Real-Time Ultrasonic Monitoring of the Injection-Molding Process

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ABSTRACT: In this study, a noninvasive and nondestructive ultrasonic technique has been used to monitor the polymer injection-molding process in an attempt to establish a fundamental understanding of the processing/morphology/ultrasonic signal relationships. The ultrasonic technique not only can provide information on solidification affected by various temperatures and pressures but also can reflect the evolution of the crystal morphology and phase morphology of polymer blends. In addition, the periodic vibration of the dynamic-packing injection-molding process, in which the melt is forced to move repeatedly in a chamber by two pistons that move reversibly with the same frequency as the solidification progressively occurs from the mold wall to the molding core part, can also be monitored with the ultrasonic velocity and attenuation. Our results indicate that the ultrasonic technique is sensitive and promising for the real-time monitoring of the injection-molding process. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 107: 94–101, 2008

Key words: injection molding; molding; processing

INTRODUCTION

Injection molding is a widely used process for the manufacturing of complex products whose qualities are generally controlled by process variables such as the temperature and pressure. To improve the quality of molded parts, proper process variables should be adopted, besides the effects of the materials themselves. So far, most investigations have been focused on posterior observations, from which the process parameters are determined. Real-time monitoring of the process not only can provide information on what happens inside the cavity but also can aid in controlling the quality and improving the efficiency of the injection-molding process. Thus, real-time monitoring is highly desired in the polymer processing industry.

Temperature and pressure sensors are widely employed to monitor the process, but the feedback from the sensors is insufficient for some desired information; for instance, the evolution of the morphology of molded parts during the process and the specific solidification in the parts are not available, although plenty of work has been done with these sensors.[1] Moreover, some other techniques, such as fluorescent sensing[2,3] and optical techniques,[4] have been adopted to investigate polymers in the cavity, but these techniques are not applicable to industry. Recently, a noninvasive and nondestructive ultrasonic technique has attracted many researchers for the online monitoring of the injection-molding process because of its easy installation and the extremely rich information obtained from the cavity during injection molding. Temperature and pressure profiles can be deduced from the ultrasonic signal.[5,6] In addition, the process stages, such as the local flow front arrival, the filling end, the detachment of the injected part from the mold wall, and the gate freezing-off time, can be read with ultrasound,[7–12] so this makes it very powerful for the monitoring and optimization of the molding process. Furthermore, ultrasound can also be used to examine the development of the solid/liquid interface,[13] the evolution of the morphology,[14] and the orientation of the polymer chain[15] during injection. These make the ultrasonic technique quite promising for *in situ* monitoring and controlling the quality of injected products.

As part of a long-term project aimed at the real-time detection of the polymer morphology during injection molding, we are seeking to establish a fundamental understanding of the processing/morphology/ultrasonic signal relationships. This article reports some preliminary results of real-time ultrasonic monitoring of the injection-molding process. An ultrasonic technique has been used to explore the solidification behavior of crystalline and noncrystalline polymers during injection-molding processing,

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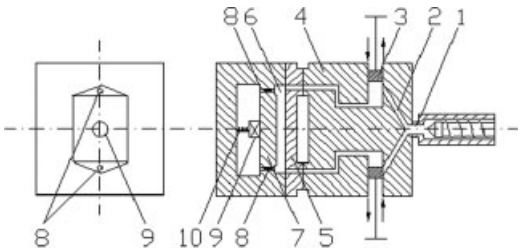

Figure 1 Schematic diagram of the device used for dynamic-packing injection molding: (1) the nozzle, (2) the sprue, (3) the piston, (4) the double live-feed device with heaters, (5) the stationary plate in contact with the cavity, (6) the cavity, (7) the mobile plate, (8) the pressure sensor, (9) the ultrasonic transducer, and (10) the spring.

and the effects of process variables, including the temperature and pressure, on the solidification of polymers and the morphology of polymer blends have been investigated. Because dynamic-packing injection molding, which relies on the application of shear stress fields to melt/solid interfaces during the packing stage by means of hydraulically actuated pistons, is a very important way of controlling the polymer morphology,[16–18] the ultrasonic characterization of dynamic-packing injection molding has also been carried out.

