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Enhancement of Injection Molding Consistency by Adjusting Velocity/Pressure Switching Time Based on Clamping Force

The velocity/pressure (V/P) switching time, the transition from the filling phase to the holding phase during the injection molding cycle, plays a crucial role in ensuring the quality of the injection molding. Improper settings can lead to a variety of defects, including oversize/undersize, excessive residual stress, flash, warpage, and the like. There are currently many V/P switching methods to choose from. For example, when the injection time or the screw position reaches a prescribed value, that is, when a specified percentage of the cavity is filled with the molten resin, the switching time can be started. These traditional V/P switching methods should work well using precision injection molding machines to ensure accurate and repeatable motion control. However, the quality of shot-to-shot injection molding still varies with environmental changes, such as varying mold/melt temperatures. In this study, we propose a V/P switching adjustment method involving part weight or maximum clamping force increments. It was found that the weight of the injection molded part was highly correlated with the maximum clamping force increment and the V/P switching time. Experimental verification by considering various settings such as V/P switching time, injection speed and holding pressure show that the adjustment method is a feasible means of assuring quality consistency.

1 Introduction

Injection molding has the advantages of high efficiency, accuracy, low cost, and the ability to produce geometrically complex components. It has become a common method for large-scale manufacturing of various plastic products in the automotive, electronics, sporting goods, medical equipment, optical lens and other industries. Typically, the injection molding process consists of several stages, namely (1) mold closing and clamping, (2) mold filling and holding, (3) cooling and plasticization to prepare for the next injection, and (4) mold opening and part ejection. Phase 1 and Phase 2 have a dominant effect on the quality of injection molded parts. For example, the filling pattern of the molten resin determines the aesthetics of injection molded parts, while the holding pressure and time determines the geometric accuracy and residual stresses. Cooling is also important because it controls the cycle time and can affect the shrinkage and warpage levels of the final products. The plasticizing process affects the quality of the molten resin, and its uniformity ensures the uniformity of successive injections. Injection speed and pressure, holding pressure and time, and melt and mold temperature are major process parameters that affect the quality of the injection. However, proper filling-to-holding switching time and sufficient clamping force values are also critical. The former is the switching time from mold filling to mold holding, also known as velocity-to-pressure switching time or V/P switching time, which has a crucial influence on the quality of injection molded parts. The latter is of some concern for part quality and machine/mold life (Huang et al., 2018). In order to obtain consistent and effective injection molding, these two factors were examined in this study.

In modern injection molding machines, two completely different control strategies are involved in the mold filling and mold holding stages, respectively. During mold filling, the screw speed is controlled such that the molten resin is forced into the mold cavity at a prescribed flow rate profile and the injection pressure is limited to a set maximum to protect the machine and the mold. In contrast, during mold packing the holding pressure is held at a prescribed holding pressure profile and the holding speed is limited to compensate for volume shrinkage due to cooling. The operating point of the split mold filling phase (speed controlled) and the mold holding phase (pressure controlled) is often referred to as the V/P switching time. In practice, properly setting and controlling the V/P switching time is critical to achieving the required injection molded part quality (Wang et al., 2018). For example, if the V/P switching time is set too early, the injection pressure may not be sufficient to force the molten resin to fill the mold, resulting in short shots, sink marks, warpage, and the like. Conversely, if the V/P switching time is set too late, too much polymer may enter the

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mold causing overfill and excessive cavity pressure. This improper switching time can result in serious residual stress/flash on the injection-molded part, or even severe mold deformation and excessive tie-bar elongation. An appropriate V/P switching time setting not only ensures that the molten resin completes the mold filling, but also produces sufficient packing in the cavity. Therefore, ideally, the V/P switching time should be set such that the cavity pressure profile rises and falls smoothly during the filling and holding phases, thereby helping to ensure that the mold is sufficiently filled during the filling phase and the molten resin is adequately compressed during the holding phase.

Various studies have shown that the cavity pressure profile detected by sensors installed within the cavity can accurately show the change in polymer melt quality during the mold filling phase (Min, 2003; Michaeli and Schreiber, 2009; Macfarlane and Dubay, 2000; Heinzler et al., 2014; Zhang et al., 2016; Hopmann et al., 2017). Regarding V/P switching control, Kazmer et al. (2010) studied seven different V/P switching variables, namely (1) screw position, (2) injection time, (3) machine pressure, (4) nozzle pressure, (5) sprue pressure, (6) cavity pressure, and (7) cavity temperature. The results show that screw position and machine pressure are suitable V/P switch point determination methods for most injection molding cases. However, for older machines, it is difficult to control the screw position with sufficient accuracy to ensure the required switching time. Furthermore, while modern all-electric driven injection molding machines provide extremely precise control of screw displacement, natural fluctuations in melt viscosity and ineffective motion control of the screw tip check valve still inevitably occur and result in inconsistently molded parts. Therefore, the use of pressure-based methods, where the V/P switching time is triggered based on the measured cavity pressure signal, is generally considered to be more reliable than the screw displacement method (Huang, 2007). Therefore, to prevent excessive pressure, it is more effective to control the switching time in the melt holding stage of precision injection molding due to the rapid rise of the cavity pressure. In particular, it is more advantageous for application in those cases having a wide parting surface to prevent flash from occurring on the injection molded part. A number of V/P switching control methods based on cavity pressure have been proposed in the literature (Agrawal et al., 1987; Gao, et al., 1996). These methods are also used for quality monitoring in the injection molding process and to further evaluate machine performance (Kelly et al., 2005). Huang (2007) proposed a pressure-based V/P switching control method in which a simple GM(1,1) grey model is used to instantly determine the volume fill point in each shot. The experimental results confirm the ability of the proposed method to determine the appropriate V/P switching time and adjust the screw displacement accordingly. However, the accuracy of the proposed method is highly sensitive to errors in the positioning of the intra-cavity sensors. Moreover, the cost of the control system is significantly increased for all systems involving the use of embedded sensors.

