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Cavity pressure based grey prediction of the filling-to-packing switchover point for injection molding

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Abstract

Filling-to-packing switchover control during injection molding plays a crucial role in ensuring the quality of the molded parts prior to production. Although this topic has been studied for years, traditional methods of filling-to-packing switchover control, such as using screw cushioning or checking injection time without indicating the actual behaviors of melt plastics being filled into the cavity, are still those mostly used in practice. The results of switchover control, therefore, are often times inaccurate while the variation in the quality of produced parts is not negligible. This study thus presents a novel method by which quick and accurate decisions concerning the ideal switchover time can be made. It has adopted a simple grey model, GM(1,1), to predict instantaneously the volumetric-filling point when monitoring the cavity pressure profile in each molding. Recently found to be a good indicator of product quality, cavity pressure profile is applied here to obtain more precise switchover control. After the experimental verification is conducted, the results reveal that the innovative switchover method yields a more uniform product weight than any traditional methods.

Keywords: Injection molding; Cavity pressure; Filling-to-packing switchover; Grey predictor

1. Introduction

Injection molding is a cyclic process consisting of four phases: filling, melt compressing (or packing), holding, and cooling, as shown by the typical cavity pressure profile in Fig. 1. The filling process starts at Point A. The cavity pressure signals begin at Point B – where the melt plastics touch the pressure sensor for the first time – and then the pressure increases steadily as the filling proceeds. The filling phase is complete at Point C, where the cavity is only volumetrically filled by the melt without being compressed. The packing process then embarks and the pressure rises rapidly to the peak value ($P_{\max}$) at Point D. Thereafter, the melt within the cavity is maintained at an assigned pressure during the holding phase, when additional plastic melt can be packed into the cavity to compensate for the plastic shrinkage caused by cooling, so as to have the mold completely filled. This process continues until the gate is frozen, as marked at Point E. The final cooling phase comes afterwards and continues to the end of the cycle. It is during this phase that the melt solidifies gradually as the coolant that circulates within the cooling channels in the mold removes the heat. The cooling and solidification rates determine the decreasing speed of the cavity pressure.

The cavity pressure profile and its repeatability remarkably influence the quality of the molded part, especially on its mass, dimensional stability, mechanical behavior, and the surface quality. Many studies have proposed that the cavity pressure profile can be used to maintain high quality product and help to control the machine in the injection-molding process [1–5]. Likewise, others indicate that one way to maintain a high yield rate from molding is to reproduce the cavity pressure curve in every shot [6–12]. Based on these studies, ideal process parameters have been selected in this study, so that the corresponding ideal cavity pressure profile is explored and reproduced by the machine in subsequent shots. Viewing that inconsistent filling-to-packing switchover settings can significantly affect the cavity pressure profile, they must therefore be controlled adequately.

Two inadequate switchover-to-holding conditions are: (1) switchover occurring too late, and (2) switchover occurring too early. The former causes an over-packed cavity, characterized

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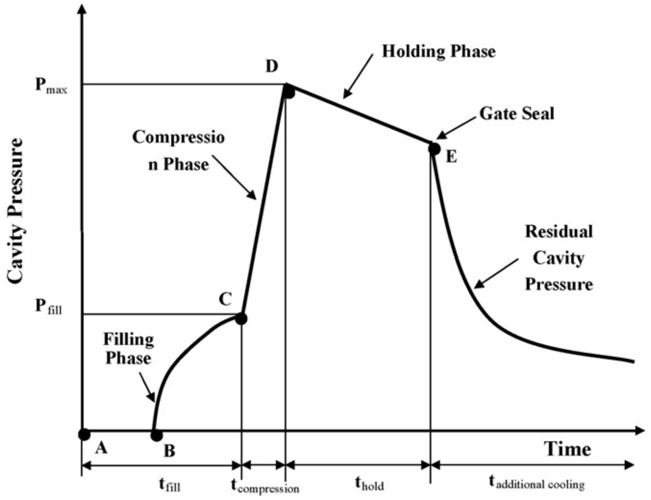