EXPERIMENTAL

Materials

Linear low-density polyethylene (LLDPE; 7042) with a melt flow index of 5.0 g/10 min was acquired from Ji Lin Petroleum Chemical Corp. (Jilin, China). Isotactic polypropylene (iPP; T30S) was purchased from Dusanzi Limited Co. (Xinjiang, China). Amorphous poly(methyl methacrylate) (PMMA) was from Acros (Belgium). An ethylene–octane copolymer (POE; Engage 8150; octane content = 25%, melt flow index = 0.5 g/10 min) was from DuPont (Delaware, USA).

Setup

The real-time monitoring was conducted in a setup for dynamic-packing injection molding. The principle of the dynamic-packing injection-molding technique is similar to that of shear controlled orientation in injection moulding (SCORIM) developed by Allan and Bevis.[19] A pilot hot-runner mold consisting of two parts was used: one double live-feed device with two hydraulically actuated pistons to keep the polymer in the melting state and to pack the polymer melt in a preferred mode and one molding unit to shape the specimen (Fig. 1). In the dynamic-packing mode, the injected melt was forced to move repeatedly in the cavity by the two reversibly moving pistons with the same frequency as the solidification occurred progressively from the mold wall to the molding core part. In the static-packing mode, the two pistons were kept stationary, and the molding process was the same as that of conventional injection molding. The stationary plate was insulated from the double live-feed device with heaters. The temperatures of the stationary and mobile plates could be controlled with circulating water. Two pressure sensors were located at the ends of the cavity to monitor the cavity pressure. The specimen was designed to be a 70 × 60 × 4 mm^3 thin square plate with two thickened fan gates, whose shape, along with the locations of the pressure sensors and ultrasonic transducer mounted opposite to the cavity on the internal side of the mobile plate (Fig. 1), is illustrated in Figure 2. The injection was performed with an SZ 100-g injection-molding machine (Tulan company, Nanjing, China).

Ultrasonic system and detection method

The ultrasonic system comprised a 5-MHz longitudinal wave pulsing/receiving transducer (5P6) (Guangdong Goworld Co., Ltd., Guangdong, China) and a PCUS10 card inserted into the main board of a computer (Guangdong Goworld Co., Ltd., Guangdong, China), which had all the components involved in ultrasonic equipment, such as a frequency generator, a wave filter, an A/D converter, and a data processor. The sampling rate was 80 Ms/s. The ultrasonic analysis system was supported by MESUS software (Guangdong Goworld Co., Ltd., Guangdong, China).

The ultrasonic monitoring was performed with a pulse–echo mode. According to the idea that ultrasound should be reflected at the interface, series of echoed signals can be recorded along the propagation direction. As illustrated in Figure 3, when ultrasound propagates through a polymer in a cavity and meets the back polymer/mold interface, the velocity and attenuation of the ultrasound in the polymer can be deduced from the flying time and amplitude of the corresponding reflected signal (U2). That is, a small flying time corresponds to a high velocity, and a low amplitude implies high attenuation.

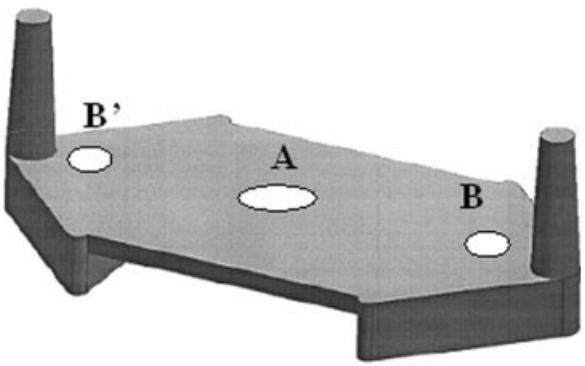

Figure 2 Schematic diagram of the injected specimen and locations of (A) the ultrasonic transducer and (B,B′) the pressure sensors.