In general, the pressure profiles detected within the mold of the injection molding system during the filling and holding phase can assume three possible modes, as shown in Fig. 1 (Chen et al., 2019). Prior to the V/P switching point, the pressure rapidly rises as the polymer melt enters the cavity at a prescribed flow rate during the filling phase (Section A–B). After reaching the V/P switching point (point B), the polymer melt continues to fill the cavity at a prescribed pressure and low injection speed; resulting in a gradual increase in pressure until the injection molding cycle enters the holding phase (point C). Thereafter, the cavity pressure profile exhibits three characteristics:

1. Pattern A: The polymer melt injected into the mold is insufficient (or just enough) to fill the voids in the cavity. As a result, no significant compression occurs, so the pressure gradually increases in the mold, and there is no discernible discontinuity in the pressure profile (see Fig. 1A).
2. Pattern B: The polymer melt completely fills the entire cavity during the filling and holding phases and thus experiences a compressive force as the holding phases proceeds. Therefore, the pressure profile shows a significant discontinuity at point C, and then gradually rises until the end of the holding phase (Fig. 1B).
3. Pattern C: Excessive polymer melt is injected into the cavity during the filling and holding phases. As a result, the melt overflows the cavity and a rapid increase in cavity pressure occurs in the holding phase. Therefore, the pressure profile shows a significant discontinuity at point C, and then increases sharply as the holding process progresses (Fig. 1C). In practice, the slope of the section C–D in the pressure profile reflects the degree of compression of polymer melt within the mold. At the same time, the reflected mold separation is also evident and consistent with the elongation of the tie bars.

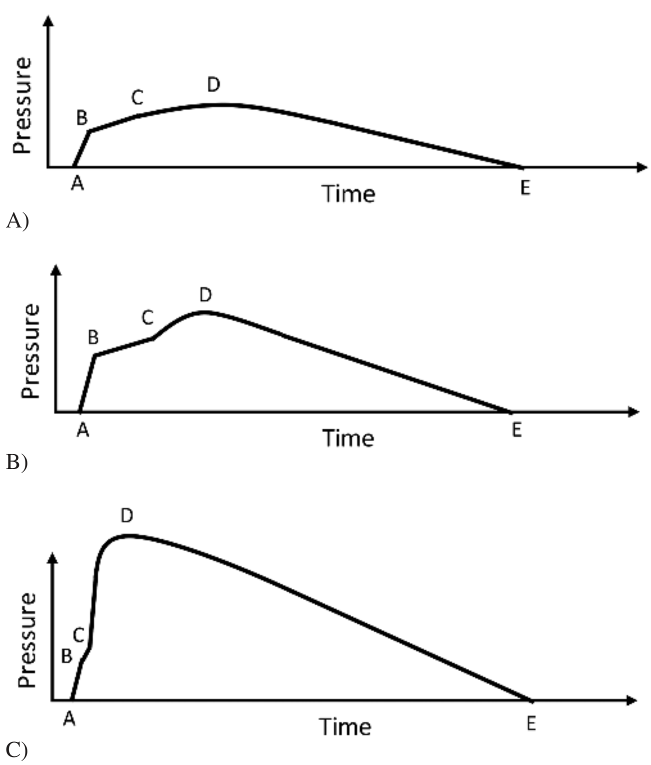

Fig. 1. Patterns of cavity pressure profile affected by V/P switching time (Chen et al., 2019), A) pattern A, B) pattern B, C) pattern C

As the molten polymer flows into the cavity during the filling phase, the cavity pressure gradually increases. At the instant when the melt fills the entire cavity, a sudden compression effect occurs, which causes an instantaneous rise in the cavity pressure. This leads in turn to a mold separation effect and an associated elongation of machine tie bars. Therefore, as shown in Fig. 2, a significant increase in the clamping force occurs. Therefore, sufficient clamping force is required to prevent mold separation due to excessive cavity pressure resulting from the melt filling the cavity. Huang and Lin (2017) proposed a method based on experimental measurements of the tie-bar elongation to determine the clamping force required to prevent mold separation. In a later study, the same group studied the effect of mold separation on the quality of the injection molded part and concluded that the clamping force setting plays a key role in determining the final part quality (Huang, et al., 2018). Chen et al. (2006) and Chen and Turng (2007) also studied the effect of mold separation on the quality of an injection molded part using a precise linear displacement sensor mounted on the outside of the mold plates. In general, the results indicate that the maximum mold separation point occurs at the V/P switching point and is highly correlated with the weight of the molded part.

