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Research Article

Quality Indexes Design for Online Monitoring Polymer Injection Molding

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Quality control is a crucial issue in the injection molding process with target of obtaining a high yield rate and reducing production cost. Consequently, effective methods for monitoring the injection conditions (e.g., pressure, velocity, and temperature) in real-time and adjusting these conditions adaptively as required to ensure a consistent part quality are essential. This study proposes a quality index based on the clamping force increment during the injection cycle, as determined by four strain gauges attached to the tie bars of the injection molding machine. Also, various quality indexes for online quality monitoring and prediction purposes based on the pressure, viscosity, and energy features extracted from the pressure profiles obtained at the load cell, nozzle, and molding cavity, respectively, are compared. The feasibility of the proposed quality indexes is investigated experimentally for various settings of the barrel temperature, back pressure, and rotational speed of the plasticizing screw. It is shown that all of the quality indexes are correlated with the injection-molded quality and hence provide a feasible basis for the realization of an on-line quality monitoring and control system. Particularly, the tie-bar elongation quality index requires no modification or invasion of the injection molding system or cavity and hence provides a particularly attractive solution for monitoring and controlling the part quality.

1. Introduction

Injection molding is a well-established technique for the mass production of plastic components. With its advantages of low cost, high efficiency, good versatility, and the ability to produce precise and complex components, injection molding is used in many fields nowadays, including electronics, sports goods, automobile components, and optical lenses. However, ensuring a consistent quality of injection-molded parts is highly challenging since the melt quality is readily affected by variations in the raw material properties, plasticizing and injection molding conditions, and machine motion characteristics. Importantly, even though current all-electric driven injection molding machines provide an extremely precise motion control, even very small variations in the raw material properties and/or plasticizing and injection molding conditions may result in significant variations in the molding quality. Furthermore, current inspection techniques focus mainly on the quality (e.g., geometrical dimensions and surface defects) of the final molded components. In other words, while they can confirm that the molded components satisfy the design criteria, in the event that they do not, they provide no clues as to why this is the case. Hence, such methods not only are time-consuming and expensive, but are also of only limited use in adjusting the injection molding conditions adaptively in such a way as to improve the consistency of the molding quality. Consequently, more effective methods for performing the on-line monitoring and control of the part quality are urgently required.

2. Literature Review

The injection molding process has traditionally been regarded as something of a "black box" since the flow behavior of the molten polymer within the cavity is unseen. Consequently, the process parameters are generally controlled through either statistical methods or simply the

personal experience of the operator. The plasticizing process in the injection molding procedure is usually performed using a reciprocating single screw that conveys, melts, and meters the molten polymer at a constant rotational speed. However, significant variations in the plasticizing quality are often observed, even when the screw motion is precisely controlled. Amano and Utsugi investigated the effects of the various injection molding parameters on the plasticizing quality and found that the quality was dominated by the shear heat in the metering zone and the absorption of the heat energy in the compression and feeding zones, which is determined primarily by the residual time of the molten polymer within the barrel [2–4]. In general, a long screw length is essential to ensure sufficient time for the raw materials to be properly heated as they pass through the feeding and compression zones, while a high rotational speed of the feed screw is necessary to expand the temperature variation of the molten polymer. Latif and Saidpour investigated the effect of the plasticizing parameters on the melt quality of PP, HDPE, and LLDPE polymer materials blended with master one percent batch colored pigment separately and found that a high back pressure and high screw rotational speed enhanced the shear rate of the molten polymer and improved the plasticization quality as a result [5]. Similar findings were also reported in the later studies of Tanoue et al. and Zhou et al., respectively [6, 7]. Khoshooee and Coates used the Taguchi robust design method to examine the effects of the back pressure, screw rotational speed, barrel temperature, screw retreat position, and speed on the plasticization quality of acrylonitrile butadiene styrene (ABS) materials [8]. The results showed that the melt quality was dominated by the barrel temperature and back pressure at slow rotational speeds of the screw. Jin et al. investigated the solid bed breakup behavior of a standard reciprocating injection screw and found that the breakage was determined mainly by the temperature and pressure of the molten polymer [9]. Hence, a careful control of the process parameters during the plasticizing process is essential to ensure the quality of the final molded components.

Modern all-electric driven injection molding machines provide highly precise and stable motion control. Moreover, the use of grey prediction methods to optimize the filling-to-packing switchover point can further enhance the quality consistency of the molded products [10]. However, minor changes in the melt quality inevitably occur during the injection molding process, and these variations cannot be entirely compensated by even the most precise motion control of the machine [11]. Even very small variations in the molten polymer quality may cause significant changes in the mechanical properties and dimensions of the molded part [12, 13]. As a result, it is essential that the melt quality be monitored in some way during the molding process such that the processing parameters can be modified if required. Accordingly, various p-V-T (pressure-volume-temperature) measuring methods have been proposed for predicting the melt quality [14–17]. Many studies have confirmed that an effective control of the p-V-T path of the molten polymer during the injection molding process improves the quality and consistency of the final product [18–21]. Wang and Mao showed that the injection molding quality is determined mainly by the pressure and temperature conditions [22]. However, in practical online quality inspection and motion control systems, the pressure signal is generally preferred since the response time is relatively quicker than that of the temperature signal [23–28].

The quality and reproducibility of injection molded components are highly correlated with the flow resistance (i.e., viscosity) of the molten polymer. However, the viscosity is traditionally measured off-line using a rheometer, and hence the measurement results are of little value in tuning the injection molding parameters adaptively in response to subtle changes in the melt quality. Hence, Gornik proposed an in-machine melt quality measurement system, in which the volumetric flow rate of the molten polymer passing through the nozzle in 10 minutes was detected using a special sensor installed within the nozzle [29]. The author additionally proposed a torque rheometer for online viscosity estimation based on the ratio of the energy consumption to the metering volume during the plasticizing stage. Aho and Syrjälä used a slit die equipped with pressure sensors to estimate the melt viscosity by measuring the ratio of the pressure gradient within the die to the volumetric flow rate of the molten polymer passing through it [30]. Kruppa et al. presented a feedback control method for calculating the viscosity of the molten polymer based on the detected nozzle pressure and temperature [31]. Asadizanjani and Gordon developed a multivariate sensor for controlling the melt quality based on pressure, temperature, and velocity measurements of the molten polymer [32, 33]. Montgomery and Gallo found that the change of the cavity pressure during the cavity filling stage ($\Delta P/\Delta t$) is proportional to the melt viscosity and hence provides a feasible means of predicting the part quality [34]. Lin et al. designed a pressure sensor bushing mounted around the nozzle for the online estimation of the molten polymer viscosity [35]. Chen et al. proposed an online melt quality monitoring system based on four quality indexes (i.e., the peak pressure, pressure gradient, viscosity index, and energy index) extracted from the signals collected from three pressure sensors mounted in the nozzle, runner, and cavity, respectively [36]. These quality indexes provide a convenient and effective means of monitoring shot-by-shot variations in the melt quality during continuous injection molding processes. As to the present study, we further proposed an online part quality inspection method based on quality indexes, in particular, a new quality index based on the clamping force increment during the injection cycle, as determined by four strain gauges attached to the tie bars of the injection molding machine. The tie-bar elongation quality index requires no modification or invasion of the injection molding system or cavity and hence provides a particularly attractive solution for monitoring and controlling the part weight quality.

During the filling phase of the injection molding process, molten polymer flows into the cavity under high temperature and pressure conditions. As the cavity fills, the pressure gradually increases. At the moment the voids in the cavity become completely full, the polymer material undergoes an instantaneous compression effect, which causes a sudden

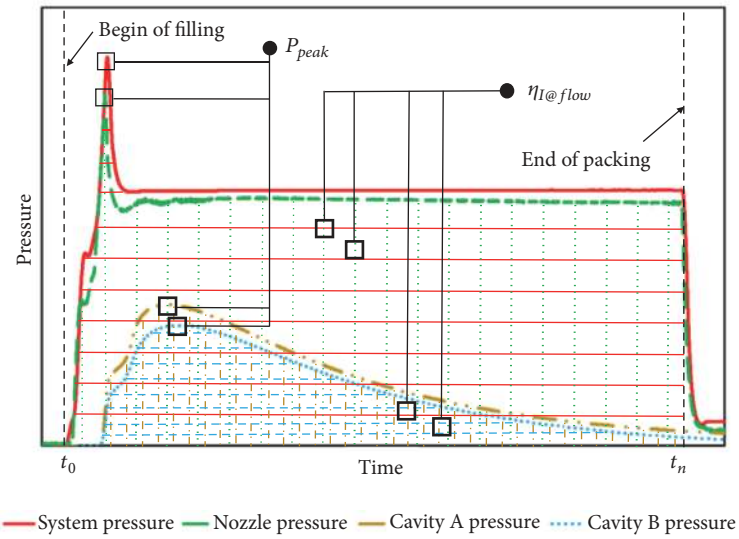

Figure 1: Peak pressure and viscosity indexes.

rise of the cavity pressure and a corresponding separation of the mold. Based on this observation, Chen et al. proposed a method for controlling the filling-to-packing switchover point by measuring changes in the tie-bar elongation profile using strain gauges attached to the tie bar structures [24, 37]. Yin et al. similarly presented a method for minimizing warpage in the injection molding process by optimizing the clamping force using a backpropagation neural network and a genetic algorithm [38]. Huang et al. confirmed that a proper setting of the clamping force is essential to enhance the quality and consistency of injection molded parts [39]. Zhao et al. developed a methodology based on ultrasonic technology to *in situ* detect clamping force [40, 41], and the advantages are simple, practical, and nondestructive.

In summary, current injection molding quality estimation methods generally exploit the signals obtained from pressure sensors located in or near the molding cavity. Such methods provide an effective approach for estimating the melt quality and tuning the processing conditions accordingly. However, they incur an additional cost in procuring the sensors and increase the time and expense of the mold setup process. Furthermore, an extremely precise positioning of the sensors is essential to prevent damage to the component during the molding process. Accordingly, the present study not only proposes three quality indexes based on the peak pressure, viscosity, and energy features extracted from the load cell, nozzle, and cavity pressure profiles, respectively, but also proposes an additional quality index based on the change in the clamping force during the injection cycle, as determined by four strain gauges mounted on the tie-bar surfaces. The feasibility of the various quality indexes for estimating the part quality is evaluated experimentally for various settings of the barrel temperature, back pressure, and rotational speed of the plasticizing screw, respectively.

