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Experimental and Theoretical Study of Melt Viscosity in Injection Process

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***Abstract*—**The state of melt viscosity in injection process is significantly influenced by the setting parameters due to that the shear rate of injection process is higher than other processes. How to determine plastic melt viscosity during injection process is important to understand the influence of setting parameters on the melt viscosity. An apparatus named as pressure sensor bushing (PSB) module that is used to evaluate the melt viscosity during injection process is developed in this work. The formulations to coupling melt viscosity with fill time and injection pressure are derived and then the melt viscosity is determined. A test mold is prepared to evaluate the accuracy on viscosity calculations between the PSB module and the conventional approaches. The influence of melt viscosity on the tensile strength of molded part is proposed to study the consistency of injection quality.

***Keywords*—**Injection molding, melt viscosity, injection quality, injection speed.

I. Introduction

INJECTION molding has been introduced for decades to produce a wide range of plastic products such as automotive, consumer electronic, and packaging products. Injection molding provides a convenient and efficient approach to mass production. Using injection molding method, it takes only little time to form desired shapes of parts.

In general, the quality stability of molded product from injection molding process must be concerned since the production rate is usually high. However, it is difficult to find out the correlation between the setting parameters and the defects of molded part due to insufficient information. For example, the residual stress may result from too much packing pressure or unsuitable switching point and is difficult to be improved by tuning only one parameter directly. It may take much time and consume a lot of plastic material to fulfill an optimization process. In addition, the information shown on the control panel of injection machine such as screw position, barrel temperature, or injection time is seldom related to the melt flow property directly. Before the mold being opened, injection process is invisible and the state of plastic melt in the mold is unknown.

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It was reported that the consistency of molded part quality was better as plastic material was molded with a relative lower viscosity [1]-[3]. Kurt et al. [4] studied the influence of cavity pressure on dimensional accuracy of parts in a four-cavity mold. They investigated the pressure trace of cavity in injection mold to determine molding quality. Chen et al. [5] provided an approach to assessed rheological properties of PS material in ultra-high injection molding. They found that the melt viscosity was influenced significantly by injection speed. Beaumont [6] provided a convenient method to calculate melt viscosity. The cavity pressure was estimated by multiplying the read data with the intensification ratio of the injection machine. However, this may cause errors in calculating the cavity pressure in case the wear of the hydraulic components of injection machine is not considered.

For pressure measurements, a pressure sensor is conventionally installed in the moving half of mold, which has a more complicated structure than that of the fixed half of mold. This complicated structure causes difficulties while mounting or dismounting the pressure sensor.

In this study, an apparatus named as pressure sensor bushing (PSB) module was designed and developed to provide a quick installation feature for pressure measurement. To avoid the complicated procedure in installing a pressure sensor into a mold, the proposed PSB module provides a designed bush integrated with a pressure sensor inside. This newly designed apparatus allows us to perform pressure measurements in injection molding process more conveniently.

In this work, a theoretical model defining the flow behavior of the plastic melt was first developed based on the rheological concept and then the methodology to establishing the relationship between injection pressure and fill time was provided. A test mold which contained a tensile-test specimen referring to ASTM D638 Standard was prepared for evaluating the influence of melt viscosity on molded part quality.

II. Formulation of Injection Pressure and Melt Viscosity Coupling

The melt viscosity has been verified as an important indication for reflecting the melt state of plastic material in molding process [6]. In order to determine the relationship between melt viscosity and molding conditions, the formulation that defines the plastic flow behavior under pressure actuation was initiated from the momentum equations and then the relationship between the cavity pressure and melt viscosity was derived based on the rheology. By taking calculations for the momentum equations, the volume rate of flow Q in a cylindrical runner can be expressed by

$$Q = \frac{n\pi R^3}{3n+1}\left(\frac{R\Delta p}{2mL}\right)^{1/n} \quad (1)$$

in which m, n, R and L are referred to the consistency index, the powder law exponent, the radius of runner, and the flow length, respectively. Note that the detailed calculation procedures for (1) can be found in our previous work [7].

Remember that the viscosity of plastic melt η used in the power law model is expressed by

$$\eta = m\dot{\gamma}^{n-1} \quad (2)$$

By substituting the consistency coefficient of plastic melt m expressed in (2) into (1), the viscosity of plastic melt η can be rewritten as

$$\eta = \left[\frac{nR}{(3n+1)L}\right]^n \frac{R}{2L}\Delta p t^n \dot{\gamma}^{n-1} \quad (3)$$

Equation (3) provides an indication for studying the effects of molding parameters, the required injection pressure, and the shear rate on the viscosity of plastic melt. For a given mold with a designate material in the filling stage of injection process, the injection stroke of the screw is fixed since the shot volume of the mold is determined and the shear rate in this stage is proportional to the inverse of the fill time t. The viscosity of plastic melt shown in (3) is consequently simplified by

$$\eta = K\Delta p t \quad (4)$$

where K is a coefficient and expressed by

$$K = \left[\frac{nR}{(3n+1)L}\right]^n \frac{R}{2L} \quad (5)$$

K is only influenced by the type of plastic material and the cavity geometry.