The displacement-based methods for controlling the V/P switching time achieve only limited success in ensuring consistent molded part quality, since melt quality variations inevitably occur shot by shot due to a variety of external factors. In other words, there is an urgent need to develop an accurate determination of V/P switching time to compensate for the defects of the molded part to achieve high quality uniformity. In addition, there is a persistent lack of scientific methods to determine the V/P switching time for different injection molds based on operator experience. Therefore, the quality of injection molded parts is always variable, and batch by batch, even shot by shot, is inconsistent. Although the V/P switching control method based on cavity pressure measurement provides a promising method to achieve more consistent injection molded part quality, the requirement for an installed sensor not only increases the installation cost, but also is mold structure invasive. There is a risk of damage to the molded parts. As a result, it is particularly attractive to use some form of externally mounted sensor to measure the quality of the molded part and adjust the V/P switching time accordingly. This study proposes a method for adjusting the V/P switching time in a continuous injection molding process based on the weight of the component, and/or the clamping force increment, which is easily detected by a strain gauge sensor mounted on the tie bar.

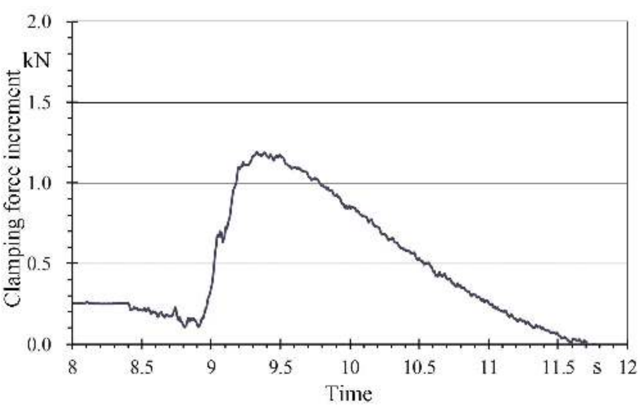

Fig. 2. Typical clamping force increment profile during the injection molding cycle

2 Method

As mentioned above, the V/P switching time has a large impact on the quality of the part; incorrect V/P switching time will lead to defects in the molded part and inadequate quality consistency. In the injection molding process, the nominal weight of the molded part can be easily calculated based on the geometry and size of the cavity and the density of the processed polymer. In addition, acceptable variations in the weight of the molded part can be determined by reference to user-specified upper and lower tolerances. Previous studies have shown that part weight can therefore be a reliable indicator of the quality of an injection molded part; values below and above the nominal value indicate that the mold is underfilled/overfilled (Huang, 2007; Huang and Lin, 2017; Chen and Turng, 2007). In this study, part weight was therefore considered a quality index and was used to adjust the V/P switching time as needed to maintain consistent molded part quality. Figure 3 shows that the proposed method begins by defining standard component weights (W_T) and allowable deviations (i.e., mass intervals). The first molded part is then produced using a predefined set of initial processing conditions, including the initial V/P switching screw position, x_i. If the weight W_i of the molded part satisfies the quality requirement (i.e., it is within the quality specification limits), the V/P switching adjustment is terminated; otherwise, the new V/P switching position is determined as follows:

If $W_i > W_T$, the V/P switchover screw position for next shot, x_{i+1}, advances.

If $W_i < W_T$, the V/P switchover screw position for next shot, x_{i+1}, is delayed.

The updated switching screw position, x_{i+1}, is then placed on the injection molding machine and a new part with weight W_{i+1} is injected. If W_{i+1} meets the quality requirement, the V/P switching adjustment process is terminated. Otherwise, a linear equation is constructed based on the measured values of W_i and W_{i+1} to calibrate according to the V/P switching screw position ($X_{V/P}$),

$$W_n = F(X_{V/P}) = \alpha X_{V/P} + \beta, \tag{1}$$

where W_n is the weight of the injection molded part produced in the n^{th} shot, and α and β are empirically derived constant values. Therefore, the predicted V/P switching screw position for the third shot can be found by a process of linear interpolation as follows:

$$x_{i+2} = \left(\frac{W_T - W_{i+1}}{W_{i+1} - W_i}\right)(x_{i+1} - x_i) + x_{i+1}. \tag{2}$$

The updating process is iteratively continued in this way until the weight W_n of the molded part satisfies the quality requirement, i.e., the part weight is continuously measured and the