3. Derivation of Quality Indexes

Figure 1 shows the pressure profiles detected by four sensors located at the load cell, nozzle, and two cavities of the injection mold, respectively, in the injection molding process. For each pressure profile, the peak pressure index, P_{peak}, indicates the maximum absolute pressure detected by the corresponding sensor during the filling, packing, and holding stages. In general, molten polymers with a higher viscosity have a relatively larger flow resistance and hence require a greater force to accomplish mold filling. According to Hele–Shaw theory, the flow behavior of the molten polymer in the molding cavity is analogous to that of viscous fluid flow within a slit [39]. Thus, the flow velocity in the x-direction varies as a function of the viscosity μ, the pressure drop ΔP over a flow distance L, and the width w and height h of the cavity [35], i.e.,

$$v_x(z) = \frac{1}{\mu}\frac{h^2}{8}\frac{\Delta P}{L}\left[1 - \left(\frac{2z}{h}\right)^2\right]. \quad (1)$$

As shown in Eq. (1), the flow velocity profile is parabolic over the cavity height (i.e., the molded component thickness), and hence the maximum velocity, $v_{x,Max} = (h^2/8\mu)(\Delta P/L)$, appears in the mid-height position of the cavity. Averaging the flow velocity along the height direction, the Hele-Shaw flow formulation can be further derived as

$$v_{x,avg} = \frac{1}{h}\int_{-h/2}^{h/2} v_x(z)\,dz = \frac{h^2}{12\mu}\frac{\triangle P}{L}, \quad (2)$$

$$Q = v_{x,avg} \bullet hw = \frac{h^3 w}{12\mu}\frac{\triangle P}{L}, \quad (3)$$

where Q is the volumetric flow rate.

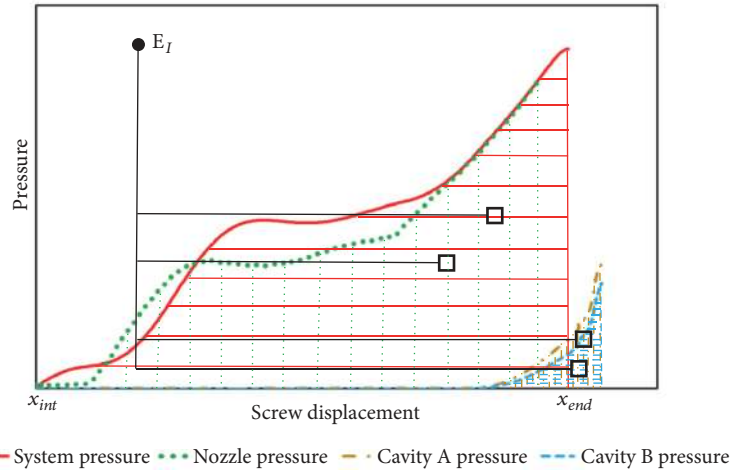

Figure 2: Energy index.

Furthermore, the instantaneous viscosity can be expressed as

$$\mu = \frac{h^2}{12L^2} \bullet \Delta P \bullet \Delta t. \tag{4}$$

In other words, the instantaneous viscosity of the molten polymer is directly proportional to the cavity height and pressure drop, ΔP, multiplied by a short time duration, Δt, and is inversely proportional to the flow distance L along the flow path during time Δt. For a given set of processing parameters (e.g., injection speed, holding pressure, and holding time), the injected volume of molten polymer in each shot is theoretically constant, and hence the flow distance L can also be taken as a constant for a uniform thickness h of the molded specimen.

The instantaneous viscosity given in Eq. (4) provides an indication of the flow resistance experienced by the molten polymer over a particular filling and holding distance. Hence, the present study proposes a new quality index designated as the melt viscosity index, $\eta_{I@flow}$, defined as

$$\eta_{I@flow} = C \int_{t_o}^{t_n} P(t)\, dt, \tag{5}$$

where C is a constant with a value which depends on the geometry of the mold cavity; $P(t)$ is the pressure signal detected over time by the corresponding sensor; and t_o and t_n represent the beginning and end times of the filling and holding process, respectively.

The mechanical energy consumed by the reciprocating screw in each shot is proportional to the viscosity of the molten polymer [29]. Accordingly, the present study proposes a further quality index, referred to as the energy index, E_I, which quantifies the energy consumed per shot by integrating the pressure profile with respect to the screw position (see Figure 2), i.e.,

$$E_I = A_{screw} \int_{x_{int}}^{x_{end}} P(x) \bullet dx, \tag{6}$$

where x_{int} is the initial position of the screw and x_{end} is the position of the screw at the end of the filling and holding process.

In injection molding systems, press-on strain sensors enclosed in a stainless steel protective foil and wrapped tightly around the cylindrical surface of the tie bars can be used to measure the surface strain directly at the mounting location in a manner similar to that of bonded tie-bar strain sensors used to measure the clamping force. In particular, the signals obtained from the press-on strain sensors yield the following measurements [38]:

$$\varepsilon_i = \frac{F_i}{EA}, \tag{7}$$

$$F_i = \frac{EA\varepsilon_i}{10^6}, \tag{8}$$

$$F_\Sigma = \sum_{i=1}^{n} F_i, \tag{9}$$

where ε_i is the strain of the i^{th} tie bar in micrometers; E is Young's modulus of the tie bar material (i.e., 210,000 N/mm^2 for the injection molding machine used in the present study); A is the cross-sectional area of the tie bars in squared millimeters; F_i and F_Σ are the clamping force of the i^{th} tie bar and the total clamping force (in kN), respectively, and n is the total number of tie bars. In Eq. (8), the item 10^6 in the denominator is used for the unit of clamping force to be kN.

Mold separation typically takes place during the period from the end of the filling stage to the end of the packing/holding stage and has a magnitude dependent on the cavity size and raw materials employed. While mold separation can often be tolerated within a limited range (e.g., 75 μm), larger separations result in flash and other undesirable quality defects. Hence, the clamping force must be carefully controlled. In practice, the mold separation effect induces an additional extension of the tie bars and hence increases the clamping force beyond the nominal value specified in

Table 1: Abbreviations of quality indexes.

Abbreviation	Definition
$P_{peak,S}$	Peak pressure index extracted from system pressure
$P_{peak,N}$	Peak pressure index extracted from nozzle pressure
$P_{peak,CavityA/B}$	Peak pressure index extracted from cavity pressure at cavity A/B
$\eta_{I@flow,S}$	Melt viscosity index extracted from system pressure
$\eta_{I@flow,N}$	Melt viscosity index extracted from nozzle pressure
$\eta_{I@flow,CavityA/B}$	Melt viscosity index extracted from cavity pressure at cavity A/B
$E_{I,S}$	Energy index extracted from system pressure
$E_{I,N}$	Energy index extracted from nozzle pressure
$E_{I,CavityA/B}$	Energy index extracted from cavity pressure at cavity A/B
$F_{\Sigma,increment}$	Total clamping force increment extracted from clamping force
$F_{\Sigma,increment@SGa}$	Clamping force increment of tie-bar A extracted from the strain gauge mounted on tie-bar A
t_{feeding}	Feeding time at the plasticization stage

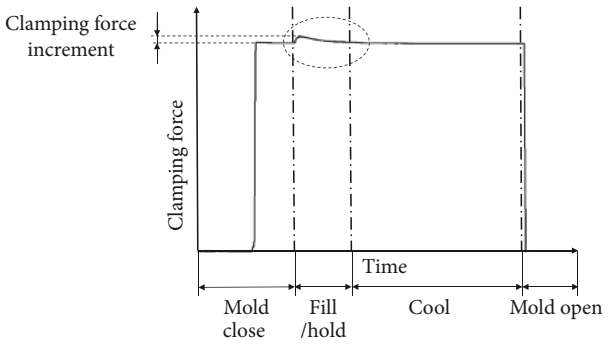

Figure 3: Clamping force increment index.

Figure 4: Photograph of experimental setup.

the design process. As shown in Figure 3, the clamping force increases rapidly toward the nominal design value as the filling, packing, and holding process proceeds and then suddenly spikes at the moment the cavity becomes completely full and the polymer resin undergoes compression. The increment in the clamping force, $F_{\Sigma,increment}$, is hence defined as an additional quality index in the present study, where it represents a measure of the degree of the mold filled with molten polymer from the injection unit. The description of quality indexes is shown in Table 1.

The quality of continuous injection molding processes is generally evaluated by comparing the part qualities of successive components. Accordingly, in the present study, the validity of the various pressure-based and force-based quality indexes described above was evaluated by examining the correlation between the quality indexes obtained at each of the monitoring positions (i.e., the load cell, nozzle, cavities, and tie bars) and the associated part quality, as determined by the thickness and weight of the molded component. In other words, for each quality index, the correlation index, r, was computed as

$$r = \frac{\sum (x - \overline{x})(y - \overline{y})}{\sqrt{\sum (x - \overline{x})^2}\sqrt{\sum (y - \overline{y})^2}}, \tag{10}$$

Table 2: Correlation index categories [1].

Strength	Correlation index
Strong	$\lvert r\rvert \geqq 0.7$
Middle	$0.7 > \lvert r\rvert \geqq 0.3$
Weak	$0.3 > \lvert r\rvert$

where x and y are quality indicators, respectively. Depending on the value obtained for the correlation index, the degree of correlation between the quality index and the melt viscosity was classified as "strong," "medium," or "weak," as shown in Table 2.