Fig. 1. The typical cavity pressure profile.

by a pressure peak in the compression phase. The pressure peak will not reduce to the lower holding pressure until the switchover because the high injection pressure is still applied after volumetric filling. Over-packing further adds weight and stress to the part, and makes de-molding more difficult. An alternative approach is to reduce the injection pressure; nonetheless, over low pressure can bring defects such as sink marks. It seems that a better solution is to switch over earlier. Switching over too early, however, may generate an under-packed cavity, characterized by a pressure drop in the compression phase. Part of the filling then takes place at the lower holding pressure, and the screw advancement subsequently increases the pressure. As a result, the injection part can be easily rejected due to reduced dimensions, being underweight, or showing sink marks.

The factors related to switchover control are injection time, screw position, hydraulic pressure, nozzle pressure, and cavity pressure.

Injection time switchover: Temperature affects the melt's viscosity, which determines the resistance of the screw advancement. Increased resistance slows the screw and prevents the cavity from being filled in the specified injection time. Reduced resistance contrastively leads to over-packing. Switchover in injection time is considered as the least efficient method.

Screw position switchover: Screw position switchover has the advantage of being influenced neither by temperature nor by viscosity. Along with injection time switchover, screw position switchover is an open-looped control strategy using screw position to measure the amount of volumetric filling. However, any leaky nozzle can mislead the machine into switching over before the cavity is filled. Over small mold cavity volume will then cause a slight variation of screw position, thereby leading to over-packing or under-packing.

Hydraulic pressure switchover: Packing the melt in the cavity must be balanced by the hydraulic pressure that drives the screw forward. A rise in such pressure during injection could be applied to detect the switchover timing. It can be discriminated from the screw tip pressure by the pressure drop at the runner system. As the pressure is perceived, the time for compressibility of the melt between the cavity and the screw tip may already delay. Therefore, hydraulic pressure is not an accurate indicator of the volumetric-filling point.

Nozzle pressure switchover: Nozzle pressure or injection pressure means the pressure of the melt in the nozzle. Nozzle pressure switchover is preferred to hydraulic pressure as the compressibility effect of the melt cushion can be avoided. However, the switchover is not without its flaws, that is, the sensors work in such environment can be easily damaged.

Cavity pressure switchover: The cavity pressure curve provides more information about the cavity than the nozzle pressure or the hydraulic pressure does. In fact, the cavity pressure during the cooling period cannot be easily measured by the nozzle senor which is surrounded by the melt all the time. The switchover points here can be determined in two ways: either at fixed cavity pressure or at volumetric-filling point "C" in Fig. 1. While both approaches avoid the problems of over-packing and under-packing, only the switching in latter approach initiates at a volumetric-filling point and completes before the maximum cavity pressure is located.

2. Cavity pressure based grey prediction switchover method

The approach of the switchover point detection from the filling-to-holding stages is adopted to measure the cavity pressure and predict the volumetric-filling point. The volumetric-filling point exhibits a significant abrupt rise in pressure, which can be easily observed by the first derivative of cavity pressure with respect to time. The grey predictor design in this research is based on a GM(1,1) grey model, featured by its light computational burden and common use in grey forecasting [13–15].

Let $P_c^{(0)}$ be the measured original sequence of cavity pressure data:

$$P_c^{(0)} = [P_c(m), P_c(m+1), \ldots, P_c(m+n)] \tag{1}$$

where n is the sample size of the grey predictor, m the time interval, and $P_c(m+n+1)$ represents the cavity pressure value measured at intervals of $m+n+1$. Considering the accumulated generating operation (AGO) on $P_c^{(0)}$, we can attain the first-order AGO sequence $P_c^{(1)}$:

$$P_c^{(1)} = [P_c^{(1)}(m), P_c^{(1)}(m+1), \ldots, P_c^{(1)}(m+n)] \tag{2}$$

where

$$P_c^{(1)}(m+k) = \sum_{i=1}^{k} P_c(m+i) \tag{3}$$

and $k = 1, 2, 3, \ldots, n$. The mean generating sequence is obtained by applying the mean generating operation to $Z^{(1)}$:

$$Z^{(1)} = [Z^{(1)}(m+1), Z^{(1)}(m+2), \ldots, Z^{(1)}(m+n)] \tag{4}$$

where

$$Z^{(1)}(m+k) = \frac{P_c^{(1)}(m+k) + P_c^{(1)}(m+k-1)}{2} \tag{5}$$

and $k = 2, 3, \ldots, n$. The first-order grey differential model, which is also called the GM(1,1) model, can be defined as follows [12]:

$$P_c(m+k) + aZ^{(1)}(m+k) = b, \quad k = 2, 3, \ldots, n. \tag{6}$$

where the coefficients a and b can be calculated by using the least-squares error method:

$$\begin{bmatrix} a \\ b \end{bmatrix} = (B^{\mathrm{T}} B)^{-1} B^{\mathrm{T}} Y \tag{7}$$

$$B = \begin{bmatrix} -Z^{(1)}(m+2) & -Z^{(1)}(m+3) & \cdots & -Z^{(1)}(m+n) \\ 1 & 1 & \cdots & 1 \end{bmatrix}^{\mathrm{T}} \quad (8)$$

where $Y = [P_c(m+2), P_c(m+3), \ldots, P_c(m+n)]$.

In brief, only the $P_c^{(0)}$ sequence is required to generate a GM(1,1) model. $P_c^{(1)}$ can then be constructed using the AGO operator, and $Z^{(1)}$ can be computed from Eq. (4). Coefficients a and b can be calculated through the least-squares error method. Thus, the GM(1,1) model, crucial for grey prediction, is well built.

If combining Eqs. (5) and (6),

$$P_c(m+k) + 0.5a(P_c^{(1)}(m+k) + P_c^{(1)}(m+k-1)) = b \quad (9)$$

or equivalently,

$$P_c(m+k) = \frac{b - aP_c^{(1)}(m+k-1)}{1+0.5a} \quad (10)$$

Hence, given $P_c^{(0)} = [P_c(m), P_c(m+1), P_c(m+2), \ldots, P_c(m+n)]$, Eq. (7) can be applied to generate a and b, and thus the predicted value $\hat{P}_c(m+n+1)$ can be obtained from the following equation:

$$\hat{P}_c(m+n+1) = \frac{b - aP_c^{(1)}(m+n)}{1+0.5a} \quad (11)$$

where the superscript "∧" indicates that the value is a predicted value. Moreover, the prediction error, $\hat{e}(m+n+1)$, can be formulated as:

$$\hat{e}(m+n+1) = \frac{|P_c(m+n+1) - \hat{P}_c(m+n+1)|}{P_c(m+n+1)} \times 100\% \quad (12)$$

The slope in the typical cavity pressure profile changes significantly at a minimum of two points. One is where the melt fronts initially encounter the cavity pressure sensor, and the other is the volumetric-filling point. Notably, the prediction error depends on the cavity pressure's gradient, derived from the first derivative of the raw data sequence $Y = [P_c(m+2), P_c(m+3), \ldots, P_c(m+n)]$. Needless to say, the predicted locations of significant changes in gradient will be markedly inaccurate. Hence, both the prediction error $\hat{e}(m+n+1)$ and the cavity pressure $P_c(m+n+1)$ are used to decide the ideal switchover time in the grey model predictive control system, as shown in Fig. 2. Initially, the cavity pressure signals are measured periodically and the four consequential values, $P_c(k-3)$, $P_c(k-2)$, $P_c(k-1)$, and $P_c(k)$ are used to construct the $P_c^{(0)}$ data sequence. The AGO sequence $P_c^{(1)}$ and the mean generating sequence $Z^{(1)}$ can be generated from Eqs. (2)–(5). Parameters a and b can be calculated from Eqs. (7) and (8). Eqs. (9)–(12) yield the prediction error, $\hat{e}(k+1)$, at time interval $k+1$. The prediction error $\hat{e}(k+1)$ and the measured cavity pressure $P_c(k+1)$ are compared with the threshold value e_{set} and the range P_{set}, respectively, so as to determine whether the ideal switchover time has arrived. If $\hat{e}(k+1)$ exceeds e_{set} and $P_c(k+1)$ is within the range of P_{set}, switching over is decided immediately. Here the threshold e_{set} is set to 50% of the prediction error value at the volumetric-filling point. The range of P_{set} is set from 90 to 110% of the volumetric-filling pressure.

