Pressure-based Methodology for Online Monitoring of Melt Quality during Injection Molding Process

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***Abstract*—Injection molding provides a convenient approach for manufacturing plastic components with a complex geometry. However, polymer melt is a non-Newtonian fluid with a shear thinning characteristic, and hence, its viscosity is highly sensitive to factors such as the shear rate, melt temperature, back pressure, and screw rotational speed during the plasticizing stage. In practical injection molding operations, process variations may have a significant effect on the melt quality, and hence, on the quality of the final molded part. As a result, online melt quality monitoring systems are of great practical importance. Accordingly, this study presents a basic method for the online monitoring of the shot-by-shot variance of the melt quality using a system of pressure sensors. The feasibility of the proposed method is demonstrated by detecting variations in the melt quality of two acrylonitrile butadiene styrene (ABS) materials with different melt flow indices.**

***Index Terms*—melt quality, pressure sensor, injection molding process**

I. Introduction

Injection molding provides a simple and efficient approach for the mass production of plastic products with complex geometries. In practice, the quality and stability of the final molded parts are strongly dependent on the processed raw material, plasticizing quality, processing parameter settings, and experience of the molten resin in filling the cavity. However, the filling behavior of molten resin is difficult to visualize, and its rheological properties are extremely difficult to predict. Traditionally, engineers seek to improve the quality of the molded parts by improving the motion control of the injection molding machine. However, injection molded parts have a variable geometry, and therefore, even with precise motion control on the injection molding machine and the fact that the hydraulic pressure curves of each shot almost overlap, the quality of the molded parts still cannot be consistently ensured. Thus, efforts to improve the quality and consistency of the injection molded parts should focus more on understanding and controlling the variations in the melt quality of the molten resin for each cycle.

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There are many factors that could influence the molded part's quality, including raw materials, plasticizing, and injection parameters, as shown in Fig. 1. In polymer processing, all the extrinsic effects of the factors on molten resin could inherently yield different rheological properties, resulting in melt quality fluctuations.

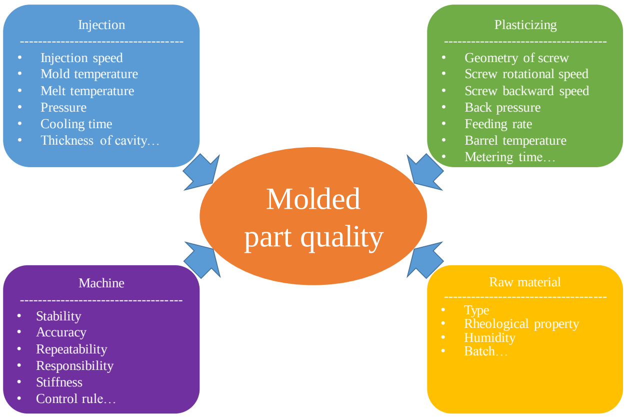

Figure 1. Extrinsic effects on the molded part's quality.

Generally, the plasticizing quality of molten resin essentially impacts the viscosity, which is affected by the shear rate, temperature, and pressure at the plasticizing stage. Accordingly, the variance of the melt quality was affected by variable rheological behavior of the filling melt. Viscosity can represent the flow behavior of the molten resin, and consequently, seriously affect the quality of the molded part. Moreover, it is virtually impossible to measure the melt quality of the molten resin using direct experimental methods. Consequently, it is generally approximated by evaluating the variance of the injection pressure sensed by equipped sensors since fluctuations in the melt quality could result in variances

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in the injection pressures as the molten resin fills at the filling stage. Amano et al. [1-3] conducted a series of investigations into the effects of processing parameters on the temperature distribution of molten resin in a barrel. The results showed that the melt quality in the barrel was dominated by two factors, namely, shear heating and heat absorption. The former factor is related to the shear rate and screw rotational speed in the metering zone, while the latter is correlated with the residence time in the feeding and compression zones. A long metering stroke requires a longer time to heat the resin sufficiently as it is conveyed through the feeding and compression zones. A high screw rotational speed results in a broad temperature distribution of the melt, and it is beneficial in enhancing the melt temperature by increasing the back pressure or enabling a reduction in the metering stroke. Jin et al. [4] investigated the behavior of solid-bed breakage and found that such breakage has a serious adverse effect on the quality of the injection molded parts. Consequently, the barrier screw must be properly designed and the processing parameters need to be appropriately chosen.