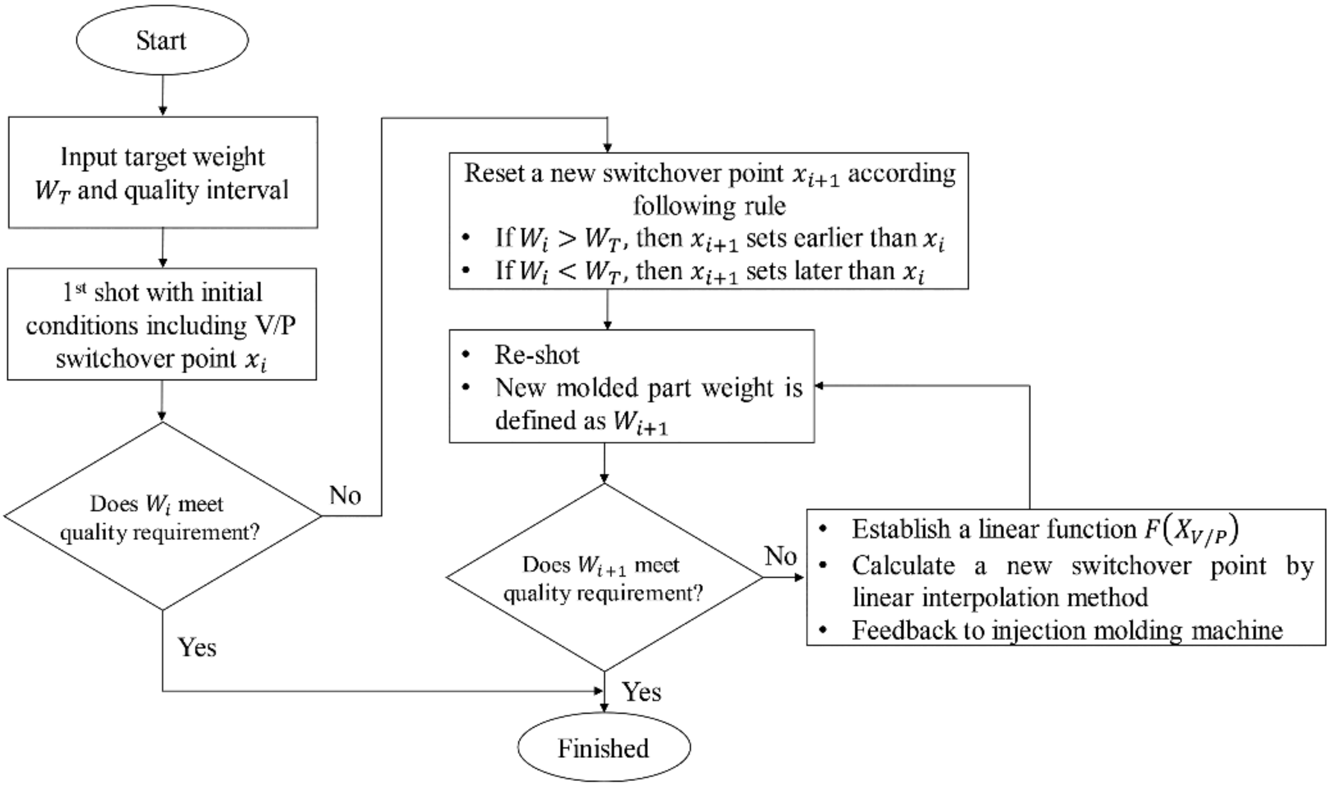

Fig. 3. Flow chart of the V/P switching time adjustment method

V/P switching screw position is adjusted as needed according to the variations of the process, material, and environment. In this study, it was found that the weight of the injection molded part was highly correlated with the maximum clamping force increment and the V/P switching time. Therefore, adjusting the V/P switching time in a continuous injection molding process can be based on the weight of the component, and even the clamping force increment.

3 Experimental

The injection molding test was carried out using an all-electric driven injection molding machine (Fanuc Co., Oshino, Yamanashi, Japan) having a maximum clamping force of 1 000 kN and a screw diameter of 28 mm. As shown in Fig. 4, the tie-bar elongation and cavity pressure were measured using a strain gauge mounted on the tie-bars of the injection molding machine and a pressure sensor in the cavity, respectively. The specifications of the sensors and DAQ card used in this study are listed in Table 1. The injection molding experiment was carried out using the two-cavity mold shown in Fig. 5. The product is a flat dumbbell test sample (ASTM D638) with a thickness of 1.2 mm. Its geometry is shown in Fig. 6. The polymer material used in this experiment was acrylonitrile butadiene styrene (ABS) (PA756, Chi-Mei Corporation, Tainan, Taiwan, ROC). The melt flow rate (MFR) of the ABS material property was 4.4 g/10 min, and the melt temperature and mold temperature were recommended to be 180 to 230 °C and 40 to 80 °C, respectively.

During the injection molding process, the compressive force experienced by the polymer melt in the cavity depends on the injection speed (which determines the inertia of the injection screw) and the V/P switching time (which determines the injection volume capacity). In addition, the mold separation increases as the holding pressure increases. Finally, the barrel temperature affects the rheological properties of the polymer melt, thus resulting in a different filling behavior. In practice, all four factors have an effect on the pressure in the cavity and the tie-bar elongation profile. Therefore, this experiment begins by measuring the cavity pressure and clamping force increments for various injection speeds, V/P switching times, holding pressures and barrel temperatures (Table 2). In order to evaluate the feasibility of the proposed V/P switching adjustment method described in Section 2, the correlations between the screw position at the time of switching, part weight and clamping force increment were also examined. The correlation index, γ, is calculated as (Neter et al., 1993)

$$r = \frac{\sum (x - x')(y - y')}{\sqrt{\sum (x - x')^2}\sqrt{\sum (y - y')^2}}, \tag{3}$$

where x and y are the above physical properties (i.e., part weight, V/P switching time which refers to the screw position, and clamping force increment). According to the value obtained by the correlation index, the degree of correlation be-