As mentioned in the previous section, the variation of melt viscosity can be regarded as an indication for the consistency of injection molding quality. The viscosity of plastic melt η expressed in (4) provides an indication for understanding the melt viscosity in injection process.

III. Experimental Work

A. Molding Material

Two materials with different melt viscosities were used in this study. The first material was acrylonitrile–butadiene–styrene copolymer (ABS, PA-707, Melt Index = 1.9, from ChiMei Corp., Taiwan) whose characteristics were excellent in the appearance of molded part. The second material (ABS, PA-756H, Melt Index = 8.5, from ChiMei Corp., Taiwan) was the same as the first material but with a different viscosity. In order to minimize the effect of thermal shrinkage, both materials were dehumidified at 80°C for 4 hours before molding process.

B. PSB Module Design and Fabrication

Fig. 1 shows the PSB module which consists of a sprue bushing and a pressure sensor. As shown in Fig. 1, another pressure sensor with the same specification as that used inside the PSB module was also installed near the gate in the cavity of the test mold. The steel material for the PSB module was AssabStavax HRC 40-52. Note that the dimension of the PSB module can be modified depending on customer's demands. The PSB module was assembled in between two mold plates of the fixed half of mold. The assembly procedure for the PSB module in the fixed half of mold is illustrated in Fig. 2. The pressure sensor used in this study was Priamus 6001A and auxiliary accessory for the measurements can be found in reference [7]. The assembly of the PSB module in the fixed half of the mold is shown in Fig. 3.

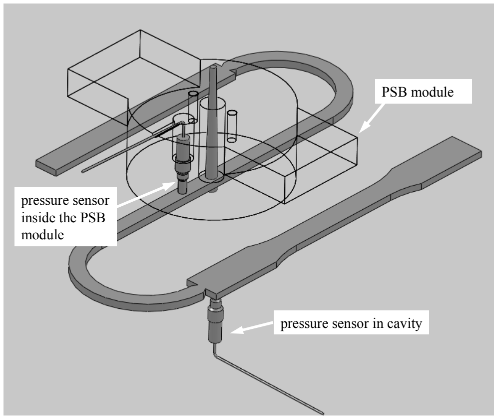

Fig. 1 Schematic drawing of arrangement of the pressure sensor inside the PSB module and the mold

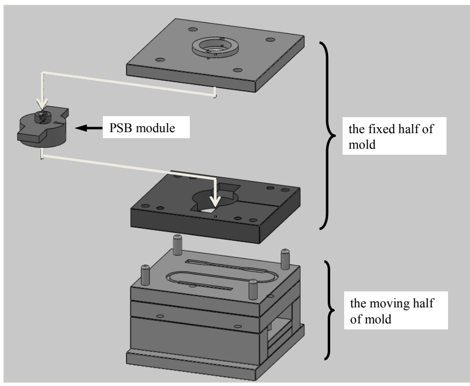

Fig. 2 Schematic illustration of assembly procedure for the PSB module in the fixed half of the mold

C. Molding Process

The molding experiments were performed on Victor Ve-80 type injection machine. The injection pressure data were collected using three different approaches: pressure measured by the PSB module and by the pressure sensor in the cavity and pressure read from the control panel of injection machine. All of these injection pressure data were collected simultaneously and used to compare their difference. In order to obtain the melt viscosity curve on the injection machine, a series of injection speeds from low to high were set and the corresponding viscosity curves were plotted for each approach.

Furthermore, in order to study the influence of melt viscosity on the consistency of the molded part quality, three different melt viscosities which represented high, moderate, and low viscosities of plastic melt individually were chosen for the study. In general, the high melt viscosity appeared in the steep portion of the viscosity curve, while the flat portion of the viscosity curve represented the low melt viscosity. The moderate melt viscosity was chosen at the bend of the viscosity curve in which the curve changed from relatively steep to flat. Three injection speeds respect to these different viscosities were set for the following study. In order to evaluate the effect of melt viscosity on process consistency, artificial perturbations in injection speed and changes of plastic material types (ABS PA-756H with low viscosity and ABS PA-707 with high viscosity) were introduced to simulate the typical variation appearing in injection molding process. Besides, the baseline variation induced by the machine itself was also implemented for investigating process consistency. A lower and higher injection speeds with respect to the nominal injection speed by -5% and +5% were chosen to simulate changes in the injection speed which could result from operator setup or machine stability. The main setting parameters of this study are summarized in Table I.