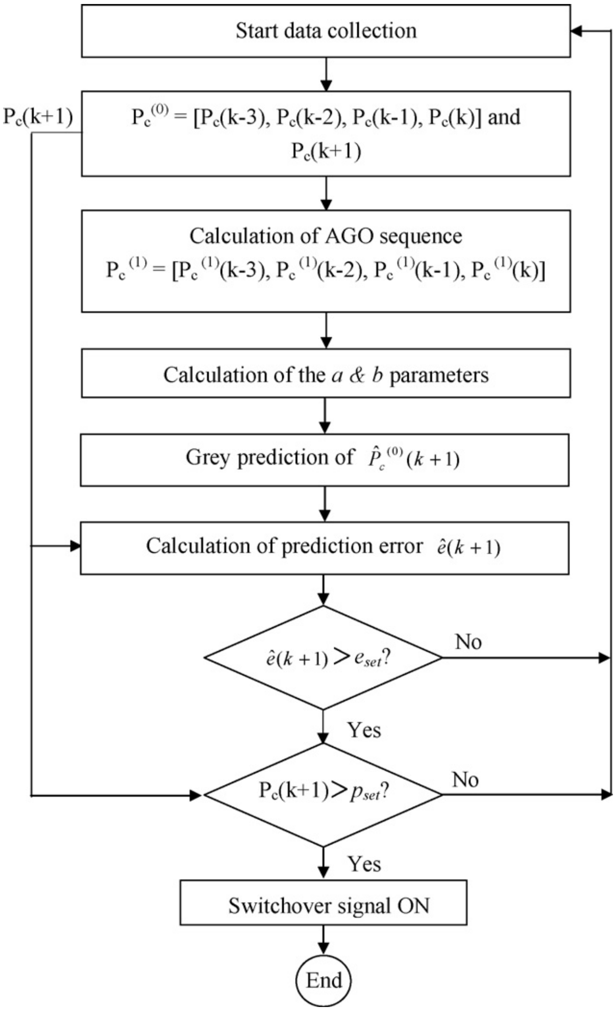

Fig. 2. Flow chart of grey prediction of switchover point.

3. Simulations and experimental tests

The mold cavity is a flat, rectangular piece with dimensions 120 mm × 20 mm × 1.2 mm and edge-gate 6 mm wide. To detect the cavity pressure profile, two Kistler 6157B piezoelectric pressure transducers are directly mounted on the cavity; one is installed near the gate and the other is far from the gate. A k-type temperature sensor is also mounted on the other cavity to ensure that the variation in the mold temperature is within desired range. The experimental platform employs a 40-tonne clamping forced injection-molding machine with a 26 mm diameter injection screw made by the Victor-Taichung Machinery Works Company. The selected plastic materials are PS (Chi-Mei PG-80) and PC (GE plastics Lexan-1130). The molding parameters setting for PS are a constant ram speed of 130 mm/s, 103.5 MPa injection pressure, 88.7 MPa packing pressure, and 1 s packing time with 60 mm/s filling speed limit. During each cycle, the signals profiles measured – including profiles of the internal switchover voltage, the hydraulic pressure, nozzle pressure, cavity pressures, and screw position – are sampled at a high rate via an eight differential-channel analog-to-digital converter. Selecting a high sampling rate is suggested for it ensures a good cavity pressure resolution. The data is managed on a Pentium-III computer, using internally developed code based on LabVIEW 5.0 virtual instruments library and language. Fig. 3 shows the recorded signals for each injection-molding cycle.