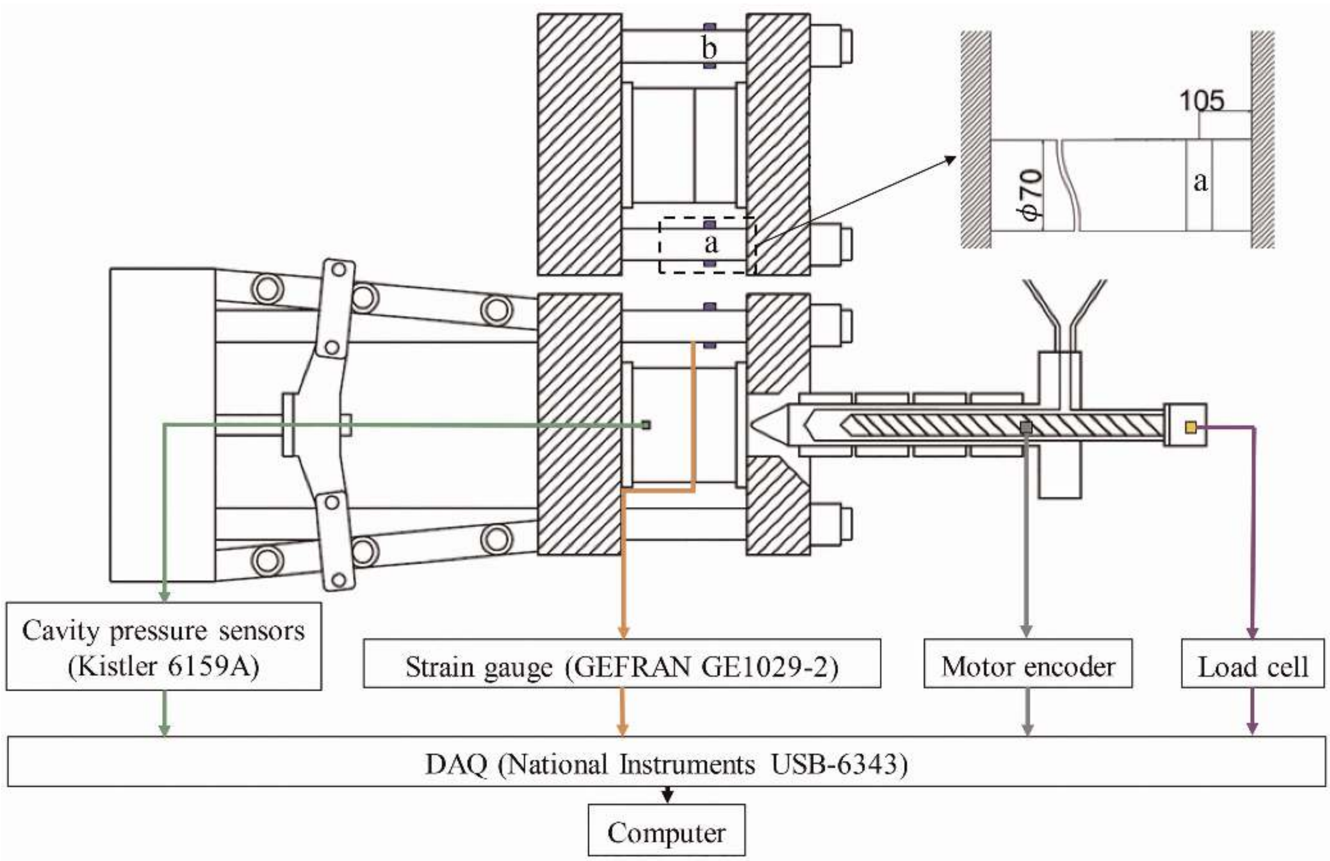

Fig. 4. Schematic showing the setting of the measuring instrument (unit: mm)

Sensor	Supplier	Type
Tie-bar strain sensor Cavity pressure sensor DAQ card	Gefran, Provaglio, d'lseo, BS, Italy Kistler, Winterthur, Switzerland National Instruments, Austin, TX, USA	GE1029 6159A USB-6343