In order to have a reliable process during injection molding, 10 shots were made before the signals or samples were collected for each set of the process conditions.

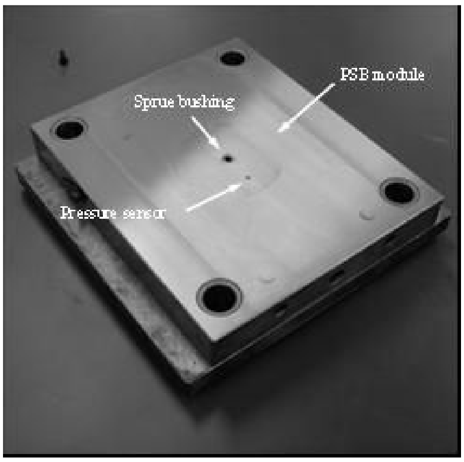

Fig. 3 Photograph of the PSB module assembled with the fixed half of the test mold

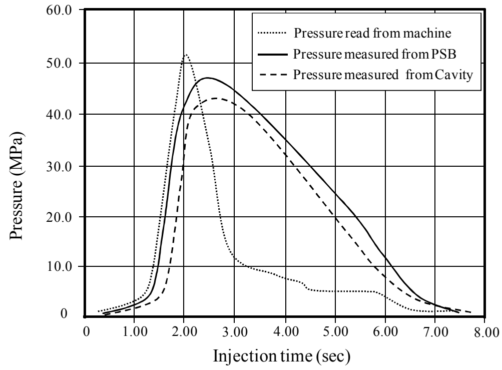

Fig. 4 (a) Plot of pressure versus injection time for different approaches

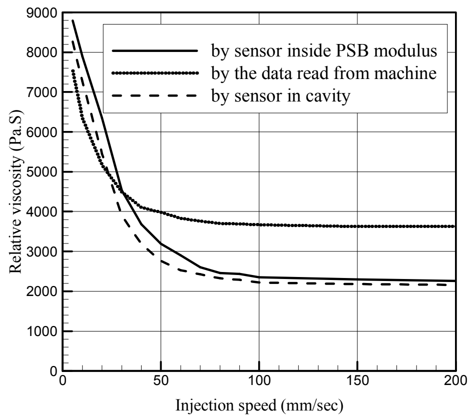

Fig. 4 (b) Effect of injection speed on the relative viscosity for plastic material ABS PA-707

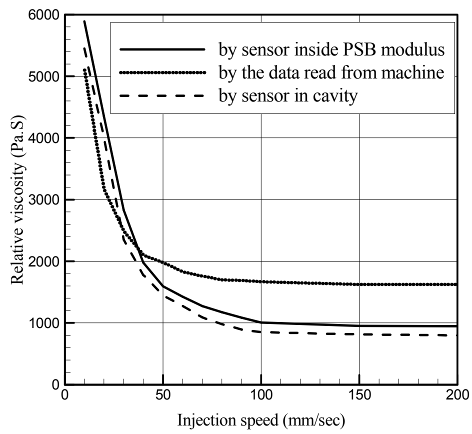

Fig. 4 (c) Plot of relative viscosity versus injection speed for plastic material ABS PA-756H

D. Characterization

In this study, the tensile strength stability of molded part was selected to study the influence of the setting parameters on the consistency of injection molding quality. All the specimens were manufactured with two materials and conditioned at 25°C and 50% relative humidity for 48 hours before test. The operation procedure of the tensile test was executed at room temperature with a pulling speed of 10 mm/min according to ASTM D638 Standard by using the test machine ZwickRoell Z010.

TABLE I
MOLDING PARAMETERS FOR MATERIALS ABS PA-707 AND ABS PA756H

ABS material	PA-707	PA-756H
Melt temperature (°C)	260~280	260~280
Mold temperature (°C)	80	80
Holding pressure (bar)	1200	1100
Holding time (s)	5.5	4.5
Cooling time (s)	32	32

IV. RESULTS AND DISCUSSION

The first example was implemented to compare the accuracy of the PSB module with the other two approaches on calculation of melt viscosity. The influence of the variation of melt viscosity on the consistency of mechanical property of the molded part was demonstrated in the second example.