The melt quality in injection molding processes is traditionally evaluated offline with a viscosity rheometer. However, Gornik [5] designed an online viscosity measurement method by means of a particular nozzle equipped with pressure and temperature sensors on an injection molding machine. Through a 10-min measurement of the melt flow rate under a specific temperature and pressure, the melt viscosity can be computed, and it represents the flowability of the batched polymer melt and is usually used to monitor the quality of raw materials. In addition, Gornik also proposed a torque rheometer for the online measurement of melt viscosity in the plasticization process. The concept is based on the fact that the energy consumption during plasticization is proportional to the amount of volume of melt in each shot, and the ratio can be indirectly used as a melt viscosity index.

$$\text{Monitoring of Feedstock Quality} = \frac{\int T \cdot \omega dt}{V_{met}} \tag{1}$$

where T is the torque of screw, ω is the rotational speed, and V_{met} is the injection volume of each shot.

Moreover, the shear rate is also proportional to the injection velocity and has a considerable influence on the variation of the melt viscosity. Aho and Syrjälä [6] measured the viscosity variation of the polymer melt in an injection molding machine using a slit die equipped with pressure sensors. Zhang et al. [7] showed that the melt viscosity is proportional to the ratio of the pressure gradient to the volumetric flow rate. Gordon et al. [8] developed an online viscosity measurement system based on a multivariate sensor capable of simultaneously detecting the cavity pressure, temperature, and melt flow velocity. The apparent melt viscosity can, therefore, be computed.

Although it was still difficult to directly measure the melt viscosity online, the melt viscosity has a positive correlation with the injection pressure; further, the flow resistance of the melt, which exhibits the viscosity of molten resin, could be represented by the integration of pressure with time during the filling stage. Gallo and Montgomery [9] presented an approach for determining the melt viscosity by sensing the cavity pressure and temperature. Lin et al. [10, 11] presented a signal processing approach based on a pressure sensor bushing (PBS) module and data acquisition module for measuring the viscosity of the flow resin during the injection process. The results showed that the injection speed had a critical effect on the rheological properties of the polymer melt, particularly at higher melt temperatures.

This study proposes a method for performing the online monitoring of the melt quality in an injection molding process by means of three pressure sensors installed in the nozzle, runner, and cavity. The feasibility of the proposed method is demonstrated by monitoring the shot-by-shot variation in the detected pressure for two acrylonitrile butadiene styrene (ABS) materials with different melt flow indices (MFIs).

II. Experiment Setup

Fig. 2 shows the experimental setup used in the present study. The melt filling path of the spiral mold had a sectional area of 15 mm × 1.5 mm (width × depth) and a total length of 1537 mm [12].

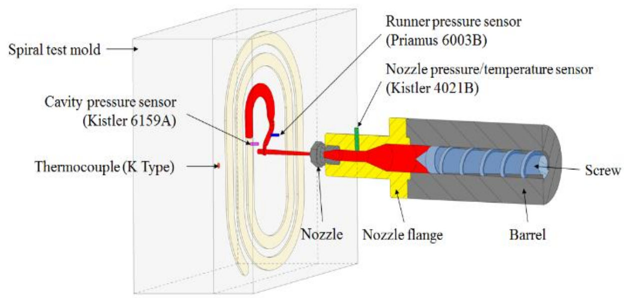
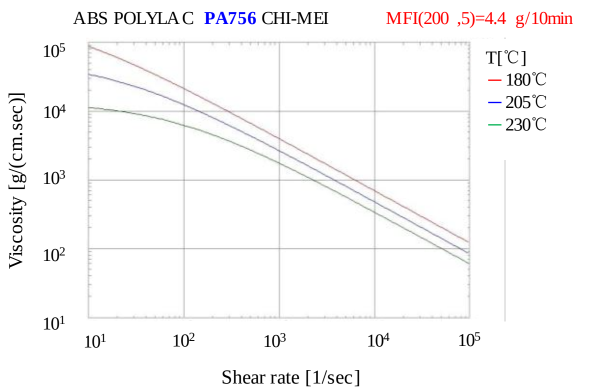


Figure 2. Spiral test mold equipped with nozzle, runner, and cavity sensors.