4. Experimental Setup

Figure 4 shows the general layout of the proposed online quality inspection system based on the four quality indexes described above. The experimental trials considered a dumbbell-shaped specimen with a length of 125 mm, a central width of 13 mm, an end width of 19 mm, and a thickness of 1.2 mm (Figure 5). The experiments were performed using two different ABS materials (both produced by Chi-Mei Corporation, Taiwan), namely, PA756 and PA756H. As shown in Table 3, the two materials have the same

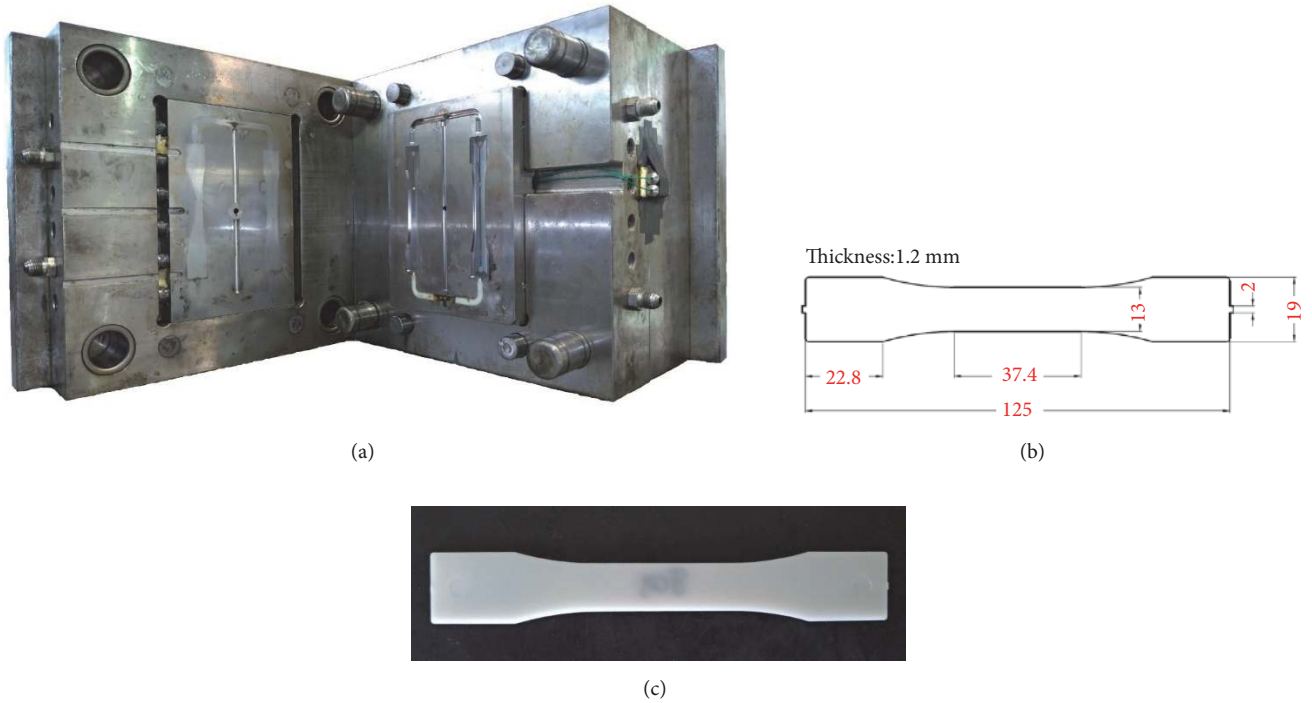

Figure 5: (a) Photograph of dual-cavity injection mold, (b) geometrical dimensions of dumbbell specimen, and (c) photograph of injection-molded part.

Table 3: Material properties and recommended processing conditions.

Property	ASTM test method	Materials	
		PA-756	PA-756H
Melt flow index (g/10min)	D1238	4.4	8
Tensile strength (MPa)	D638	48	40
Density (g/cm^3)	D792	1.05	
Hardness (R scale)	D785	115	
Processing conditions			
Mold Temp. (°C)	40-80	Solid. Temp. (°C)	120
Melt Temp. (°C)	180-230	Eject. Temp. (°C)	100

Table 4: Machine specification.

FANUC Roboshot S-2000i100B	Specification	Unit
Injection unit	Screw diameter (mm)	28
	Injection stroke (mm)	95
	Injection pressure (MPa)	240
	Injection speed (mm/s)	330
Clamping unit	Clamping force (kN)	1000

recommended processing conditions. However, the melt flow index (MFI) of PA756 is lower than that of PA756H. In other words, PA756 has a higher viscosity than PA756H under the same injection conditions. The injection molding trials were performed using an all-electric injection molding machine (ROBOSHOT S-2000i100B, FANUC, Japan) with the specification shown in Table 4.

As shown in Figures 6 and 7, the measuring system consisted of four pressure sensors located at the load cell, nozzle, and two cavities of the dumbbell molding chamber (CP_a and $CP_)$, respectively, and four strain gauge sensors (SG_a, SG_b, SG_c, and SG_d) attached to the four tie bars of the injection molding machine, respectively. The specifications of the various sensors are listed in Table 5. For each experimental

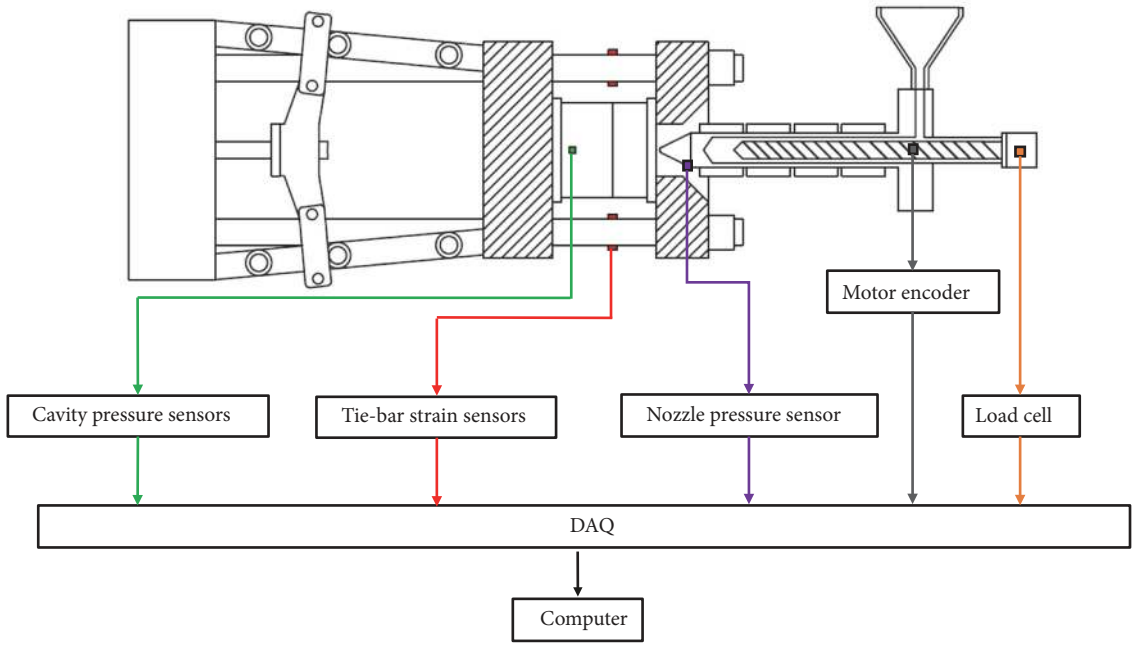

Figure 6: Schematic illustration of injection molding quality monitoring system.

Table 5: Sensor specifications.

Sensor	Supplier	Type
Nozzle pressure sensor	Kistler	9247A
Cavity pressure Sensor	Kistler	6159A
Tie-bar strain sensor	GEFRAN	GE1029
DAQ card	National Instruments	USB-6343

Table 6: Process parameter settings for varied plasticizing parameters experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing time (s)	5
Injection speed (mm/s)	90	Cooling time (s)	15
V/P switch (mm)	15	Mold temperature (°C)	60
Packing pressure (MPa)	105	Clamping force (kN)	600
Varied parameters			
Barrel temperature (°C)		205, *210*, 215, 220	
Back pressure (MPa)		5, *10*, 15, 20	
Screw rotational speed (rpm)		50, *100*, 150, 200	

Note: the italic letters act as fixed parameters as the one of them performs.

trial, the molding quality was evaluated by measuring the component weight and geometrical dimensions at points A_1, A_2, B_1, and B_2 (see Figure 7).

5. Results and Discussion

5.1. Effects of Melt Quality Fluctuations on Molded Part Quality. Injection molding experiments were performed to examine the effects of the three main processing parameters, namely, the barrel temperature, back pressure, and screw rotational speed, on the part quality (as determined by the part weight and thickness). Figure 8 shows the average part weight and average part thickness as measured over 30 continuous shots performed using PA756 as the raw material and various values of the three processing parameters. The parameter settings are listed in Table 6. For all values of the barrel temperature, back pressure, and screw rotational speed, a high correlation ($r = 0.99$) exists between the part thickness and the part weight. Therefore, the part weight can be regarded as a feasible indicator of the molded part quality.

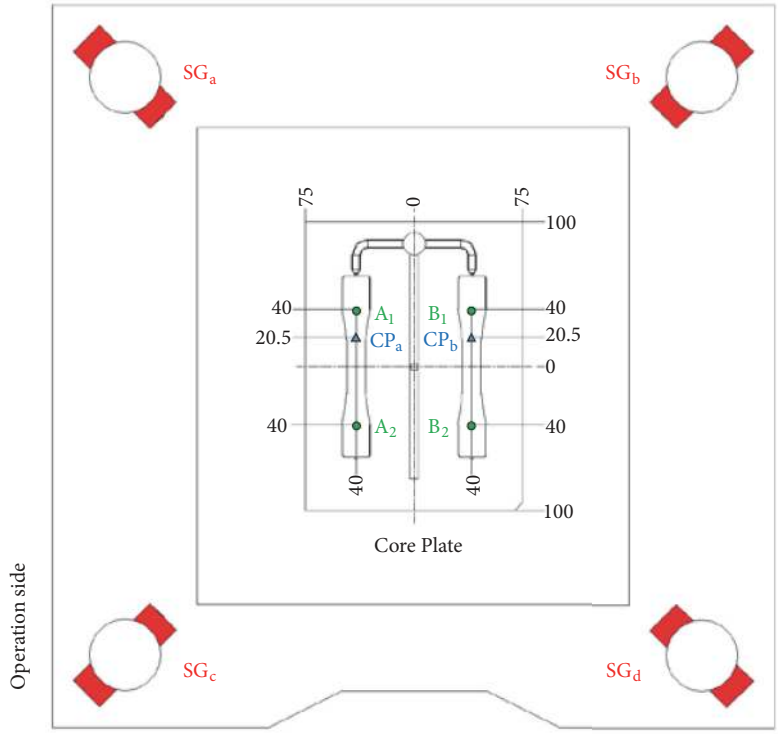

Figure 7: Detailed arrangement of cavity sensors (CP_a – CP_b) and strain gauge sensors (SG_a – SG_d).