A. Comparison of PSB Module with Other Approaches

In injection molding process, plastic melt was forced into the cavity of mold by the screw of injection machine with certain pressure. The peak value of the required pressure curve corresponds most directly to viscosity-induced pressure drops across the cavity. Hence, the peak value of the cavity pressure was collected and substituted into (4) and (5) for the calculation of melt viscosity. In order to validate the PSB module developed in this work, another two approaches for collecting pressure data were also implemented and their difference was compared. The cavity pressure curves with respect to the injection time were similar from low to high injection speeds. Fig. 4 showed an example of these pressure curves at injection speed of 75 mm/sec using material ABS PA-707. Note that the pressure data acquired from the control panel of injection machine was multiplied by an intensification ratio and regarded as predicted pressure inside the cavity [6]. As shown in Fig. 4 (a), the pressure curve derived from the control panel of the machine decayed much more quickly because the actuation of the injection screw stopped as the filling process was terminated. The pressure curve received from PSB module was very similar to that received from the pressure sensor in the cavity. In fact, these two pressure curves represented more accurate pressure values in comparison with that estimated from the machine. The corresponding relative viscosity curves for different injection speeds were plotted in Fig. 4 (b). The relative viscosity curve provided comparative information for the change of the melt viscosity. The viscosity curves derived from the PSB module and the cavity pressure sensor were similar. The viscosity curve calculated by the data read from the control panel of the machine flattened down earlier than those from the other two approaches. Although the peak value of the pressure data acquired from the control panel of injection machine was the highest, the corresponding fill time was the least. This led to an earlier decrease of viscosity. The curve derived from the machine started to change from high to moderate viscosity at injection speed 30 mm/sec. In fact, the melt viscosity at this injection speed was still high. Similar results for another material ABS PA-756H were shown in Fig. 4 (c). It also showed that the time for a moderate melt viscosity calculated by the control panel of injection machine appeared earlier than the others. According to this curve, an improper setting on injection speed may cause large variation of the molded part quality. Oppositely, injection speed setting based on PSB module or pressure sensor in cavity is more reliable.

B. Influence of Injection Speed on Consistency of Molded Part Quality

The test mold which contained a tensile-test specimen was prepared to evaluate the influence of injection speed on the variation of the tensile strength. According to Figs. 4 (b) and (c), three injection speeds were selected for plastic materials ABS PA-707 and ABS PA-756H to demonstrate the effect of the imposed speed perturbations on the molding quality. These injection speeds were 25 mm/sec, 75 mm/sec, and 125 mm/sec, which corresponded to high, moderate, and low viscosities. The variations of these test results caused by the injection speed perturbations were expressed by using the standard deviation of all the test data (tensile strength and dimension) for each injection speed. In addition, the variation of the baseline process was also included for comparison. The standard deviation of the tensile strength for two plastic materials, where it represents the process variability due to the perturbations and the baseline variation for each injection speed, was illustrated in Fig. 5. The variation of the tensile strength showed significant process shift at low injection speed, and was decreased with the increase of injection speed. These data show apparently that high injection speed and moderate injection speed have less process variations than slow injection speed by 53% and 26% for material ABS PA-707 as well as by 70% and 34% for material ABS PA-756H, respectively. It is also observed that the process variations caused by the baseline variation for low viscosity material ABS PA-756H are less than those for high viscosity material ABS PA-707 at low, moderate, and fast injection speed by 23%, 10%, and 9.8%, respectively.

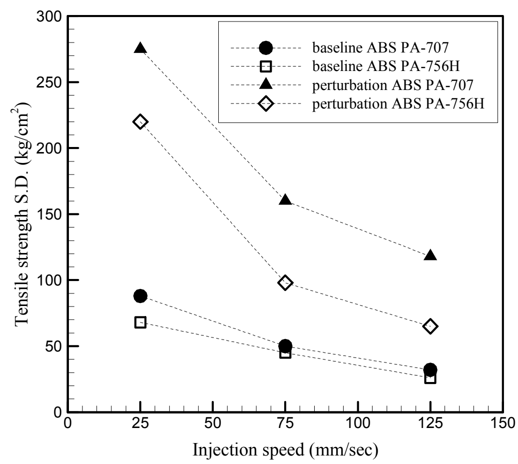

Fig. 5 Plot of tensile strength standard deviation versus injection speed

V. CONCLUSIONS

In this work, an apparatus named as PSB module was developed to provide a simplified installation feature for pressure measurements in injection process. A validation of this apparatus was also implemented and compared with the other approaches. The results show that the accuracy of the apparatus was higher than that of conventional approaches. The results verified that higher injection speeds in the filling stage of injection process caused the melt viscosity decrease and was helpful to reduce the variation of the molding quality. However, the injection speed should not be too high in case the shear-induced defects happen. In addition, the utility of the PSB module was a simple and timesaving approach for pressure measurements.

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