An integrated pressure/temperature sensor was installed in the nozzle of the injection molding machine, while two pressure sensors were installed in the runner and cavity. In addition, a K-type thermocouple was embedded in the test mold to monitor the variations in the mold temperature. The specifications of the various sensors are shown in Table I. The injection molding experiments were performed using a FCS AF-110 closed-loop hybrid injection molding machine with specifications listed in Table II. All of the experiments were performed using the processing parameters shown in Table III, and the holding stage was notably excluded. The experiments used two different ABS materials (both supplied by Chi-Mei Corporation, Taiwan), namely, PA756 and PA756H. The two materials have the same recommended processing conditions. However, the MFI of PA756 (4.4) is lower than that of PA756H (8.0). In other words, PA756 has a higher viscosity than PA756H under the same injection conditions, as shown in Fig. 3.

Before collecting the experimental data, a minimum of 200 shots were performed to obtain steady-state conditions.

(a)



(b)

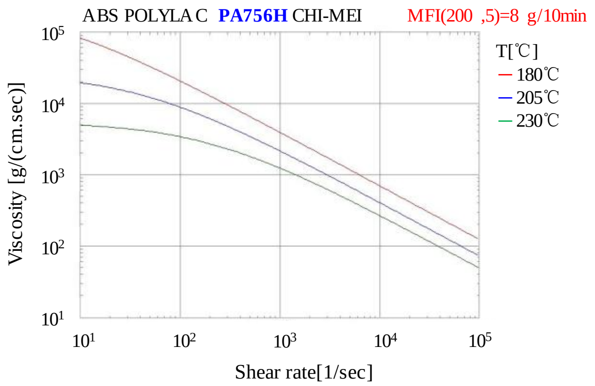


Figure 3. Viscosity versus shear rate corresponding to (a) PA756 and (b) PA756H.

TABLE I. SENSOR SPECIFICATIONS.

Item	Specification		
Manufacturer	Kistler	Priamus	Kistler
Type	4021B	6003B	6159A
Compensation press. range	0-3000 bar	0-2000 bar	0-2000 bar
Compensation temp. range	0~350□	N/A	N/A
Linearity	±0.5% FSO	≦±1.0% FSO	≦±1.0% FSO
Sensitivity	<±0.5% FSO	Approx. -5.0 pC/bar	Approx. -2.5 pC/bar

TABLE II. SPECIFICATION OF INJECTION MOLDING MACHINE.

FCS AF-110		
Injection Unit	Specification	Value
	Screw diameter (mm)	32
	Injection stroke (mm)	150
	Injection pressure (kgf/cm^2)	2215
	Injection speed (mm/s)	600
Clamping Unit	Clamping force (tonf)	110

TABLE III. PARAMETERS USED IN INJECTION MOLDING PROCESS.

Item	Value
Resin temp. (℃)	230
Mold temp. (℃)	60
Injection speed (mm/s)	90
Back pressure (MPa)	1
V/P switch (mm)	8
Packing time (s)	0
Feeding delayed time (s)	10
Cooling time (s)	30

III. RESULTS AND DISCUSSIONS

Thermoplastic polymer materials behave as non-Newtonian fluids with complex rheological properties when heated above a specific temperature. Consequently, the flow behavior of the polymer melt is affected by several different factors, and they give rise to distinct fluctuations in the melt quality from one shot to the next. In the present study, it is proposed that the variation in the melt quality is manifested by changes in the pressure induced during the injection process in the nozzle, runner, and cavity. Fig. 4 shows a typical result obtained for the change in pressures at three detection points during the injection of PA756.

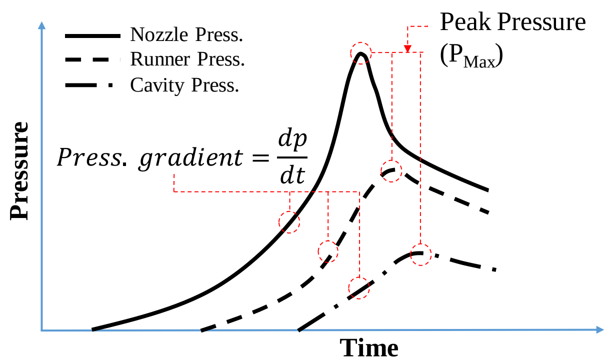


Figure 4. Typical pressure profiles measured at the nozzle, runner, and cavity during the injection of PA756.