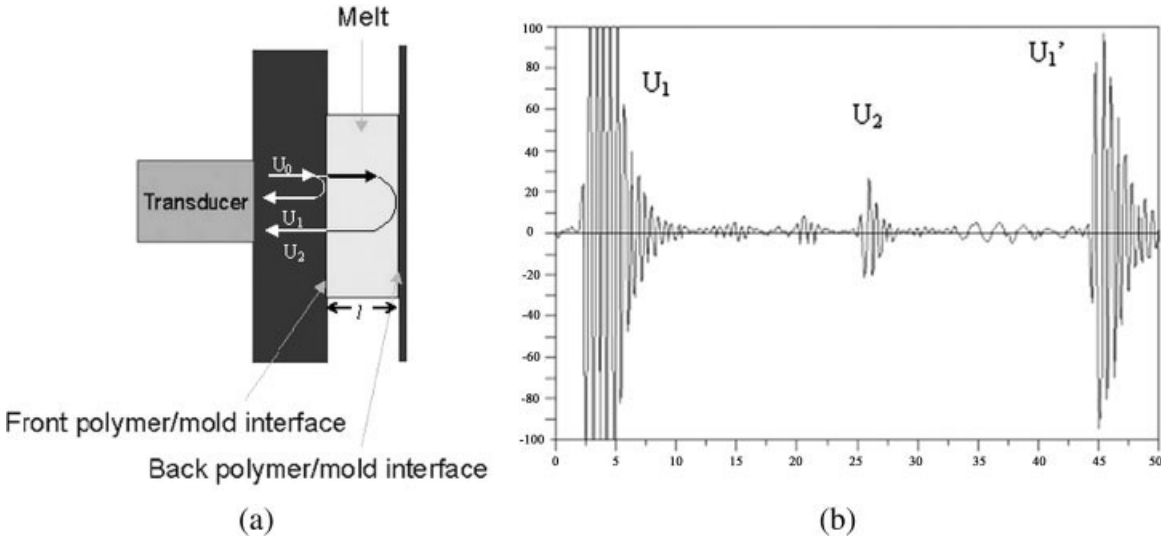

Figure 3 Schematic of the ultrasonic behavior of propagation at polymer/mold interfaces and corresponding echoed signals. U0 refers to the incident wave; U1 indicates the first echo reflected from the front polymer/mold interface, whereas U1′ implies the second echo reflected from the front polymer/mold interface; and U2 is the first echo reflected from the back polymer/mold interface.

RESULTS AND DISCUSSION

Ultrasonic behavior of LLDPE and PMMA

Semicrystalline LLDPE and amorphous PMMA have been adopted to investigate the ultrasonic characterization of different solidifications. Figure 4 shows the variation of the relative velocity deduced from the reciprocal of the flying time of signal U2 and the cavity pressure with the processing time during the injection molding of LLDPE. In terms of the relative velocity, four characteristic regions labeled on the figure are listed. The first one occurs between 0 and 4 s and provides information on the filling of the polymer. Before 3 s, no local flow front arrives. However, between 3 and 4 s, the rapid increase in the relative velocity and cavity pressure indicates the arrival of the melt and the end of filling at 4 s. In the second region between 4 and 9 s, both the velocity and pressure drop abruptly, and the relative velocity reaches its minimum at 9 s. However, from 9 to 35 s, the relative velocity rises slowly again. Then, the signal disappears, and the velocity suddenly drops to zero between 35 and 36 s. This indicates the detachment of the polymer from the mold and the formation of a gas gap.[20]

In the second region, the velocity decreases with the drop in the cavity pressure, and in this case, the pressure dominates the ultrasonic velocity. During propagation in polymer media, the ultrasonic velocity is closely related to the modulus of the polymer, which can be remarkably influenced by the cavity pressure, especially when the polymer exists in the melt state.[21,22] Therefore, the drop in pressure will reduce the modulus of the polymer melt and, subsequently, lower the ultrasonic velocity. Around 9 s, the cavity pressure almost drops to the minimum, and the steady increase in the velocity after 9 s should be attributed to the gradual solidification, which leads to the rise in the modulus.