Table 1. Sensors specifications

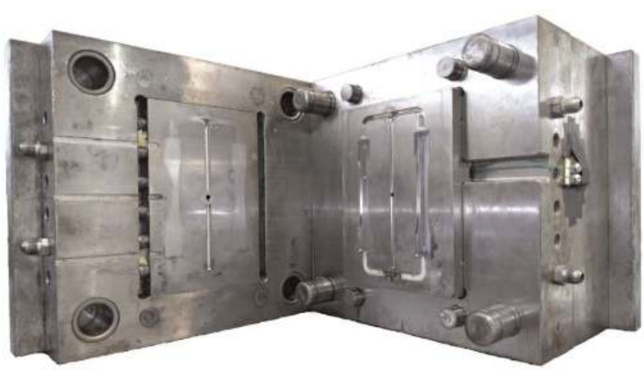

Fig. 5. Injection mold with two cavities

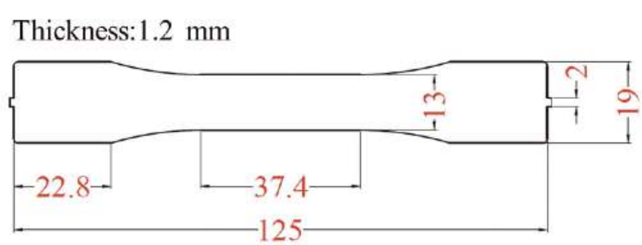

Fig. 6. Geometry of the dumbbell-shaped specimen designed according to ASTM D638

Fixed parameters			
Feeding stroke (mm)	40	Holding time (s)	5
Screw rotational speed (min^{-1})	100	Cooling time (s)	15
Injection pressure (MPa)	150	Mold temperature (°C)	60
Back pressure (MPa)	7	Clamping force (kN)	600
Varied parameters			
Injection speed (mm/s)	60, 80, 100, 120, 140, 160		
V/P switch (mm)	11, 12, 13, 14, 15, 16		
Holding pressure (MPa)	80, 100, 120, 140, 160		
Barrel temperature (°C)	195, 200, 205, 210, 215, 220, 225, 230		

Table 2. Process conditions used in the preliminary investigation

tween the two attributes is classified as "strong", "medium" or "weak", as shown in Table 3 (Neter et al., 1993).

4 Results and Discussion

4.1 Correlation Analysis

As described in Section 2, this study proposes a V/P adjustment method based on part weight deviation. Since the measurement of the weight of each part after ejection from the cavity is time consuming, an alternative way of estimating the weight of the part is proposed in this study. The clamping force increment profile provides a convenient and reliable method for estimating the pressure value in the cavity under a wide range of processing conditions, as discussed in the previous section. Therefore, we investigated the possibility of using the clamping force increment profile to predict the weight of each shot ejected from the mold.

Figure 7 shows the changes in part weight (W_{part}) and maximum clamping force increment ($CF_{i,peak}$) relative to the varying V/P switching time. There is good agreement between the two profiles because the V/P switching time of the reference screw position is gradually set. In particular, both W_{part} and $CF_{i,peak}$ are non-linearly reduced with an early setting of the switching time, and when the compression of the polymer melt in the mold is insufficient, the density of the injection molded part becomes lower. Figure 8 shows the results of the correlational analysis between the V/P switching time, the weight of the part and the maximum clamping force increment shown in Fig. 7. The results confirmed that there is a strong correlation

Strength	Correlation index
Strong	|r| ≥ 0.7
Medium	0.7 > |r| ≥ 0.3
Weak	0.3 > |r|

Table 3. Correlation index category (Neter et al., 1993)

between these three attributes. In other words, the part weight is largely dependent on the V/P switching time and is also closely related to the maximum clamping force increment. Therefore, the feasibility of using the clamping force increment profile to predict the weight of the part was confirmed.

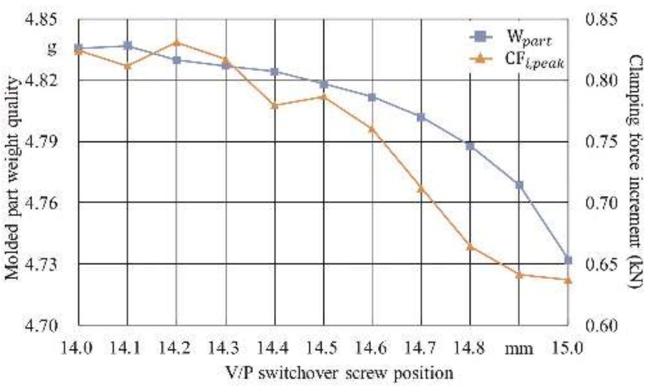

Fig. 7. The effect of the V/P switching position of the screw on the weight of the molded part and the clamping force increment

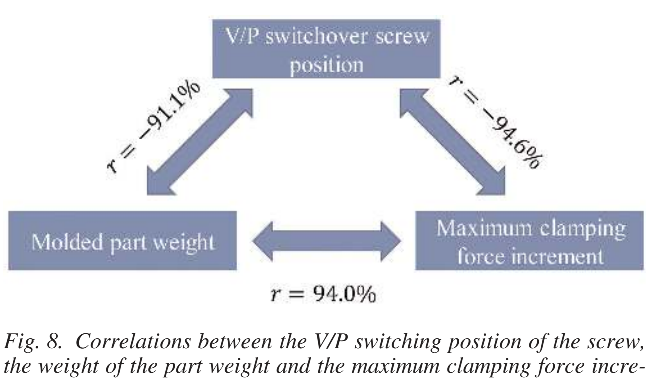

Fig. 8. Correlations between the V/P switching position of the screw, the weight of the part weight and the maximum clamping force increment

4.2 *Experimental Verification with Different Injection Speeds, V/P Switching Times and Holding Pressures*