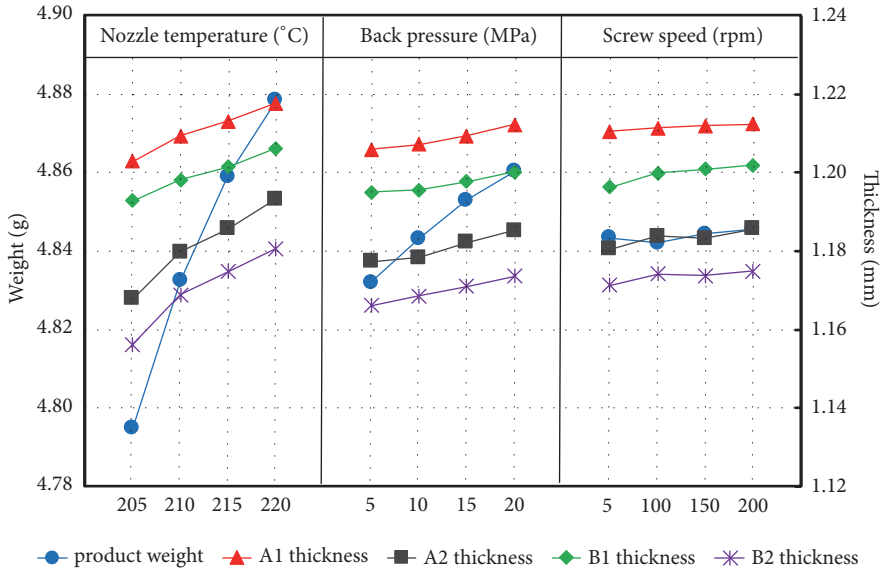

Figure 8: Variation of part weight and thickness for various plasticizing parameters.

5.1.1. Barrel Temperature. Table 7 shows the processing parameters used to investigate the effect of the barrel temperature (205, 210, 215, and 220°C) on the flow ability of the molten polymer during the injection molding process. Figure 9 shows the corresponding results obtained for the four quality indexes and the molded part weight. It is seen in Figures 9(a), 9(c), and 9(e) that the peak pressure, viscosity, and energy indexes derived from the load cell and nozzle pressure profiles reduce with an increasing barrel temperature. A higher barrel temperature reduces the viscosity of the molten polymer and therefore reduces the pressure required to drive the resin into the mold. As a result, the energy consumption also reduces. As the molten polymer leaves the nozzle and flows through the runner into the cavity, its

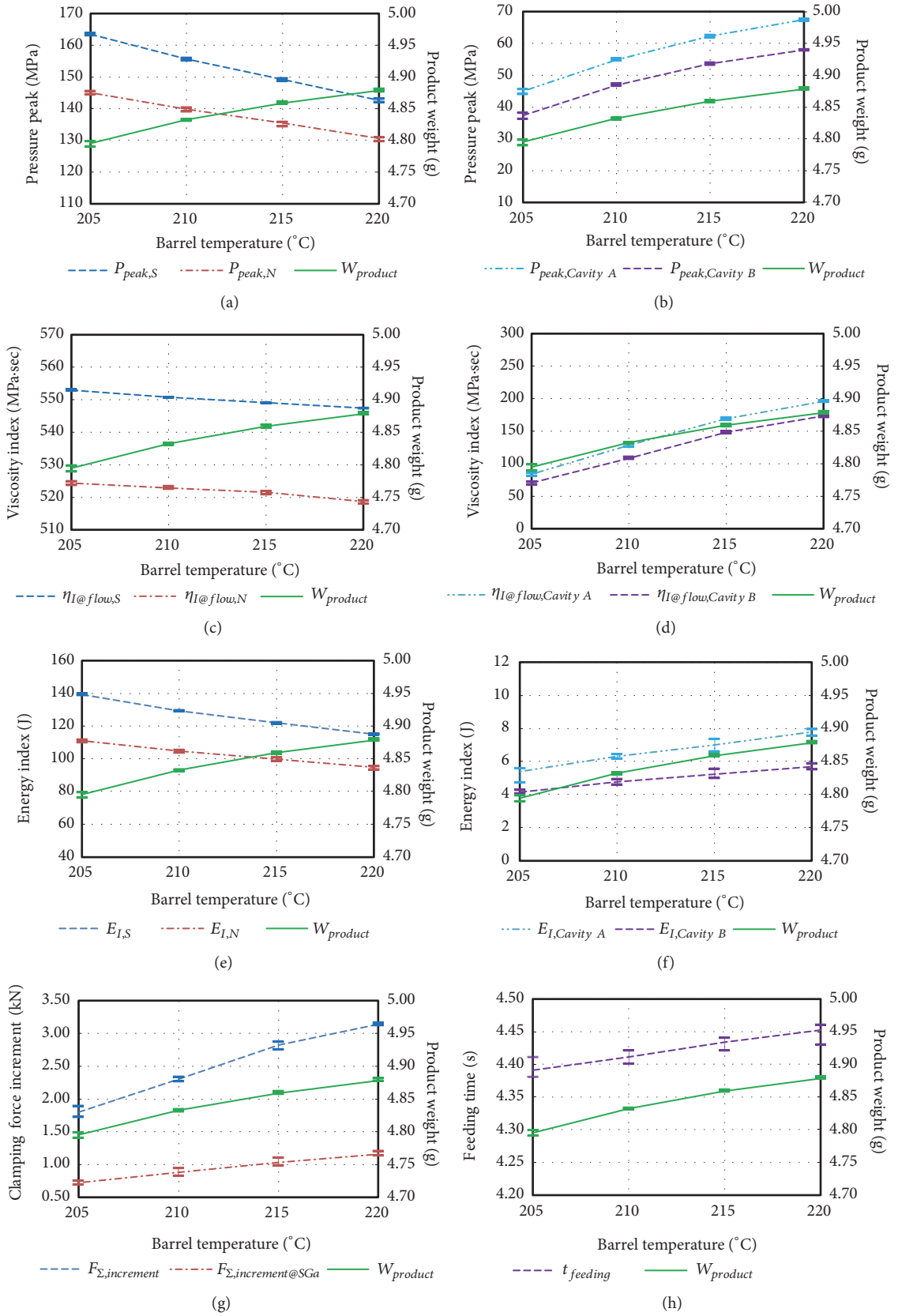

Figure 9: Variation of quality indexes and product weight with barrel temperature.

Table 7: Process parameter settings for varied barrel temperature experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing pressure (MPa)	105
Back pressure (MPa)	10	Packing time (s)	5
Screw rotational speed (rpm)	100	Cooling time (s)	15
Injection speed (mm/s)	90	Mold temperature (°C)	60
V/P switch (mm)	15	Clamping force (kN)	600
Varied parameter			
Barrel temperature (°C)		205, 210, 215, 220	

Table 8: Process parameter settings for varied back pressure experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing pressure (MPa)	105
Barrel temperature (°C)	210	Packing time (s)	5
Screw rotational speed (rpm)	100	Cooling time (s)	15
Injection speed (mm/s)	90	Mold temperature (°C)	60
V/P switch (mm)	15	Clamping force (kN)	600
Varied parameter			
Back pressure (MPa)		5, 10, 15, 20	

Table 9: Process parameter settings for varied screw rotational speed experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing pressure (MPa)	105
Barrel temperature (°C)	210	Packing time (s)	5
Back pressure (MPa)	10	Cooling time (s)	15
Injection speed (mm/s)	90	Mold temperature (°C)	60
V/P switch (mm)	15	Clamping force (kN)	600
Varied parameter			
Screw rotational speed (rpm)		50, 100, 150, 200	

flow and compressive abilities increase. Moreover, the gate-frozen time is delayed with an increasing barrel temperature. Consequently, more molten polymer is forced into the cavity, and thus the peak cavity pressure and part weight increase, as shown in Figures 9(b) and 9(d), respectively. The energy consumption also increases, as shown in Figure 9(f). The higher cavity pressure at higher barrel temperatures increases the mold separation effect, and hence the clamping force increment detected by the tie-bar elongation sensors also increases, as shown in Figure 9(g). Finally, Figure 9(h) shows that the screw feeding time increases by around 0.06 s as the barrel temperature increases from 205 to 220°C.

5.1.2. Back Pressure. Table 8 shows the processing parameters used to investigate the effect of the back pressure (5, 10, 15, and 20 MPa) on the flow ability of the molten polymer during the injection molding process. Figure 10 shows the corresponding results obtained for the four quality indexes and molded part weight, respectively. It is seen in Figures 10(a)–10(f) that the peak pressure index, viscosity index, and energy index all increase with an increasing back pressure. A higher back pressure results in a greater density and viscosity of the molten polymer and therefore increases the pressure required to drive the resin into the mold. As a result, the energy consumption also increases. As the molten polymer leaves the nozzle and flows through the runner into the cavity, the varying back pressure does not change the gate-frozen time. However, the greater amount of molten polymer injected in the filling stage leads to an increased part weight, as shown in Figure 10(f). Furthermore, the greater cavity pressure induced under a higher back pressure enhances the mold separation effect and therefore increases the clamping force increment, as shown in Figure 10(g). A higher back pressure prolongs the screw retreating time in the plasticizing stage. Hence, the screw feeding time increases by almost 1.1 s as the back pressure is increased from 5 to 20 MPa, as shown in Figure 10(h).

5.1.3. Screw Rotational Speed. The effect of the shear rate on the quality of the molten polymer was investigated by performing injection tests with screw rotational speeds of 50, 100, 150, and 200 rpm, respectively. The remaining processing parameters were set as shown in Table 9. Figure 11 shows the corresponding results for the four quality indexes and molded part weight, respectively. In general, the results show that the peak pressure, viscosity, and energy indexes which are obtained from the system, nozzle, and cavity pressure profiles vary only very slightly with the screw rotational speed