As illustrated in Figure 5, the variation of the amplitude of signal U2 with the processing time also takes on four characteristic regions. The first and last ones equally donate to the filling and detachment stages. In the second region (4–7 s), the rapid drop in the amplitude, that is, the quick rise in the ultrasonic attenuation, is related to the variation of the melt viscosity. Generally, a high melt viscosity induces high attenuation in viscoelastic media. At the end of the filling (4 s), the melt viscosity reaches its

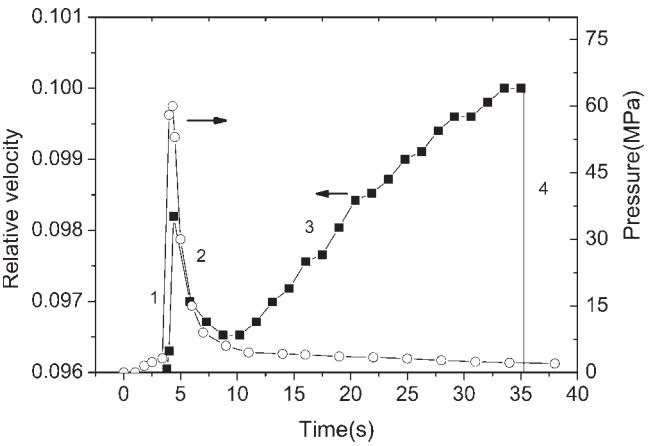

Figure 4 Variation of the pressure in the cavity and the ultrasonic relative velocity in LLDPE with the process time during static-packing injection molding.

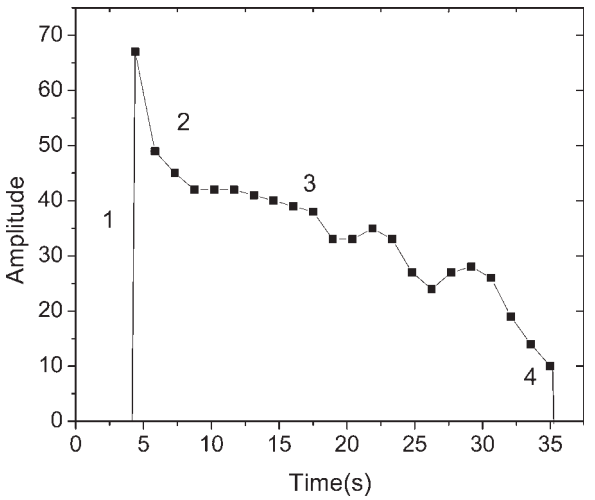

Figure 5 Variation of the amplitude from the back mold/polymer interface for LLDPE with the process time during static-packing injection molding.

minimum because of the preferred orientation of the polymer chain along the flow direction caused by the shear flow; herein, the attenuation is minimum. However, from 4 to 7 s, the melt viscosity abruptly increases because of the cease of flow and the decrease in the temperature.

As for amorphous PMMA, the relationship of the ultrasonic velocity and attenuation with the processing time is similar to that of LLDPE, as shown in Figures 6 and 7, except for the difference in the variation of the attenuation with time after 9 s. That is, the attenuation decreases with time for PMMA, whereas it increases with time for LLDPE. This is ascribed to their different solidification behaviors. During the solidification of amorphous PMMA, the chains are frozen, and the elasticity of the polymer is improved gradually. As a result, ultrasonic attenuation, mainly from the viscoelastic absorption loss, decreases (Fig. 7). However, as far as crystalline