As expected, all the three pressures increase initially as more resin is injected into the cavity. In evaluating the fluctuations in the melt quality during a continuous injection molding operation, the present study considers two particular characteristics of the pressure profiles, as shown in Fig. 4, namely, the peak pressure and the rate of change of pressure (i.e., the pressure gradient). Physically, the pressure peak of the measured pressure curve represents the maximum injection pressure during the injection stage, while the pressure gradient indicates the instantaneously required injection pressure to drive the molten resin. Since the repeatability and reliability of the measurement is important, we performed the experiment twice with identical processing parameters and the same batch of raw material. Fig. 5 shows the peak pressures measured at the nozzle, runner, and cavity over 30 successive shots of PA756.

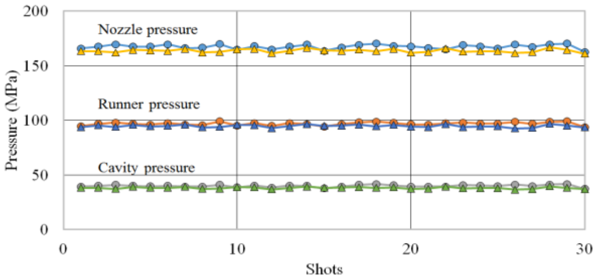
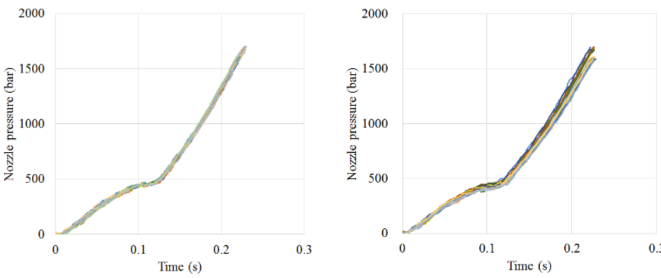


Figure 5. Peak pressures measured at the nozzle, runner, and cavity for 30 continuous shots of PA756.

From a detailed inspection, the standard deviation of each set of pressure results is less than 3%. Hence, the reliability and stability of the pressure measurement system is confirmed.

Figs. 6(a)-(c) show the detected pressure profiles at the nozzle, runner, and cavity for 30 repeated shots of PA756. It is observed that for each set of results, the pressure profiles virtually overlap one another. Hence, it is inferred that the rheological properties of the filling polymer during the injection stage for each shot are similar, which, in turn, implies a similar melt quality. Moreover, the stability of the measurement system is reconfirmed. Comparably, Figs. 6(d)-(f) show the equivalent results obtained when injecting PA756 pellets (approximately 15 shots) followed by PA756H pellets (approximately 15 shots). As described above, the rheological properties of PA756 and PA756H are slightly different (i.e., PA756 has a MFI of 4.4, while PA756H has a MFI of 8.0). Thus, the pressure profiles measured at the nozzle, runner, and cavity can be categorized into two distinct groups, where the lower group relates to the PA756H material with a higher MFI. Overall, however, the tendencies of the pressure curves for the two different ABS materials are similar. Hence, it is inferred that the proposed pressure-based system provides a reliable means of monitoring fluctuations in the melt quality during continuous injection experiments.

(a) (d)



(b) (e)

(c) (f)

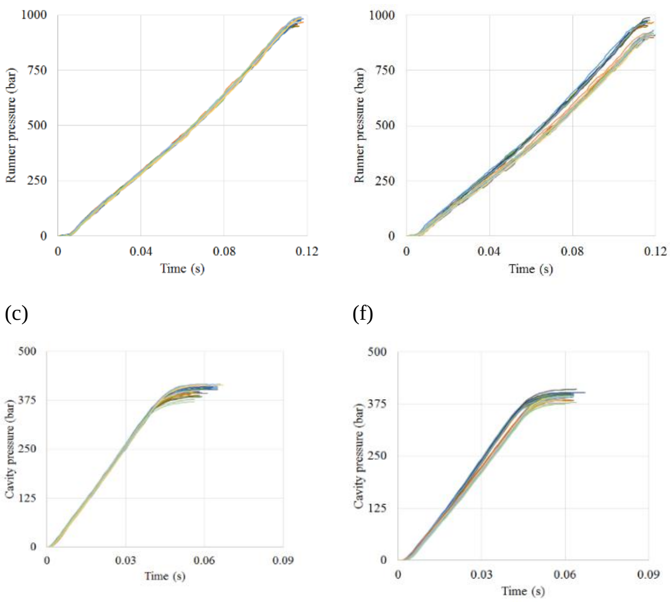
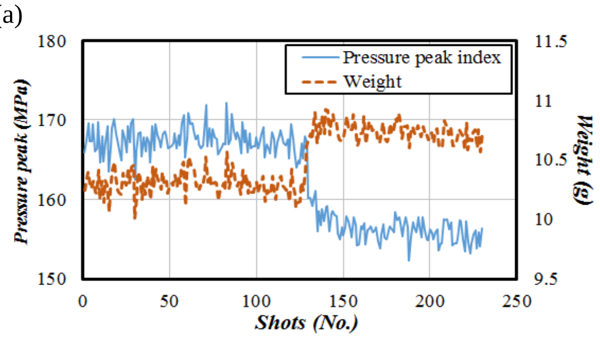