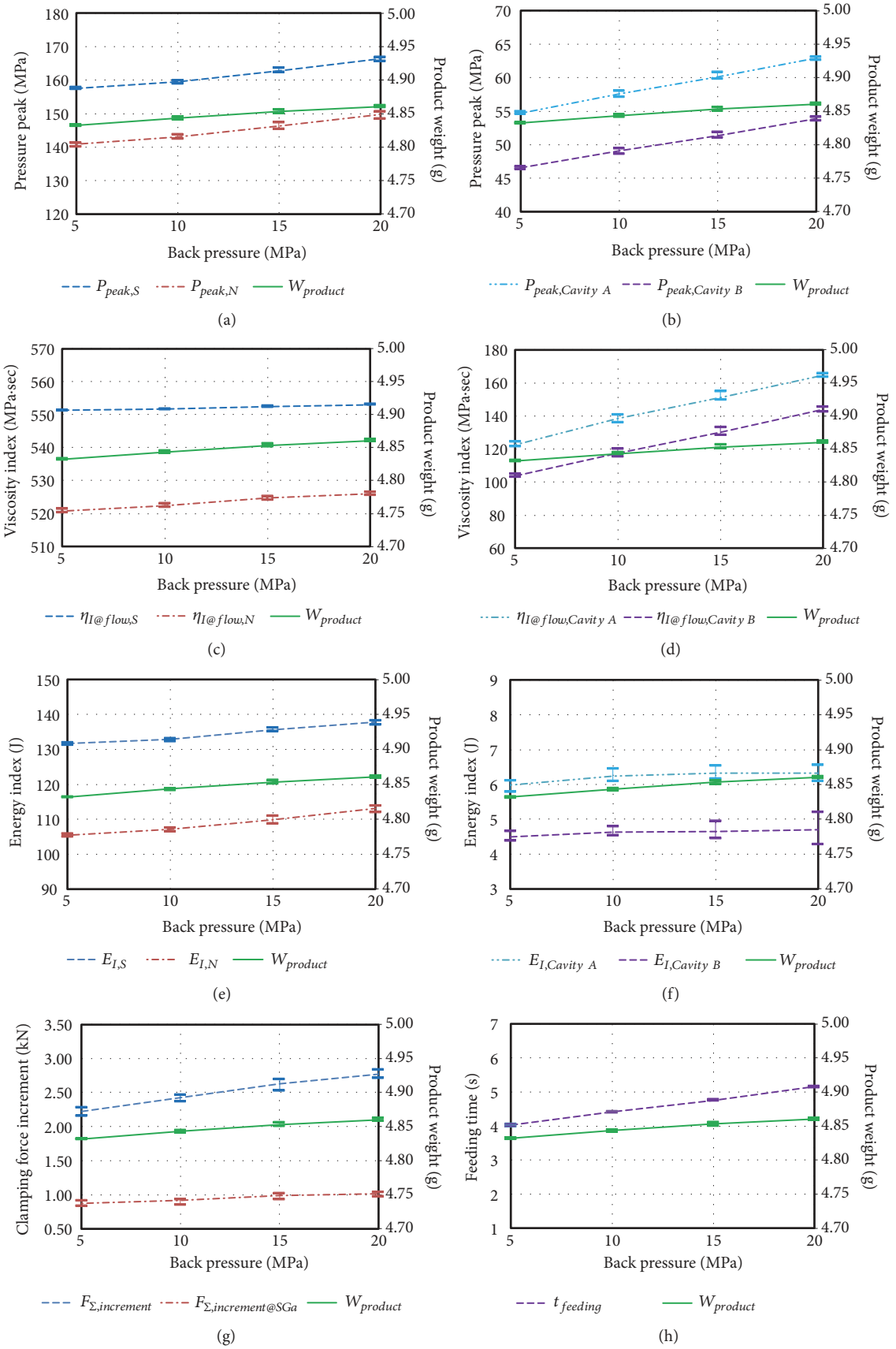

Figure 10: Variation of quality indexes and product weight with back pressure.

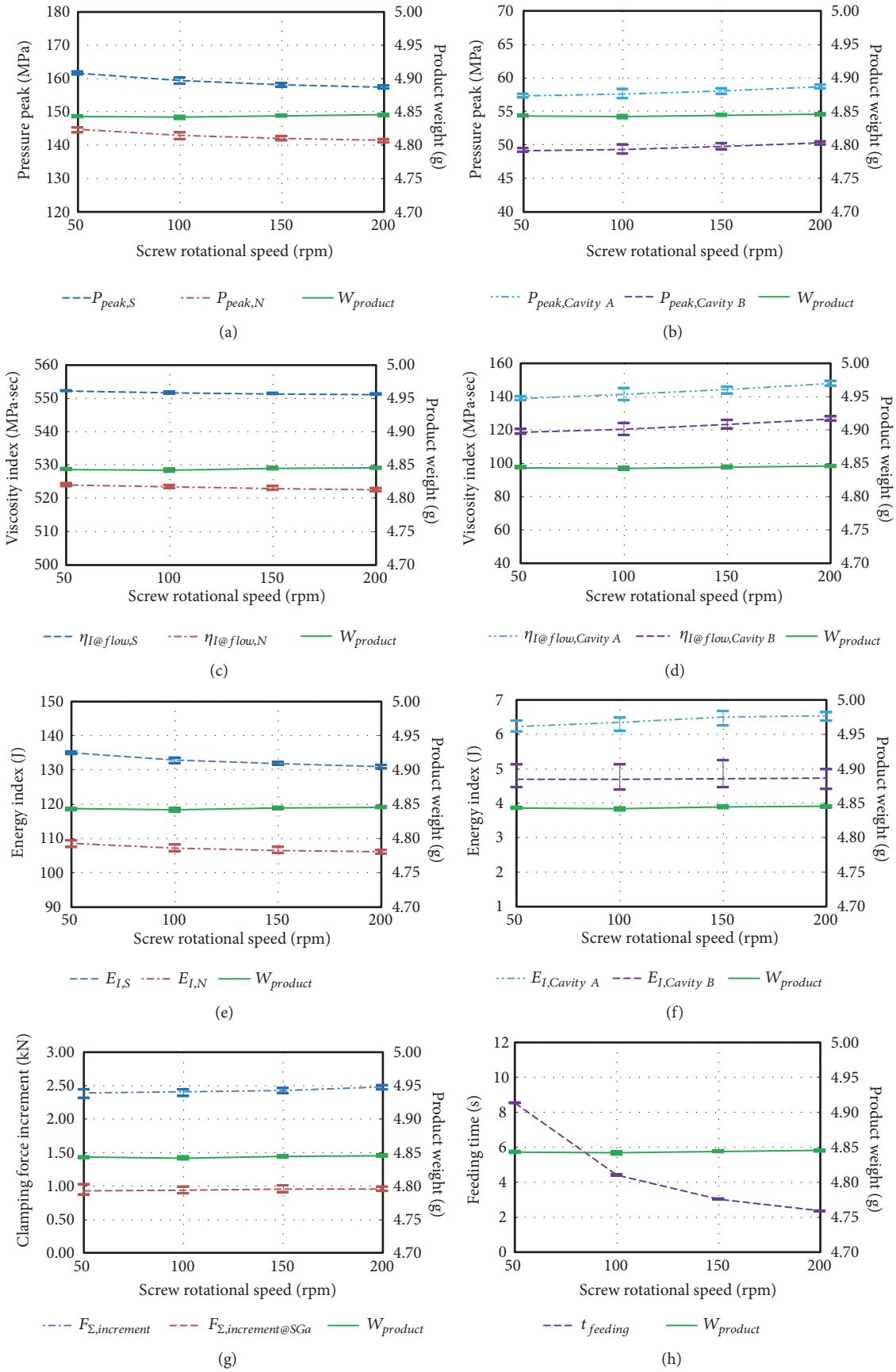

Figure 11: Variation of quality indexes and product weight with screw rotational speed.

Table 10: Process parameter settings for shot-by-shot melt viscosity fluctuation experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing pressure (MPa)	105
Barrel temperature (˚C)	210	Packing time (s)	5
Back pressure (MPa)	10	Cooling time (s)	15
Injection speed (mm/s)	90	Mold temperature (˚C)	60
screw rotational speed (rpm)	100	Clamping force (kN)	600
V/P switch (mm)	15		
Varying parameter (Blended materials)			
% of PA756/% of PA756H	100/0, 80/20, 60/40, 40/60, 20/80, 0/100		

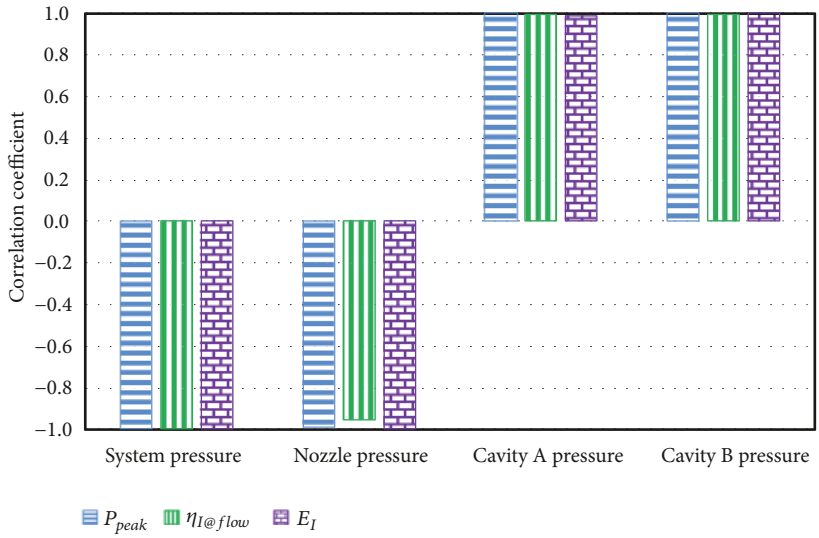

Figure 12: Correlation between pressure-based quality indexes and product weight for various barrel temperatures.

(see Figures 11(a)–11(f)). However, the part weight increases slightly as the screw rotational speed increases. Consequently, the clamping force increment also increases slightly, as shown in Figure 11(g). A higher screw rotational speed shortens the screw retreating time in the plasticizing stage. Consequently, the screw feeding time reduces by approximately 6.2 s as the screw rotational speed is increased from 50 to 200 rpm, as shown in Figure 11(h).

5.2. Correlation between Quality Indexes and Part Quality. As described in the previous section, the present study considered four different quality indexes, namely, the peak pressure, the viscosity, the energy, and the clamping force increment. Moreover, the first three indexes were monitored at four different positions, namely, the load cell of the injection molding system, the nozzle, and the two cavities of the mold die. The correlation between the index values and the quality (i.e., weight) of the injection-molded components was investigated for each of the processing conditions shown in Tables 7~9. For each experimental setting, 30 injection tests were performed using PA756 as the raw material. The correlation values obtained using Eq. (10) for each experimental setting were then averaged over the 30 samples to obtain a representative value for each index. Figures 12–14 show the corresponding results obtained for different barrel temperatures, back pressures, and screw rotational speeds, respectively. The results presented in Figure 12 confirm that the pressure-derived quality indexes are all highly correlated with the part quality for all values of the barrel temperature (i.e., r = -0.95~-1.00 for the load cell and nozzle indexes and r = 0.99~1.00 for the cavity indexes). For the experiments performed with different back pressures, the peak pressure, viscosity, and energy indexes present similarly high correlation values (r = 0.92~1.00), as shown in Figure 13. Finally, for the experiments performed with different screw rotational speeds, the peak pressure and viscosity indexes extracted from the load cell and nozzle pressure profiles exhibit a medium correlation with the part quality (r = -0.61~-0.77) and while those extracted from the cavity pressure profiles have a strong correlation with the part quality (r = 0.73~0.99) (see Figure 14).