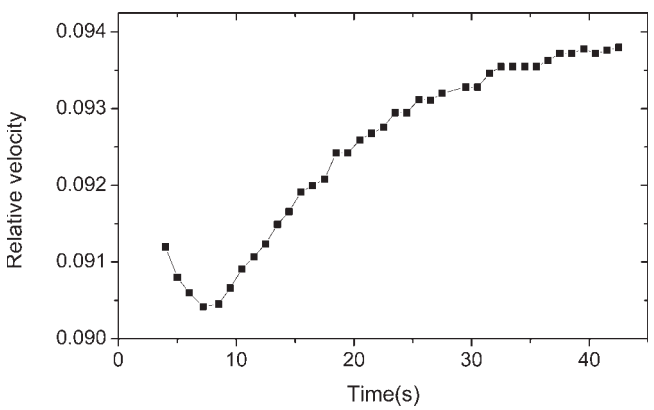

Figure 6 Variation of the ultrasonic relative velocity in PMMA with the process time during static-packing injection molding.

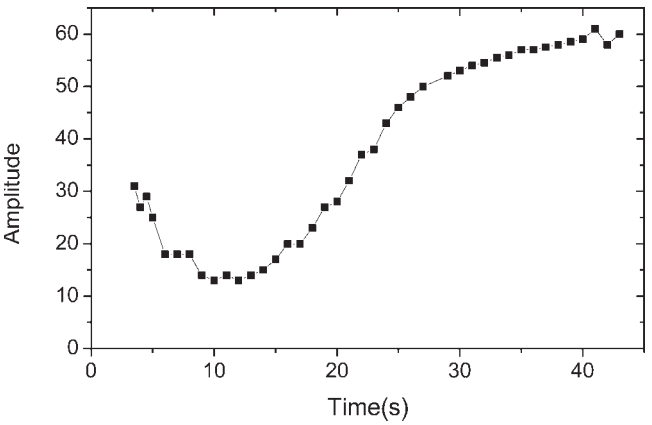

Figure 7 Variation of the amplitude from the back mold/polymer interface for PMMA with the process time during static-packing injection molding.

LLDPE is concerned, although the increase in the elasticity will equally reduce the attenuation, the crystallites that form during solidification will induce a scattering loss inversely and even play a major role in controlling ultrasonic attenuation. Thus, the attenuation rises because of the occurrence of more and more crystallites during the process of solidification (Fig. 5).

Effect of the temperature on solidification detected by ultrasound

In injection molding, the temperature, including the melting temperature and mold temperature, will influence the process of solidification and consequently affect the ultrasonic behavior. Figure 8 shows the effect of the mobile-plate temperature on the ultrasonic velocity. At any temperature, the trend of the velocity variation with time is the same: a

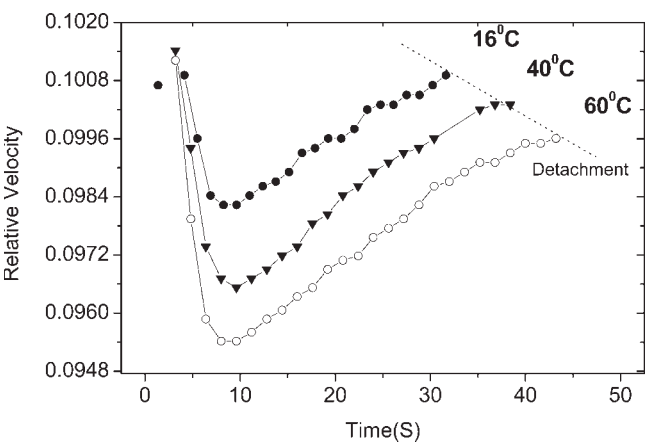

Figure 8 Effect of the mobile-plate temperature on the ultrasonic velocity in LLDPE. The melting temperature is 240°C, whereas the stationary plate temperature is 168°C. The injection pressure is 60 MPa.