3.1. Short shot experiment

The short shot experiment has been conducted to elucidate the trend of collected signal profiles in relation to the melt front behaviors within the cavity. For example, Fig. 3 presents the phenomena involved in the PS's filling the mold cavity, which can be divided into five stages. (a) The melt enters the sprue before reaching the slag well, and the hydraulic pressure and the nozzle pressure both increase steadily. (b) The melt contacts the slag well, where the hydraulic pressure and the nozzle

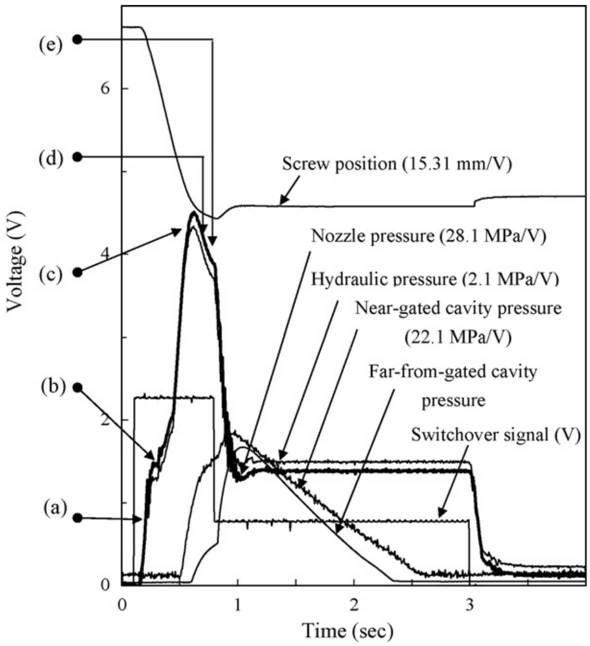

Fig. 3. The signal profiles measured during one injection-molding cycle (materials: PS).

pressure profiles decline because the slag well provides extra volume to the melt. (c) The melt passes through the gate and fills one-third the length of the cavity. When the melt passes through the gate where the cross section is suddenly reduced, both hydraulic and nozzle pressures increase to the peak values. Meanwhile, when the melt has filled one-third the length of the cavity, in which a pressure sensor is installed, the cavity pressure signals appear. (d) The melt travels along four-fifths of the length of the cavity. As the melt continues to fill the cavity, the resistance increases and then causes the near-gate cavity pressure to increase. Also, the hydraulic and nozzle pressures decline to their pre-set filling values. (e) Melts volumetrically fill the cavity and start being compressed, where the gradients of the cavity pressure profiles suddenly change and elevate to their maximal values. However, other pressure profiles do not exhibit such behavior. When shrinkage occurs during holding and cooling process, the cavity pressure profile declines continuously until the gate is sealed.

The pressure profiles in Fig. 3 reveal that the peak hydraulic and nozzle pressures clearly occur when the melt flows through the gate. However, both pressure profiles fail to provide information about the filling behaviors within the cavity. By contrast, the cavity pressure profiles not only yield relatively detailed information, but also are sensitive to the volumetric-filling point. That is, the profiles provide no information to describe the filling behaviors until the melt makes contact with the installed sensors. Thereafter, the peak values are obtained as soon as the melt is compressed. The far-from-gate cavity pressure is smaller than the near-gate pressure due to the pressure loss as the melt attempts to overcome the resistance along the filling path.

Table 1 shows the simulation results of using PC and PS materials at various sensing positions. The results reveal that e_{fill} is smaller than e_{B} for PC, whereas it is just the opposite for PS. It is clear that a smaller switchover range makes the switching over decision more difficult to make, and that the switchover decision range vary according to the process parameter settings and materials. Moreover, e_{fill} is smaller than e_{B} near the gate, but is larger far from the gate. The obtained switchover range of the far-from-gate cavity pressure profile exceeds that of the near-gate pressure. That means, sensing position can significantly affect the switchover range.

