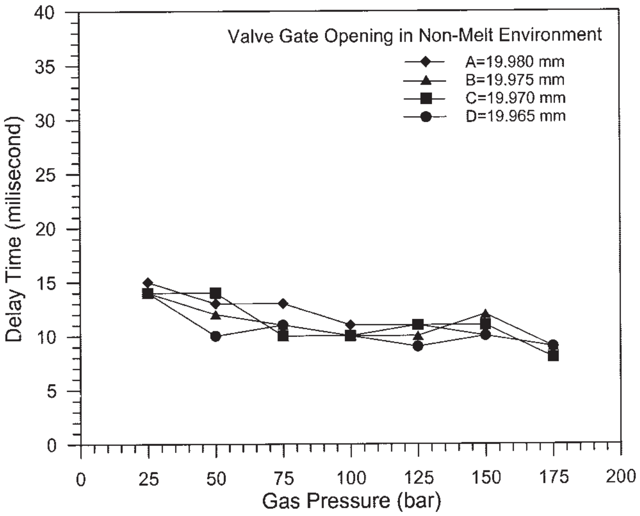

Figure 10 Variations of the response time of a valve gate opening in a nonmelt environment with gas pressures under various piston sizes.

sure transducer, from which the delay times of valve opening at different gas pressures have been estimated; they are listed in Figure 9.

For pistons of various diameters (whose sizes are marked A, B, C, and D) linked to valve gates, the response time may be different under the same gas pressure because of the different friction between the exterior surface of the piston and the inner surface of the driving cylinder. In addition, different gas pressures may also affect the friction and drive the pistons at different speeds. The delay times of valve-gate opening versus the gas pressure in non-melt-filled and melt-filled environments for various piston sizes are given in Figures 10 and 11, respectively. From the experimental results, we have found that a high gas pressure may introduce small leakage leading to extra resistance for piston movement. For valve-gate opening under a nonmelt condition, the delay times show less influence by the size of the piston and gas pressure than under a melt-filled condition. As expected, the delay time of the valve gate can be reduced to less than 15 ms. As far as valve-gate opening in a melt-filled environment is concerned, it shows slightly higher delay times than those in a nonmelt situation. In addition, it is highly sensitive to the size of the piston, especially at a low gas pressure. However, the delay times of valve-gate opening are less than 50 ms and are thus still suitable for thin-wall molding. With respect to the effect of the gas pressure on the response time of the valve gate, Figures 10 and 11 show that the delay time decreases with increasing gas pressure, especially under the condition of a melt-filled environment. For valve gate A and a piston diameter of 19.970 mm, for example, a response time of 14 ms at 25 bar reduces to 8 ms at 175 bar under a nonmelt condition, and a response time of 35 ms at 25 bar reduces to 14 ms at 175 bar in a melt-filled situation. At this point, it is worthwhile to compare the measured delay time performance of valve-gate opening in a melt-filled environment with a pressure transducer and accelerometer with a piston diameter of 19.965 mm (Figs. 9 and 11, respectively). The delay times measured by pressure transducers are greater. It is not easy to obtain the exact traveling time from beneath the valve gate to the embedded pressure transducer. The LVDT monitoring to estimate the screw location and the associated melt front velocity may introduce an extra delay time. Using an accelerometer for direct valve-gate-opening measurements shows an advantage over pressure transducers, particularly in a higher gas pressure situation, although both are suitable for monitoring valve-gate opening. Figure 12 shows the variation of the delay time for valve gates A and B under different gas pressures with a piston size of 19.980 mm. On examining the data, we find almost the same delay times for both gates A and B at high operating gas pressures. In summary, the delay time for the valve-gate shaft movement in a nonmelt environment can be reduced to about 8 ms, whereas it increases to about 12 ms in a melt-filled environment, by the choice of the 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 with the same injection filling time, whereas different gate operation methods were implemented, including single-gate opening, sequential-gate opening, and concurrent-gate opening for the melt-filling process. The associated molding pressures within the mold cavity and