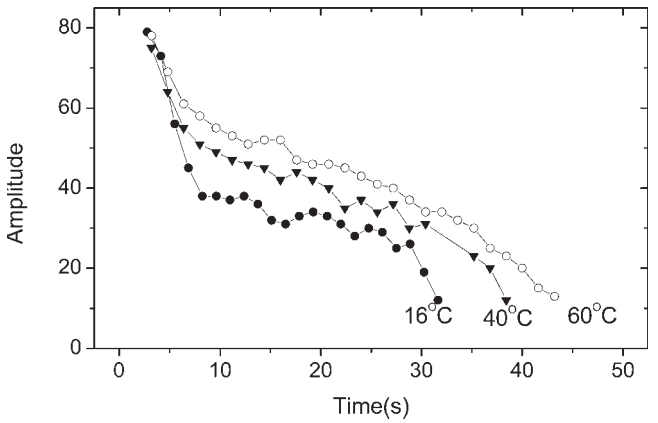

Figure 9 Effect of the mobile-mold temperature on the amplitude of the echo signal for LLDPE. The melting temperature is 240°C, whereas the stationary plate temperature is 168°C. The injection pressure is 60 MPa.

drop between 4 and 9 s and a rise after 9 s. Nevertheless, the degree of the drop in the velocity increases with increasing temperature. According to the previous discussion, the velocity is dominated by the cavity pressure in this stage. From 4 to 9 s, the drop in the pressure is independent of the mold temperature, but a high temperature causes an elevated dependence of the ultrasonic velocity on the pressure.

According to the Tait equation,[23] specific volume v decreases with increasing pressure p at a constant temperature T, but the lower T is, the weaker the effect is of p on v:

$$v(p,T) = v(0,T)\left\{1 - c\ln\left[1 + \frac{p}{p(T)}\right]\right\} \quad (1)$$

where c is the universal constant for the Tait equation, $p(T)$ is the temperature dependence of the parameter for the Tait equation, and $v(0,T)$ is the specific volume at atmospheric pressure. Generally, a low value of v corresponds to a high value of bulk modulus B, which finally determines ultrasonic velocity (longitudinal wave) c_L:

$$c_L = \sqrt{\frac{(B + 4/3G)}{\rho}} \approx \sqrt{B/\rho} \quad (2)$$

where G is the shear modulus and ρ is the density of the materials. Therefore, the ultrasonic velocity in the polymer is finally affected by the cavity pressure and temperature of the polymer. Under constant pressure, a high temperature results in a low velocity; a high pressure induces a high velocity at a constant temperature. Furthermore, the effect of the pressure on the velocity becomes weaker and weaker as the temperature decreases.

When the melting temperature and injection pressure are kept constant, the ultrasonic velocity is independent of the mold temperature at the end of the filling (4 s) because of the same polymer temperature (Fig. 8). However, after 4 s, a lower mold temperature causes a decrease in the polymer temperature because of quicker heat exchange from the polymer to the mold, and this induces a weaker effect of the pressure on the velocity. Therefore, at 9 s, the velocity corresponding to 16°C is the highest because of the weakest effect of pressure on the velocity in comparison with the other mold temperatures (40 and 60°C). A low mold temperature also quickens the solidification, so after 9 s, a lower mold temperature corresponds to a higher velocity and a shortened detachment time, as shown in Figure 8.

Figure 9 illustrates the effect of the mold temperature on the ultrasonic attenuation. A lower mold temperature corresponds to higher attenuation. This can be attributed to the fact that more crystallites are formed at a higher rate of solidification at the same moment, and this consequently enlarges the attenuation for scattering loss. When the melting temperature is changed, similar phenomena can be observed.

Effect of the injection pressure on solidification detected by ultrasound

Figures 10 and 11 show the effects of the injection pressure on the ultrasonic velocity and attenuation for LLDPE, respectively. The effect of pressure is similar to that of temperature: a high injection pressure corresponds to a low ultrasonic velocity and attenuation. This may be related to the temperature of the polymer in the cavity. It is clear that additional heat originates from the friction between the