Table 1
Simulation results using PC and PS materials at various sensing positions

	PC		PS	
	Near-gate	Far-from-gate	Near-gate	Far-from-gate
$p_{\max}$ (MPa)	35	34	35	28
p_{fill} (MPa)	27.5	10	23	9
e_{B} (MPa)	1.8	1	1.8	0.8
e_{fill} (MPa)	10	4	3.7	4.7
p_{set} (MPa)	27.5	10	23	9
e_{set} (MPa)	0.3–1	0.5–4	0.7–3.7	0.5–4.7

4. Performance evaluation and discussions

No matter the switchover methods using injection time, screw position, or the innovative methods, respectively, employing near-gate and far-from-gate cavity pressure profiles have been experimentally investigated. Each product's weight is derived to compare and contrast the product quality under every method. The PS materials are used in the experimental verification. Twenty samples are collected under each molding condition to ensure sufficient repeatability, and examples of the cavity pressure distribution are shown in Fig. 4. Weights of all samples have been measured without the sprue-runner system before being averaged. Table 2 summarizes the experimental results.

In light of the injection quality, the injection speed and the injection pressure are found to be the most important parameters affecting product's quality during the filling phase. A higher speed or pressure suggests that higher cavity pressure will generate earlier. Increasing the injection speed can raise the maximum pressure and the pressure integral even though the change in the volumetric-filling pressure is insignificant. Increasing the pressure comparatively will boost the volumetric-filling pressure. An over high pressure can further result in over-packing followed by a residual cavity pressure before mold opening. Therefore, holding pressure and holding time seriously affect the injection quality during the holding phase. Poor holding param-

Table 2
Experimental results obtained by the four switchover methods (20 trials)

	Weight (g)		$P_{\max}$ (MPa)		P_{index} (MPa s)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Screw position	2.9065	0.0044	33.98	1.114	37.96	2.438
Injection time	2.9050	0.0053	32.86	1.896	35.26	4.126
Near-gate GM(1,1)	2.9146	0.0029	35.75	0.258	43.37	1.363
Far-from-gate GM(1,1)	2.9132	0.0029	28.93	0.676	29.58	2.245

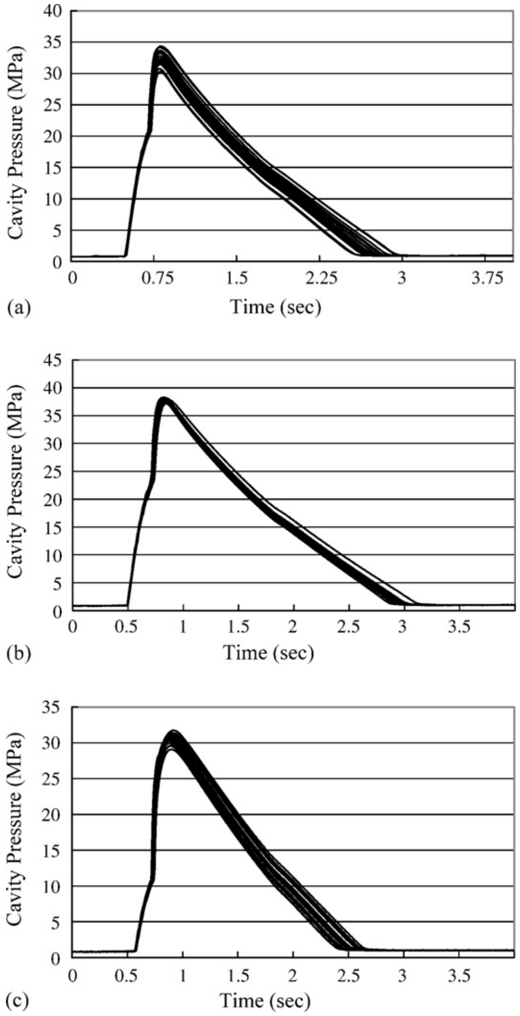

Fig. 4. Twenty trials cavity pressure profiles obtained using: (a) screw position switchover, (b) near-gate GM(1,1) switchover, and (c) far-from-gate GM(1,1) switchover.