Figure 15 shows the correlation coefficients between the clamping force index and the four molded part quality measures obtained in the experiments performed at different barrel temperatures, back pressures, and screw rotational speeds. The correlation coefficients for the experiments performed with different barrel temperatures and barrel speeds vary in the range of 0.96~0.99, while those for the experiments performed with different screw rotational speeds vary in the range of 0.76~0.89. In other words, the clamping force increment index has a good correlation with

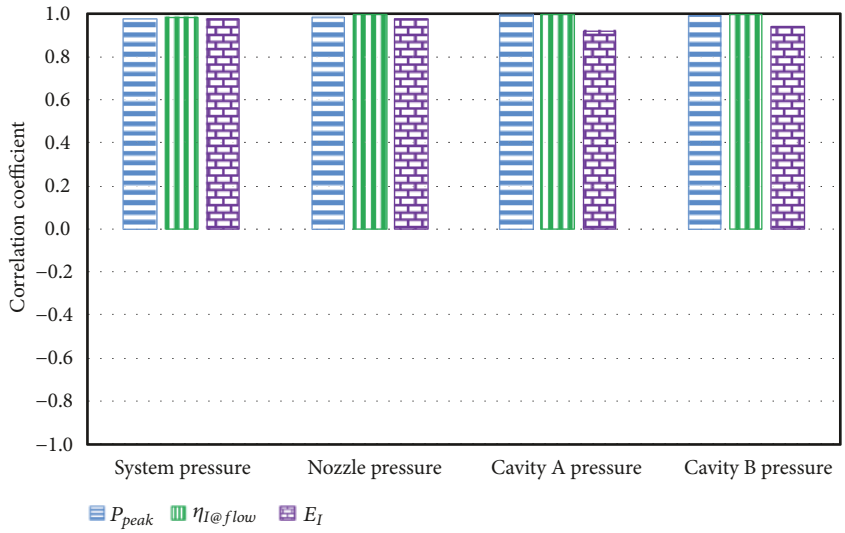

Figure 13: Correlation between pressure-based quality indexes and product weight for various back pressures.

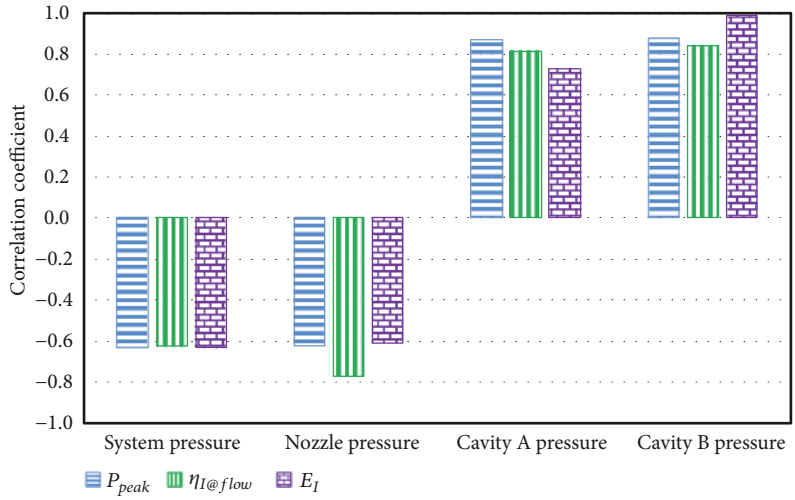

Figure 14: Correlation between pressure-based quality indexes and product weight for various screw rotational speeds.

the part quality under various injection conditions and thus provides a feasible means of estimating the molten polymer quality during the injection molding process.

Of the four pressure signals obtained from the proposed measurement system (i.e., the load cell pressure, the nozzle pressure, and the cavity void pressures (A and B)), only those obtained at the load cell and nozzle (i.e., upstream of the actual injection molding process) provide a full history of the rheological changes which take place during mold filling. Therefore, the quality indexes extracted at the load cell and nozzle provide a better indication of the mold filling quality than those extracted from the cavity. In particular, the quality indexes obtained from the load cell and nozzle pressure profiles provide a better indication of the viscosity variations which take place during the initial filling stage, while those extracted from the cavity pressure profiles provide a better indication of the viscosity variations which take place at the end of filling and hence give a better estimation of the final part quality.

In general the results presented in Figures 12–15 show that all four quality indexes provide an effective means of estimating the melt quality. However, the clamping force increment index is particularly attractive for monitoring and control purposes since it not only provides a good indication of the melt quality, but is also operationally straightforward since it can be implemented using simple stick-on strain gauges without the need for cavity invasion.

5.3. Detection of Melt Quality Fluctuations. To test the ability of the monitoring system to detect changes in the melt quality during continuous molding, injection molding experiments were performed using PA756 pellets for approximately 50 shots followed by the gradual addition of 20% PA756H pellets every 50 shots until 100% PA756H was achieved

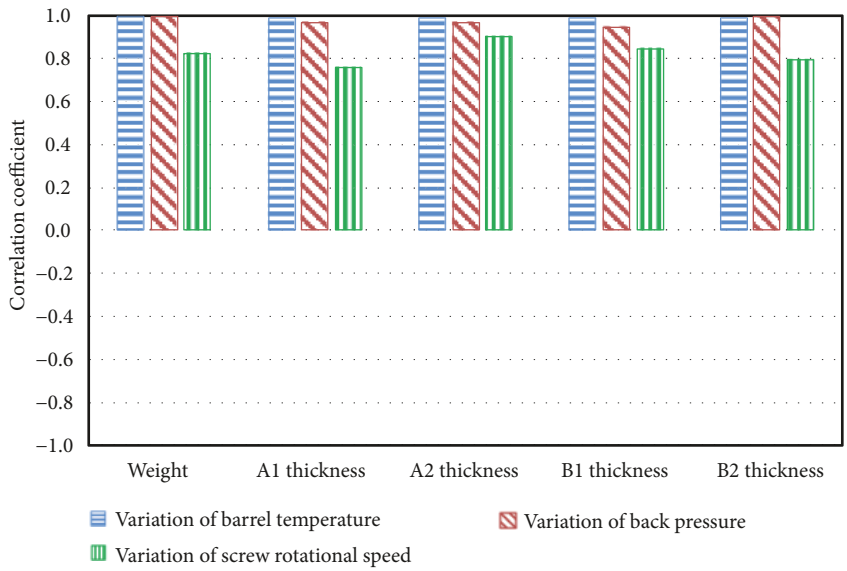

Figure 15: Correlation between clamping force increment index and molded part quality measures for various plasticizing parameters.

Table 11: Process parameter settings for varied V/P switchover position experiments.

Fixed parameters			
Feeding stroke (mm)	40	Packing pressure (MPa)	105
Barrel temperature (°C)	210	Packing time (s)	5
Back pressure (MPa)	10	Cooling time (s)	15
Injection speed (mm/s)	90	Mold temperature (°C)	60
screw rotational speed (rpm)	100	Clamping force (kN)	600
Varied parameter			
V/P switch (mm)	14, 16, 14.2, 15.8, 14.4, 15.6, 14.6, 15.4, 14.8, 15.2, 15		

(see Table 10). Notably, PA756 and PA756H have a similar rheological behavior. However, as mentioned earlier, the melt flow index (MFI) of PA756H is higher than that of PA756. In other words, PA756 has a greater viscosity than PA756H and is thus expected to induce significantly different quality index responses.

Figures 16 and 17 show the shot-by-shot variations in the clamping force increment index, peak pressure index, viscosity index, and energy index, respectively. The results confirm that when the PA756 pellets are gradually replaced with PA756H, the clamping force increment quality index and part weight increase (see Figures 16(a) and 16(b)). In other words, the ability of the proposed quality indexes to reveal crude changes in the viscosity of the molten polymer induced by a change in the raw material is confirmed. The peak pressure, viscosity, and energy quality indexes derived from the load cell and nozzle pressure profiles decrease with an increasing PA756H addition. By contrast, the quality indexes derived from the cavity pressure profiles increase. For both materials, all of the quality indexes fluctuate continuously over the course of the shot-by-shot injection process. In other words, all of the quality indexes provide the means to detect subtle changes in the viscosity (i.e., melt quality) from one shot to the next.

Figure 18 shows the correlation coefficients between the various quality indexes and the part weight, as evaluated using the measurement results obtained in the shot-by-shot injection tests. All of the quality indexes exhibit a strong correlation with the part weight. In particular, the quality indexes computed from the signals acquired at the load cell and nozzle, respectively, have a strong negative correlation with the part weight, while those derived from the cavity pressure signals and measured clamping force, respectively, exhibit a strong positive correlation with the part weight. Overall, the results confirm that all of the quality indexes can be used to predict the quality of the molded parts.

5.4. Detection of Changes in V/P Switchover Position. A final series of experiments was performed to confirm the ability of the clamping force increment quality index to detect variations in the part quality caused by changes in the V/P switchover position. Table 11 shows the corresponding processing parameters. As shown, the V/P point was initially set as 15 mm and was then adjusted to a new value every 5 shots. Figure 19 confirms that the clamping force quality index is strongly correlated with the part weight for all values of the V/P switchover position. For the nominal V/P position (15 mm), the total clamping force and clamping