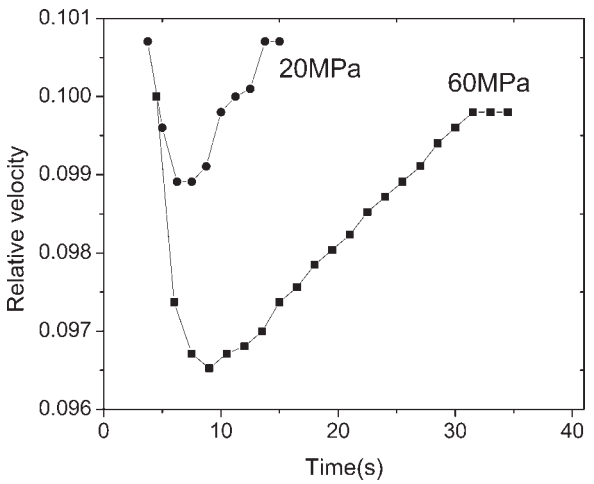

Figure 10 Effect of the injection pressure on the ultrasonic velocity in LLDPE. The mobile-plate temperature is 30°C, whereas the stationary plate temperature is 150°C; the melting temperature is 240°C.

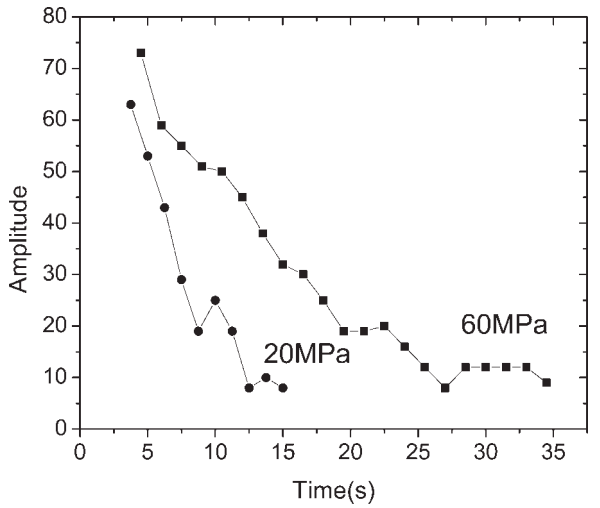

Figure 11 Effect of the injection pressure on the amplitude of the echo signal for LLDPE. The mobile-plate temperature is 30°C, whereas the stationary plate temperature is 150°C; the melting temperature is 240°C.

polymer chains while they are flowing. Generally, a rise in the injection pressure can quicken the flowing of the polymer melt; as a result, more heat can be converted. Therefore, at the same moment, the polymer injected under a higher pressure has a higher temperature, although the melting temperature is kept constant.

Ultrasonic characterization of the phase morphology for polymer blends

For a crystalline polymer, a different solidification rate gives rise to different ultrasonic attenuation, which is based on the dependence of the attenuation on the crystal morphology. To investigate the ability of ultrasound to characterize the phase morphology of polymer blends, an iPP/POE (60/40) blend was adopted for our experiment. It has been verified that at a high melting temperature, this system is almost miscible; however, phase separation occurs when this blend is injected into a mold as the polymer temperature decreases.[24] Figure 12 illustrates the variation of the phase morphologies of an iPP/POE blend with the thickness from the skin layer to the core layer for an injected specimen. The homogeneous morphology of the skin layer shows that this blend in the melt state is miscible. However, from the skin to the core layer, the sizes of the dispersed POE phase become larger and larger because more and more time is left for the blend to perform the process of phase separation. According to the principle of ultrasonic attenuation, the scattering loss caused by the dispersed phase contributes to acoustic attenuation. Therefore, it is easily predicted that such a scattering loss will increase with the processing time because more dispersed phase particles are formed during solidification. Figure 13 shows that ultrasonic attenuation increases with time. As dis-