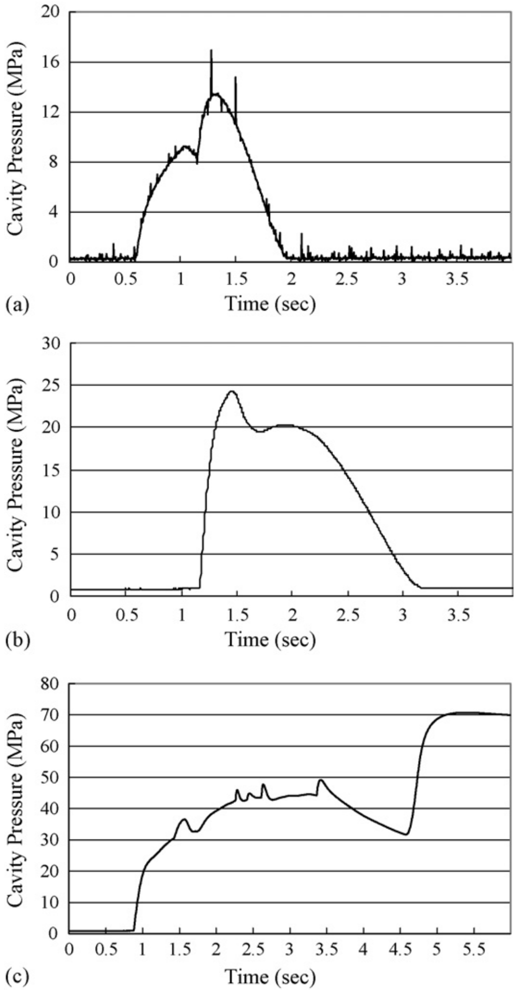

Fig. 5. Switchover failure caused by: (a) signal noise distortion, (b) failing to recognize the volumetric-filling point, and (c) mold deformation.

eter settings make the melt either flow back from the cavity or over-packed near the gate area.

4.1. Possible reasons for switchover failure, and associated constraints

The following factors merit our attention in that they may deteriorate the GM(1,1) grey prediction. (1) Noise appearing in the cavity pressure signal will amplify while passing through the GM(1,1) model. The prediction error and the volumetric-filling pressure may thus be incorrect and then lead to a wrong switchover point, as shown in Fig. 5(a). Therefore, the noise should be effectively filtered out. (2) The injection parameter setting should be appropriate. High-speed and high-pressure parameter settings for thin-walled injection molding produce an insignificant volumetric-filling point and make the switchover point unrecognizable, as shown in Fig. 5(b). Furthermore, a mold deflection, shown in Fig. 5(c), can cause uncontrollable switching over by generating abnormal cavity pressure profiles. (3) The sensor's location can affect the results of switchover. For instance, sensor near the gate can yield an ambiguous volumetric-filling point, so that rough switching over may occur if a low sampling rate is used. When the change of pressure gradient at the switchover point is less significant than that at far-from-gate, it will cause an incorrect switchover or make decision-making impossible. Viewed in this light, the sensor must not to be located too close to the gate especially for thin-walled molding. Moreover, over short duration between the volumetric-filling point and the compression phase will make switching over initiate too late, thus bringing a flash.

5. Conclusions

The innovative grey prediction model, GM(1,1), is adequate for switchover decision-making. The main procedure is to: (1) collect three consecutive cavity pressure data; (2) predict the next value; (3) calculate the prediction error, namely the absolute difference between the prediction value and the measured value; (4) determine whether the cavity pressure is within the p_{set} range as well as the prediction error is within the e_{set} range. If the conditions are positive, the switching over will be activated. Computational simulation of GM(1,1) grey prediction further determines two peaks in the prediction error profile, one at the sensor location and the other at the volumetric-filling point. Varying the sensing location or the parameter settings can change the determined results. An insufficient sampling rate or changing the sensing locations in switching over affects variation in the product quality. It is also found that sensing near-gate less easily determines the switching over point than sensing far-from-gate, although sufficient time is required in the latter case to complete the switching. The method of switching over can considerably affect the distribution of the product's mass, too. Consequently, the innovative grey prediction method yields more reliable and accurate results than other methods. Meanwhile, it can guarantee the product quality as the maximum pressure and its integral are deeply correlated with product's weight.

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