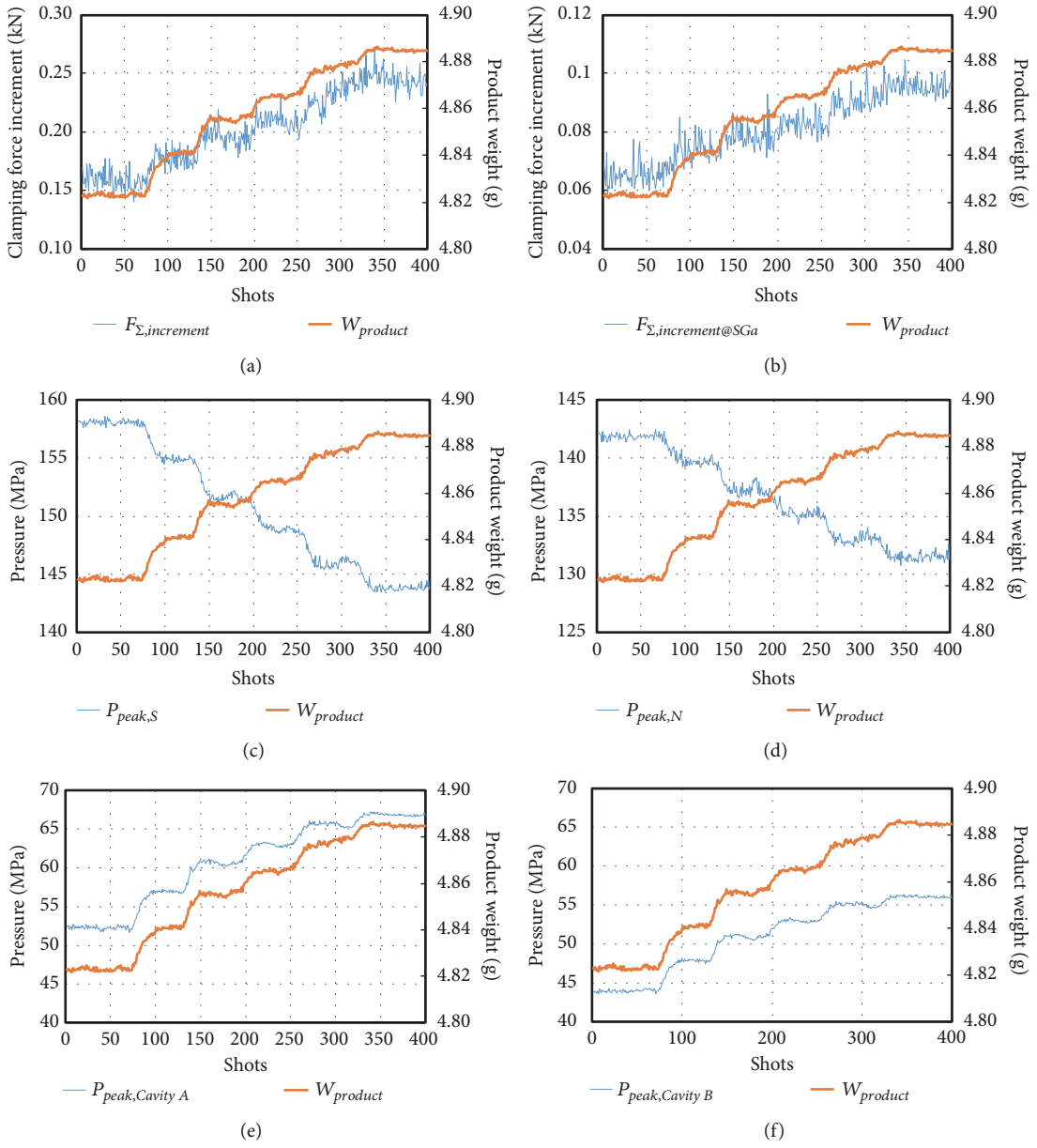

FIGURE 16: Melt quality fluctuation as revealed by force and pressure quality indexes.

force increment are 544 kN and 3.01 kN, respectively, while the average value and range of the part weight are 4.815 g and 0.010 g, respectively. In general, the results show that, for minor changes of the V/P switchover position from the nominal position, the part weight varies only very slightly. Nonetheless, this small change in the part weight can still be predicted by the single clamping force increment or total clamping force increment index. In other words, the feasibility of the proposed clamping force increment index for estimating the part quality is further confirmed.

6. Conclusions

The mechanical and physical properties of injection-molded components are critically dependent on the viscosity of the molten polymer. However, the polymer materials used in the injection molding process have a complex rheological behavior, and hence the viscosity tends to vary from cycle to cycle. Consequently, online methods for monitoring changes in the part quality are essential in predicting the quality of the final molded components and adjusting the processing parameters accordingly. This study has thus proposed three quality indexes derived from the pressure profiles obtained at the system load cell, nozzle, and molding cavities, respectively, and an additional quality index derived from the clamping force increment measured at the tie bars of the injection molding machine. These types of part quality indexes are revealed to monitor the quality variations of molten polymer. The experimental results support the following main conclusions.

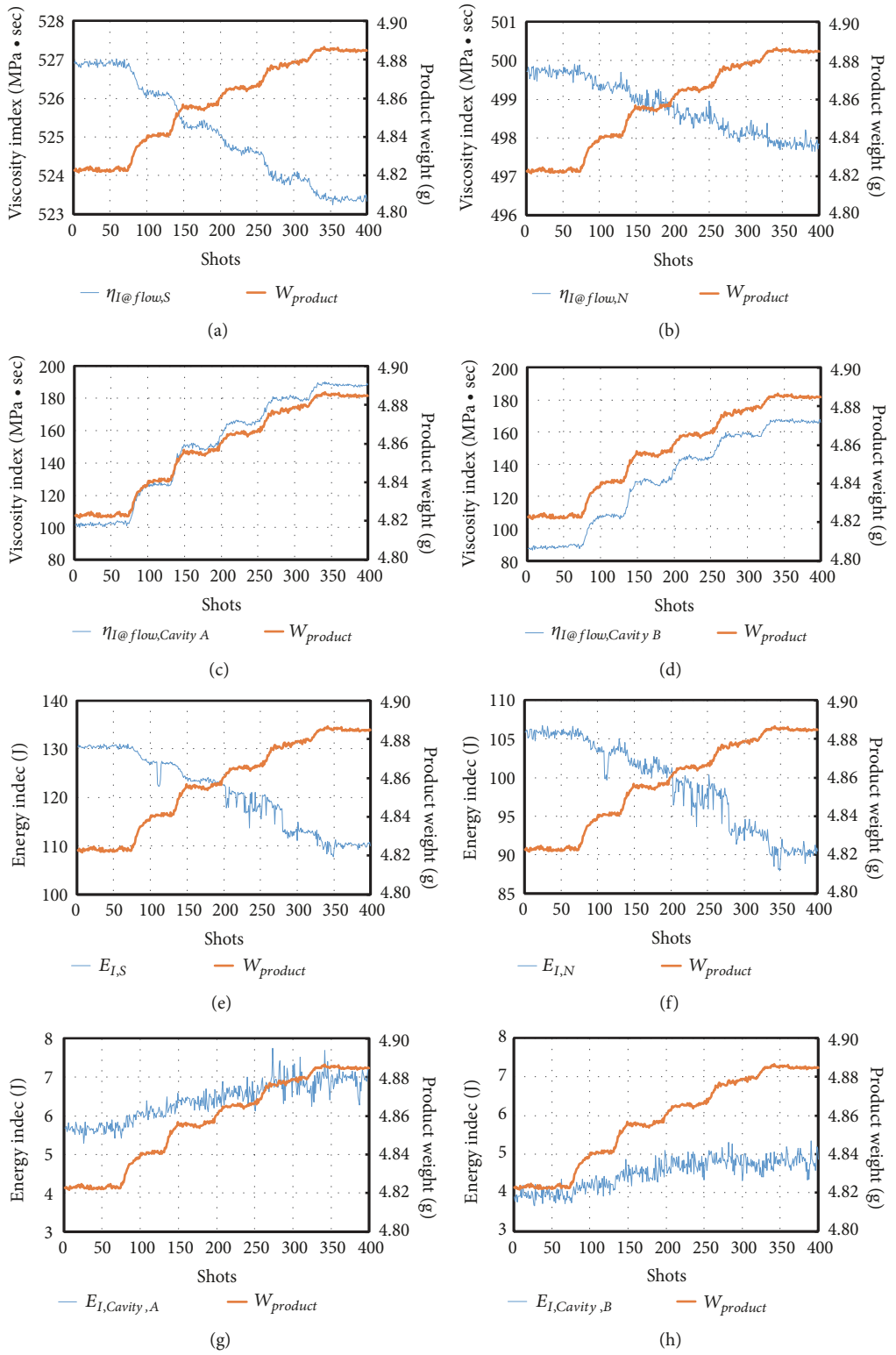

Figure 17: Melt quality fluctuation as revealed by viscosity and energy quality indexes.

(1) The plasticization parameter settings affect the initial quality of the molten polymer and therefore influence the final part weight. The barrel temperature and back pressure have a particularly strong effect on the part quality. By contrast, the screw rotational speed has a more minor effect since it acts for only a short duration. Overall, the results show that the three plasticization parameters can be ordered in terms of

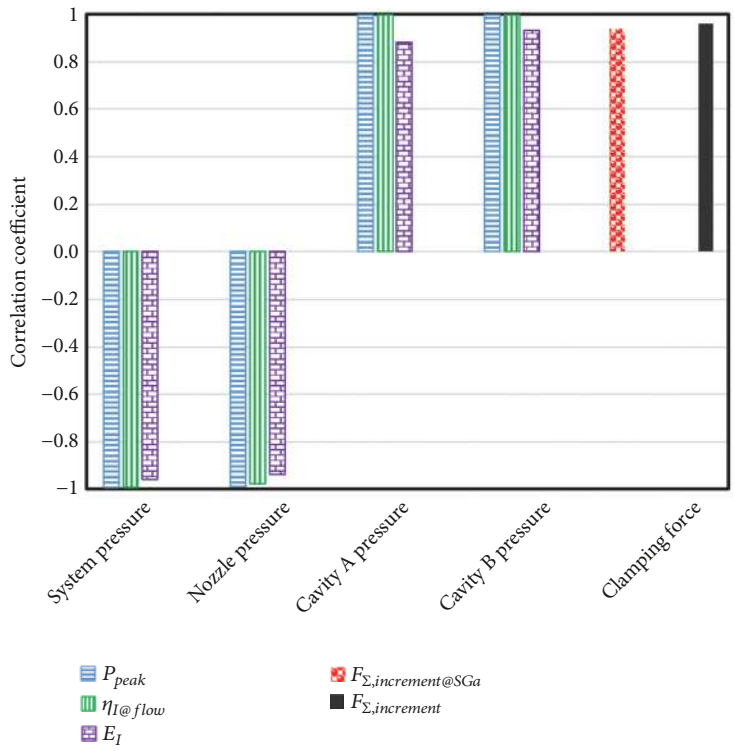

Figure 18: Correlation between quality indexes and product weight for various melt quality fluctuations.

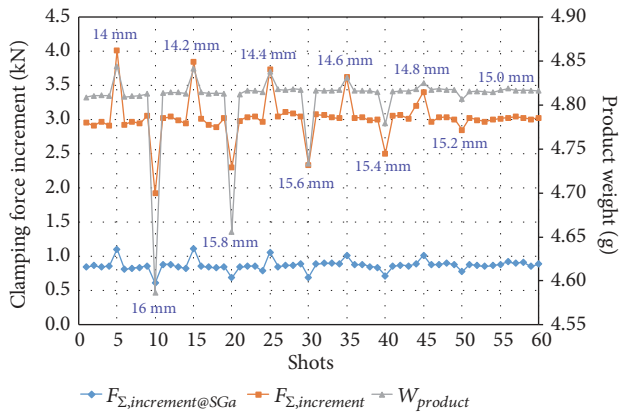

Figure 19: Shot-by-shot variation of clamping force quality index and product weight for various V/P switchover positions.

a decreasing effect on the part quality as follows: (i) barrel temperature, (ii) back pressure, and (iii) screw rotational speed.