The effectiveness of the V/P switching adjustment method was experimentally studied using the processing parameters shown in Table 4. When deliberately changing the injection speed, V/P switching time and holding pressure, it was found that the weight of the injection molded parts fluctuated. An appropriate V/P switching time was determined by the method proposed in this work, which refers to the quality specification limits of the injection molded parts, and its feasibility and practicability are verified by experiments. Based on the geometry of the molded part (see Fig. 6) and polymer density (1.05 g/cm^3), the nominal weight of the part was calculated to be 4.870 g, and the specified tolerance was limited to 4.870 ± 0.0025 g. For the first shot, the molded part weight was found to be 4.860 g, which was less than the nominal value and exceeded the specification limit. In addition, the corresponding maximum clamping force increment was found to be 1.198 kN. Our V/P switching adjustment method suggests that the V/P switching time should be moved from 7.0 mm to 6.8 mm to increase the amount of polymer melt entering the cavity. The result shows that the part weight increased to 4.867 g (formerly 4.860 g), which is closer to the boundaries of the quality specification limits. In addition, the measured maximum clamping force increment is 1.319 kN, which is higher than the previous shot (1.198 kN). Using the linear interpolation rules given in Eq. 2, the ideal V/P switching time is determined to be 6.69 mm, and the corresponding part weight is 4.872 g, which falls within the weight limits of the specification. In addition, the corresponding maximum clamping force increment was found to be 1.387 kN.

Table 5 shows the part weight, V/P switching time and maximum clamping force increment for each of the above 3 shots. The part weight was observed to be closely related to the V/P switching time ($r = -0.99$) and the maximum clamping force ($r = 0.99$). To test the robustness of the proposed V/P switching time adjustment method, the injection speed was increased to 80 mm/s, while all other processing parameters were assigned the same values as shown in Table 4. The molded part produced in the first shot was found to have a weight of 4.881 g (inconsistent with the quality requirement) and a maximum clamping force of 1.381 kN. Therefore, the V/P switching time is set to 7.20 mm in advance according to the proposed method. The part was found to weigh 4.877 g (still inconsistent with the quality requirements) and the maximum clamping force was 1.286 kN. Therefore, the V/P switching time is further increased to 7.24 mm. The resulting injection molded part weighs 4.869 g and therefore meets quality requirements. As shown in the lower row of Table 5, the molded part weight is closely related to the V/P switching time

Initial injection molding process parameters			
Feeding stroke (mm)	40	V/P switchover (mm)	7
Screw rotational speed (min^{-1})	100	Holding pressure (MPa)	100
Barrel temperature (°C)	210	Holding time (s)	5
Back pressure (MPa)	7	Cooling time (s)	15
Injection pressure (MPa)	150	Mold temperature (°C)	60
Injection speed (mm/s)	60	Clamping force (kN)	600

Table 4. Initial process parameters settings used to evaluate the proposed V/P switching time adjustment method

Shot number		1	2	3	Correlation index
Initial setting	W_{part} (g)	4.860	4.867	4.872	
	$X_{V/P}$ (mm)	7.000	6.800	6.690	–0.99
	$CF_{i,peak}$ (kN)	1.198	1.319	1.386	0.99
Varying injection speed	W_{part} (g)	4.881	4.877	4.869	
	$X_{V/P}$ (mm)	7.00	7.20	7.24	–0.83
	$CF_{i,peak}$ (kN)	1.381	1.286	1.261	0.85
Varying V/P switching time	W_{part} (g)	4.852	4.861	4.868	
	$X_{V/P}$ (mm)	8.00	7.800	6.890	–0.91
	$CF_{i,peak}$ (kN)	0.980	1.069	1.306	0.95
Varying holding pressure	W_{part} (g)	4.909	4.904	4.872	
	$X_{V/P}$ (mm)	7.000	7.200	8.680	–1.00
	$CF_{i,peak}$ (kN)	1.626	1.566	1.387	0.99

Table 5. Correlation analysis of part weight with V/P switching time and maximum clamping force increment performed through various process parameter settings

(r = −0.83) and the maximum clamping force increment (r = 0.85). A similar finding was obtained in another series of experiments conducted with an initial V/P switching position of 8 mm or a holding pressure of 120 MPa (all remaining parameters were assigned the values shown in Table 4). In other words, regardless of the injection speed, V/P switching time or the initial value of the holding pressure, the proposed method is able to determine the appropriate setting of the V/P switching time in only 3 shots. Therefore, the practical feasibility of the proposed method was confirmed.

4.3 *Experimental Verification with Different Barrel Temperatures*

This verification involved different barrel temperatures, with the first 50 shots set to 210 °C and the next 60 shots set to 215 °C. The tolerance of the part weight is ±0.005 g with respect to the average weight of good parts. In adding to requiring part weights within specifications, the V/P switching time adjustment strategy is further modified to maintain product weight within a more consistent range. In other words, with reference to the maximum clamping force increment, we activate the control law even if the product weight is within specification. Therefore, the yield area of the maximum clamping force increment is defined as two regions: (1) region 1, tolerance ±2σ, and (2) region 2, tolerance ±σ. The adjustment of the screw position for V/P switching varies with respect to these two regions, whereas the step size for adjusting the screw position of region 1 is large (i. e., 0.2 mm in this case) and the step size for the region 2 is small (i. e., 0.1 mm in this case). It is worth noting that the step size is determined by the weight, the diameter of the screw, and the accuracy of the machine motion. Figure 9 shows a comparison of part weight deviations without/with V/P switching time adjustment rules for different barrel temperatures. If there is no recommended V/P switching time adjustment, when the barrel temperature of shot 51 rises to 215 °C, the part weights after shot 61 all exceed the specification limit (Fig. 9A). In contrast, Fig. 9B illustrates that part weight is held within specification limits after shot 58. More importantly, after shot 81, the weight of the part is held to a higher level of uniformity. In order to compare results with/without the V/P switching time adjustment rule, the standard deviation of the product mass is calculated. Table 6 shows that the V/P switching time adjustment method can reduce the effects of different barrel temperatures, and the standard deviation of part weight is reduced from 0.0038 g (shots 1 to 50) to 0.0005 g (shots 81 to 100).