Figure 6. Pressure profiles measured at the nozzle, runner, and cavity for 30 continuous shots of (a)-(c) only PA756 and (d)-(f) PA756 followed by PA756H.

To further investigate the feasibility of using the detected pressure peak and pressure gradient to evaluate the melt quality fluctuations, an additional experiment was performed in which PA756 pellets were injected for 125 shots approximately and PA756H pellets were then further injected. Figure 7 shows the corresponding results at the nozzle. For reference purposes, the weight of the molded part obtained in each shot is also shown. As expected, the pressure peak values for the PA756 shots are higher than those of the PA756H shots due to the former's lower MFI (greater viscosity), as shown in Fig. 7(a). Moreover, the weight of the PA756H part retrieved from the mold is greater than that of the PA756 part since the lower viscosity of the PA756H melt results in a longer flow length, and hence, the driving pressure requirement was less for PA756H as compared to that for PA756. The tendencies of the pressure gradient for the two materials, as shown in Fig. 7(b), are consistent with those of the peak pressure. With regard to the runner and cavity, the experimental results are in good agreement with those for the nozzle.

(a)



(b)

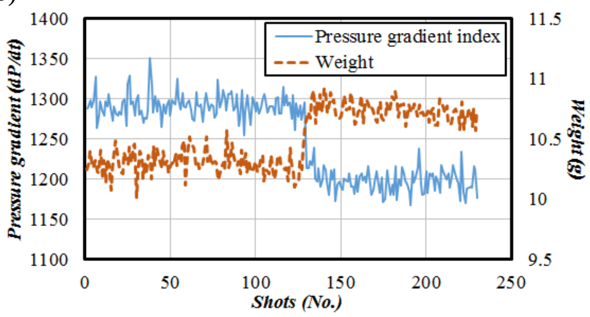


Figure 7. Detected pressure results for 125 shots of PA756 followed by PA756H in the nozzle: (a) peak pressure and (b) pressure gradient. Note that the weight of the molded part is also shown in each case.

IV. Conclusions

The melt quality has a significant effect on the mechanical and physical properties of injection molded components. However, it is extremely difficult to measure changes in the molten state of the polymer resin in situ during the injection molding process. While various authors have claimed the ability to do so, the proposed solutions are applicable only to the particular installation considered in this study. In other words, they cannot be generalized to all types of injection molding setups. Consequently, the melt quality is usually approximated by measuring the viscosity of the molten resin. The present study has proposed a method for evaluating the melt quality of the molten resin by measuring the changes in pressure in the nozzle, runner, and cavity during the injection process. Injection experiments have been performed using two ABS materials with different MFIs, namely, PA756 (MFI = 4.4) and PA756H (MFI = 8.0). The experimental results have shown that the peak pressure and pressure gradient for PA756 (with a higher viscosity) are relatively higher than those for PA756H (with a lower viscosity). In other words, the results confirm the ability of the proposed method to detect material-related changes in the viscosity of the molten resin. Furthermore, for each material, the peak pressure and pressure gradient profiles obtained over repeated shots show continuous fluctuations, which implies a continuous change in the viscosity (melt quality) from one shot to the next. In a future study, the detected peak pressure and pressure gradient values will be used as a monitoring signal in experiments aimed at achieving a more consistent melt quality in the injection molding process. In addition, the effect of melt quality on the injection molded part would also need investigation. Moreover, the integrations of time and screw position under the sensing pressure curve during the injection stage are also attractive to discuss whether they are suitable signals corresponding to injection molding quality or not.

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