(2) The quality indexes revealed in this work all provide a good indication of the injection molding quality under the considered processing conditions. Particularly, the quality of the molten polymer at the initial filling stage and the end of filling is quite different. The pressure signals obtained from upstream of the injection molding process provide a full history of the rheological change which takes place during mold filling. Therefore, the related quality indexes provide a good indication of the viscosity during the initial filling stage. By contrast, the quality indexes extracted from the downstream only reflect final molded part quality. Anyhow, these quality indexes, in particular with the clamping force increment index, have a strong correlation with the part qualities and they can all be used to predict the quality of the molded part.

(3) When PA756 pellets are gradually replaced with PA756H pellets with a lower viscosity, quality indexes derived from the cavity pressure signals and clamping force increase.

(4) The clamping force increment quality index is capable of detecting even very small (~0.2 mm) changes in the V/P switchover position.

(5) All of investigated quality indexes in this work provide a feasible means of detecting changes in molded part quality. In particular, clamping force increment quality index can be implemented using simple stick-on strain gauges and requires no modification or invasion of the injection molding system or cavity. Accordingly, it provides a particularly attractive solution for the online monitoring and control of the injection molding process.

Data Availability

Data is available upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] J. Neter, W. Wasserman, and G. A. Whitemore, *Applied Statistics*, Pearson, New York, NY, USA, 4th edition, 1993.

[2] O. Amano and S. Utsug, "Temperature measurements of polymer melts in the heating barrel during injection molding. Part I. Temperature distribution along the screw axis in the reservoir," *Polymer Engineering & Science*, vol. 28, pp. 1565–1571, 1988.

[3] O. Amano and S. Utsugi, "Temperature measurements of polymer melts in the heating barrel during injection molding. Part 2: Three-dimensional temperature distribution in the reservoir," *Polymer Materials Science & Engineering*, vol. 29, p. 171, 1989.

[4] O. Amano and S. Utsugi, "Temperature measurements of polymer melts in the heating barrel during injection molding. Part 3: Effects of screw geometry," *Polymer Engineering & Science*, vol. 30, p. 385, 1990.

[5] L. Latif and H. Saidpour, "Assessment of plastic mixture quality in injection moulding process," *Polymer Testing*, vol. 16, no. 3, pp. 241–258, 1997.

[6] S. Tanoue, A. Hasook, T. Itoh, M. Yanou, Y. Iemoto, and T. Unryu, "Effect of screw rotation speed on the properties of polystyrene/organoclay nanocomposites prepared by a twin-screw extruder," *Journal of Applied Polymer Science*, vol. 101, no. 2, pp. 1165–1173, 2006.

[7] X. Zhou, Y. Zhang, T. Mao, and H. Zhou, "Monitoring and dynamic control of quality stability for injection molding process," *Journal of Materials Processing Technology*, vol. 249, pp. 358–366, 2017.

[8] N. Khoshooee and P. D. Coates, "Application of the Taguchi method for consistent polymer melt production in injection moulding," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 212, pp. 611–620, 1998.

[9] Z. Jin, F. Gao, and F. Zhu, "An experimental study of solid-bed break-up in plasticization of a reciprocating-screw injection molding," *Polymer Engineering & Science*, vol. 44, pp. 1313–1318, 2004.

[10] M. S. Huang, "Cavity pressure based grey prediction of the filling-to-packing switchover point for injection molding," *Journal of Materials Processing Technology*, vol. 183, no. 419, 2007.

[11] Z. Chen and L. S. Turng, "A review of current developments in process and quality control for injection molding," *Polymers for Advanced Technologies*, vol. 24, pp. 165–182, 2005.

[12] S. C. Nian, C. Y. Wu, and M. S. Huang, "Warpage control of thin-walled injection molding using local mold temperatures," *International Communications in Heat and Mass Transfer*, vol. 61, pp. 102–110, 2015.

[13] S. C. Nian, M. H. Li, and M. S. Huang, "Warpage control of headlight lampshades fabricated using external gas-assisted injection molding," *International Journal of Heat and Mass Transfer*, vol. 86, p. 358, 2015.

[14] J. F. Luyé, G. Régnier, B. P. Le, D. Delaunay, and R. Fulchiron, "PVT measurement methodology for semicrystalline polymers to simulate injection-molding process," *Journal of Applied Polymer Science*, vol. 79, p. 302, 2001.

[15] S. Chakravorty, "PVT testing of polymers under industrial processing conditions," *Polymer Testing*, vol. 21, no. 3, pp. 313–317, 2002.

[16] C. B. Park, S. S. Park, D. Ladin, and H. E. Naguib, "On-line measurement of the PVT properties of polymer melts using a gear pump," *Polymers for Advanced Technologies*, vol. 23, p. 316, 2004.

[17] J. Wang, P. Xie, Y. Ding, and W. Yang, "On-line testing equipment of P–V–T properties of polymers based on an injection molding machine," *Polymer Testing*, vol. 28, pp. 228–234, 2009.

[18] H. Zuidema, G. W. M. Peters, and H. E. H. Meijer, "Influence of cooling rate on pVT-data of semicrystalline polymers," *Journal of Applied Polymer Science*, vol. 82, p. 1170, 2001.

[19] M. H. E. van der Beek, G. W. M. Peters, and H. E. H. Meijer, "A dilatometer to measure the influence of cooling rate and melt shearing on specific volume," *International Polymer Processing*, vol. 20, pp. 111–120, 2005.

[20] M. H. E. van der Beek, G. W. M. Peters, and H. E. H. Meijer, "The influence of cooling rate on the specific volume of isotactic poly(propylene) at elevated pressures," *Macromolecular Materials and Engineering*, pp. 443–455, 2005, vol. 290, no. 443, 2005.

[21] S. C. Chen, K. J. Wang, C. W. Chang, S. P. Sun, and K. H. Lee, "Verification of numerical approach and experiment in using PVT properties of polymer to control injection molded products," in *Proceedings of the SPE/ANTEC 2016*, vol. 1, pp. 1243–1248, Indianapolis, IN, USA, 2016.

[22] J. Wang and Q. Mao, "A novel process control methodology based on the PVT behavior of polymer for injection molding," *Advances in Polymer Technology*, vol. 32, pp. E474–E485, 2013.

[23] B. H. Min and J. Mater, "A study on quality monitoring of injection-molded parts," *Journal of Materials Processing Technology*, vol. 136, no. 1, 2003, 136, 1, 2003.

[24] Z. Chen and L. S. Turng, "Injection molding quality control by integrating weight feedback into a cascade closed-loop control system," *Polymer Engineering & Science*, vol. 47, p. 852, 2007.

[25] W. Michaeli and A. Schreiber, "Online control of the injection molding process based on process variables," *Polymers for Advanced Technologies*, vol. 28, p. 65, 2009.

[26] C. Hopmann and A. Reßmann, "Self-optimizing in injection molding and the problem at compensating viscosity fluctuations," in *Proceedings of the SPE/ANTEC 2014*, vol. 2, pp. 1706–1710, Las Vegas, NV, USA, 2014.

[27] F. A. Heinzler, M. Mistier, and J. Wortberg, "Quality improvement by enhanced pressure controlled injection molding," in *Proceedings of the SPE/ANTEC 2014*, vol. 2, pp. 1694–1699, Las Vegas, NV, USA, 2014.

[28] J. F. Zhang, P. Zhao, Y. Zhao, J. Y. Huang, N. Xia, and J. Z. Fu, "On-line measurement of cavity pressure during injection molding via ultrasonic investigation of tie bar," *Sensors and Actuators A: Physical*, vol. 285, p. 118, 2019.

[29] C. Gornik, "Viscosity measuring methods for feedstocks directly on injection molding machines," *Materials Science Forum*, vol. 591-593, pp. 174–178, 2008.

[30] J. Aho and S. Syrjälä, "Shear viscosity measurements of polymer melts using injection molding machine with adjustable slit die," *Polymer Testing*, vol. 30, no. 6, pp. 595–601, 2011.

[31] S. Kruppa, R. Schiffers, M. Würtele, and G. P. Holzinger, "Integrated process monitoring and process control of injection molding machines and molds," in *Proceedings of the SPE/ANTEC 2013*, vol. 1, pp. 1674–1679, Cincinnati, OH, USA, 2013.

[32] N. Asadizanjani, R. X. Gao, Z. Fan, and D. O. Kazmer, "Viscosity measurement in injection Molding using a multivariate sensor ASME/ISCIE 2012," in *Proceedings of the International Symposium on Flexible Automation*, vol. 1, pp. 231–237, St. Louis, MO, USA, 2012.

[33] G. Gordon, D. O. Kazmer, X. Tang, Z. Fan, and R. X. Gao, "Quality control using a multivariate injection molding sensor," *The International Journal of Advanced Manufacturing Technology*, vol. 78, p. 1381, 2015.

[34] S. Montgomery and V. Gallo, "Achieve process transparency with in-mold cavity sensors," *Plastics Technology*, vol. 39, 2012.

[35] C. C. Lin, W. T. Wang, C. C. Kuo, and C. L. Wu, "Experimental and theoretical study of melt viscosity in injection process," *International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, vol. 8, pp. 687–691, 2014.

[36] J. Y. Chen, K. J. Yang, and M. S. Huang, "Online quality monitoring of molten resin in injection molding," *International Journal of Heat and Mass Transfer*, vol. 122, no. 681, 2018.

[37] Z. Chen, L. S. Turng, and K. K. Wang, "Adaptive online quality control for injection-molding by monitoring and controlling mold separation," *Polymer Engineering & Science*, vol. 46, p. 569, 2006.

[38] F. Yin, H. Mao, and L. Hua, "A hybrid of back propagation neural network and genetic algorithm for optimization of injection molding process parameters," *Materials & Design*, vol. 32, p. 3457, 2011.

[39] M. S. Huang, S. C. Nian, J. Y. Chen, and C. Y. Lin, "Influence of clamping force on tie-bar elongation, mold separation, and part dimensions in injection molding," *Precision Engineering*, vol. 51, p. 647, 2018.

[40] Y. Zhao, P. Zhao, J. F. Zhang, J. Y. Huang, N. Xia, and J. Z. Fu, "On-line measurement of clamping force for injection molding machine using ultrasonic technology," *Ultrasonics*, vol. 91, p. 170, 2019.

[41] P. Zhao, Y. Zhao, J. F. Zhang, J. Y. Huang, N. Xia, and J. Z. Fu, "Ultrasonic measurement of clamping force for injection molding machine," *Journal of Polymer Engineering*, vol. 39, p. 388, 2019.