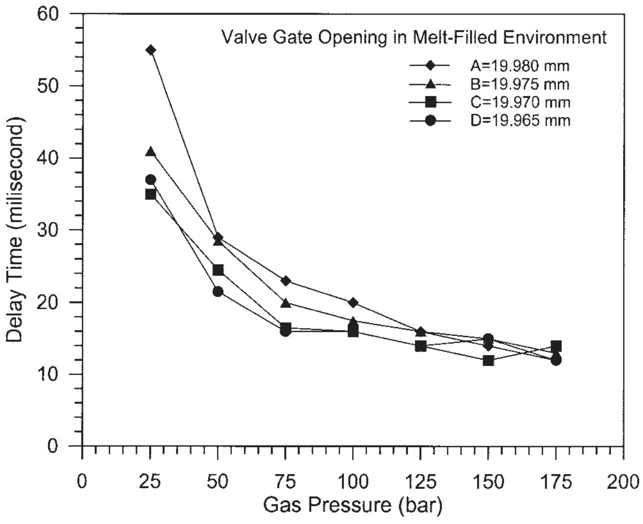

Figure 11 Variations of the response time of a valve gate opening in a melt-filled environment with gas pressures under various piston sizes.

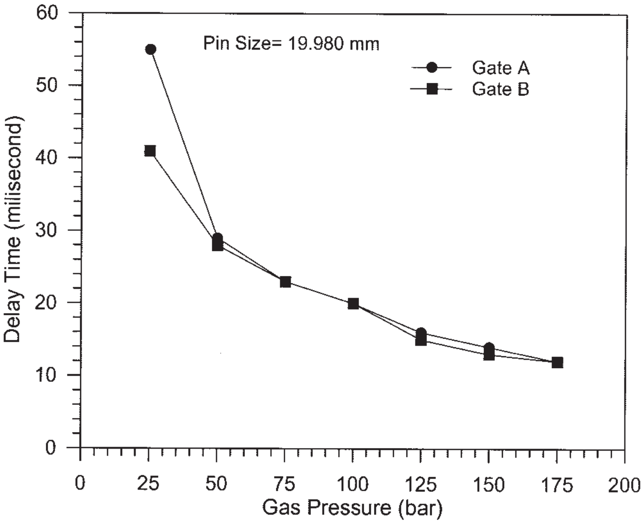

Figure 12 Delay time of valve gates A and B in a melt-filled environment under specified piston sizes.

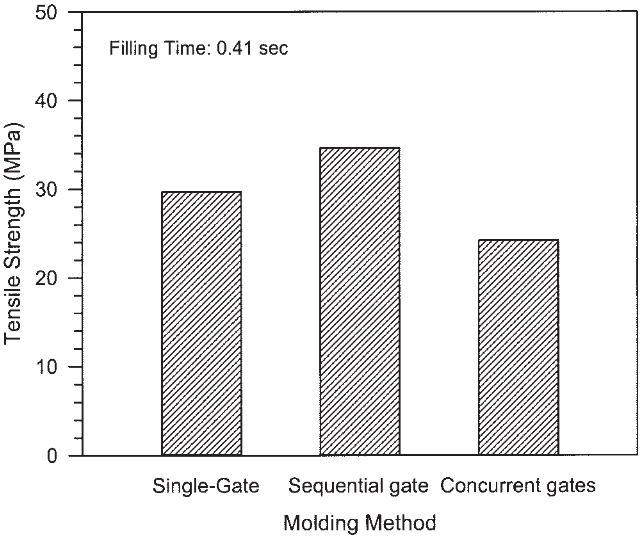

Figure 14 Maximum tensile strength under the condition of three different gate designs for molding.