In this work, we have also experimentally verified that continuous barrel temperature changes may occur in actual operation. For shots 1 to 30, the barrel temperature is intentionally set to 210 °C, followed by 215 °C for shots 31 to 60, 210 °C for shots 61 to 90, and 205 °C for shots 91 to 120, and 210 °C for shots 121 to 170. Table 7 shows a comparison of product weight consistency between V/P switching time control with and without the adjustment. Corresponding to the change of the barrel temperature, the product weight changes as calculated for every 30 shots is greatly reduced to 0.0004 to 0.0008 g (original value is 0.0007 to 0.0021 g). In addition, the range of the average is reduced to 0.01 g (original value is 0.04 g).

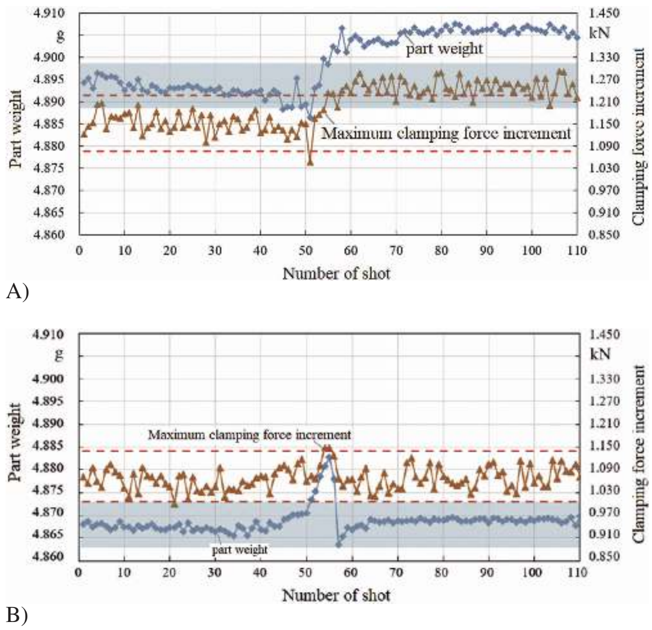

Fig. 9. Without (A) and with (B) V/P switching time adjustment method for the comparison of different barrel temperatures

Shot number	Part weight	
	Average g	Standard deviation g
1 – 50	4.869	0.0038
81 – 110	4.869	0.0005

Table 6. The effect of the V/P switching time adjustment method on the weight of the part (continuously changing barrel temperature)

5 Conclusions

During the injection molding process, the V/P switching time has an important influence on the quality of the molded part. Traditionally, the V/P switching positions have been manually set based on operator experience without supporting scientific evidence. In addition, in the actual injection molding processes, the optimum V/P switching time may change batch by batch or even shot by shot due to natural variations in melt quality. Therefore, a more rigorous and adaptive technique is needed to set the initial V/P switching time and then adaptively adjusting the switching time during the injection molding process. Therefore, this study proposes a V/P switching time adjustment method based on part weight or clamping force increment. The feasibility of the proposed method has been experimentally demonstrated under a series of representative processing conditions. The main conclusions of this study can be summarized as follows:

1. The characteristics of the clamping force increment profile under different process parameter conditions are similar in quality to the characteristics of the cavity pressure profile. Therefore, the tie-bar elongation measurement provides a

V/P switching time adjustment	Part weight	Shot number				
		1–30	46–60	76–90	106–120	121–170
Without	Average (g)	4.867	4.888	4.871	4.848	4.871
	Standard deviation (g)	0.0015	0.0015	0.0007	0.0021	0.0011
With	Average (g)	4.874	4.877	4.867	4.867	4.875
	Standard deviation (g)	0.0008	0.0004	0.0005	0.0007	0.0006

Table 7. The effect of the V/P switching time adjustment method on the weight of the part (continuously changing barrel temperature)

viable way to estimate the pressure in the cavity without the need for an embedded pressure sensor.

2. In view of the early setting of the V/P switching time, the polymer melt undergoes only limited compression in the mold during the holding phase. However, as the V/P switching time is delayed, the amount of polymer melt injected into the cavity increases, so the magnitude of the compressive force caused in the holding phase also increases. Due to the large mold separation effect, the larger compressive force increases the pressure within the mold and the clamping force increment.
3. There is a strong correlation between the V/P switching time and the weight of the molded part, and there is also a strong correlation between the maximum clamping force increment and the V/P switching time and the weight of the molded part. Therefore, the method proposed in this study can be implemented using the sensed value based on the maximum clamping force increment instead of the measured molded part weight. The feasibility of the V/P switching time adjustment method based on the maximum clamping force has been confirmed by experiments.

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