the oil hydraulic cylinder were measured. Graphical displays of the maximum mold cavity pressure and maximum oil hydraulic cylinder pressure with a filling time of 0.41 s can be found in Figure 13. The maximum mold cavity pressures were 553, 493, and 468 bar for a single gate, a sequential valve gate, and a concurrent double valve gate, respectively. The maximum pressures of the oil hydraulic cylinder were 60, 55, and 48 bar. From the measured results, we have found that single-gate molding needs not only a higher machine injection pressure but also a higher mold cavity pressure. Both the concurrent valve gates and sequential valve gate require lower molding pressure. The reason can be attributed to the flow length. The flow length ratios (ratios of the maximum flow length to the thickness) were 105, 80, and 55 for the single gate, sequential gate, and concurrent valve gates, respectively. Consequently, the sequential gate reduces the molding pressure more efficiently than the concurrent valve gates if both have the same flow length. Finally, it is worthwhile to check part performance, such as the mechanical strength. The presence of weld lines in the concurrent valve gates results in a tensile strength (24.2 MPa) lower than that of single-gate molding (29.7 MPa) and sequential-gate molding (34.6 MPa; Fig. 14). Molding using a sequential gate has the advantages of a single gate (i.e., without a weld line) and concurrent valve gates (i.e., a lower flow length ratio). In summary, as expected, developing a fast-response sequential-valve-gate system for thin-wall injection molding results in thin-wall injection-molded parts without a weld line and good cosmetic quality as well as better tensile strength requiring a lower injection filling pressure.

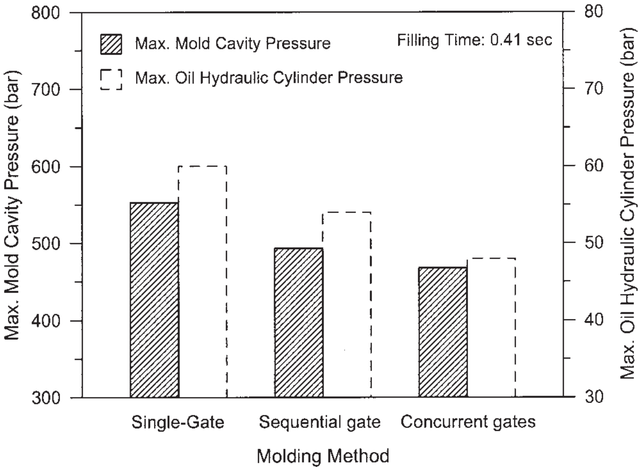

Figure 13 Maximum mold cavity pressure and maximum oil hydraulic cylinder pressure under the condition of three different gate designs for molding.

CONCLUSIONS

The characterization of valve-gate opening and closing based on a pneumatic-driven control system suitable for thin-wall injection molding was conducted in this study. The illustration of the developed system was also carried out under different molding designs using single-gate, sequential-gate, and concurrent-double-gate opening. The associated molding pressure and tensile strength of molded thin-wall parts were compared to evaluate the system's applicability. On the basis of the experimental observations and measured results, the following conclusions were drawn:

1. The pneumatic control and monitoring systems for the characterization of valve-gate opening in

both non-melt-filled and melt-filled environments have been successfully established with three sensor technologies: a CCD camera, pressure transducers, and a shock accelerometer. Using an accelerometer provides a direct measurement of valve-gate opening under all conditions and seems to be the most reliable for measurements of the delay time in valve-gate opening.

2. In a nonmelt environment, the delay time of valve-gate opening shows less influence from the driving gas pressure and the tolerance between the driving piston and the inner cylinder surface than in a melt-filled environment. Under a melt-filled environment, the delay time of the valve gate increases significantly and becomes more sensitive to the variation of the 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 under the melt-filled condition.
4. The delay time for valve-gate shaft movement in a nonmelt environment can be reduced to about 8 ms, whereas it increases to about 12 ms in a melt-filled environment, by the choice of the 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 a weld line and good cosmetic quality as well as better tensile strength and lower molding pressure.

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