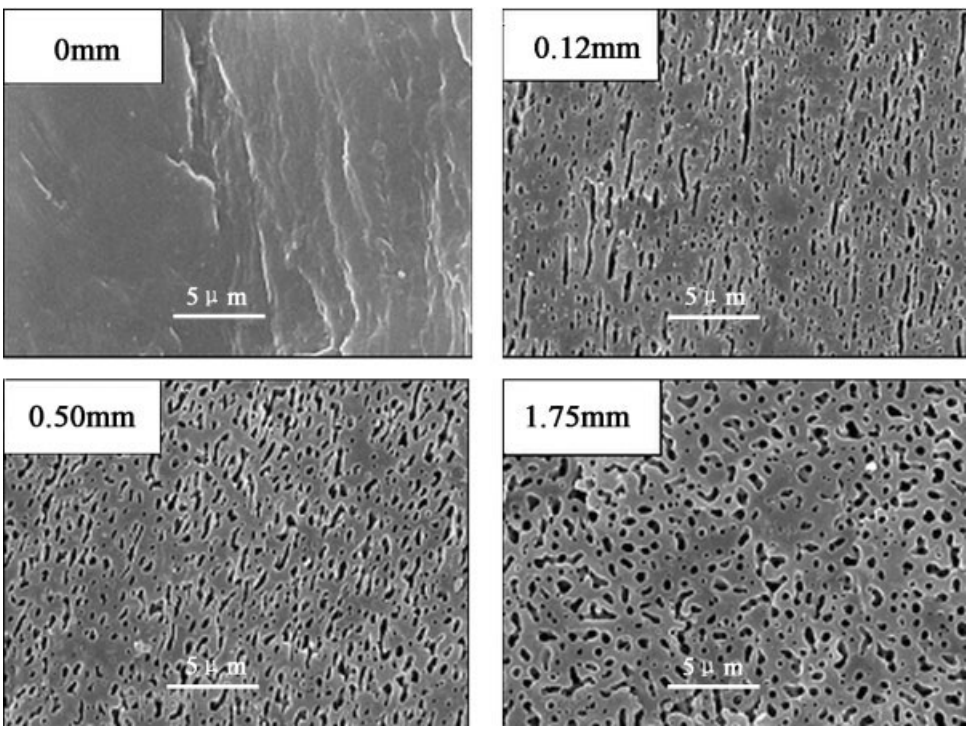

Figure 12 Morphologies of an iPP/POE blend with the thickness from the skin layer to the core layer for an injected specimen.

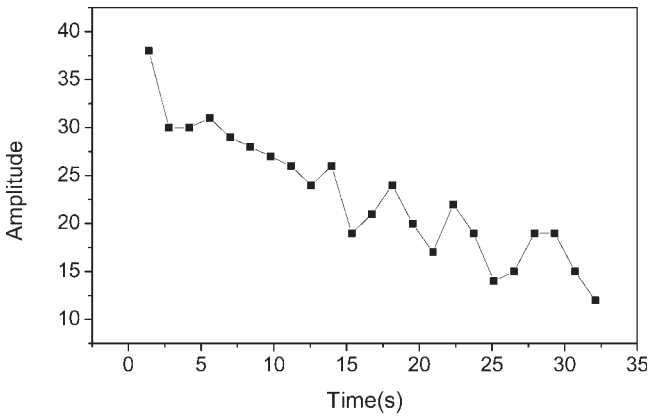

Figure 13 Variation of the echo signal amplitude for iPP/POE blends with time during static-packing injection molding.

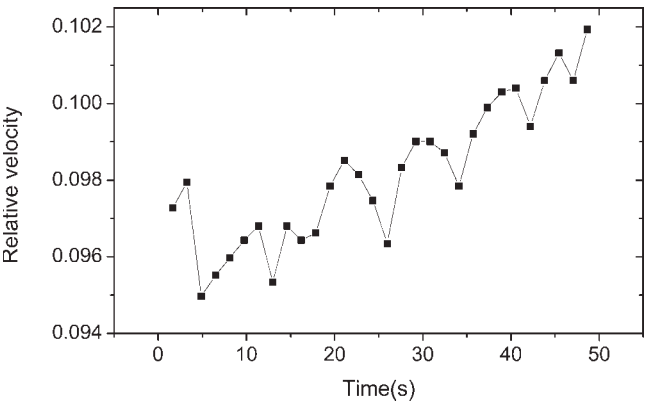

Figure 15 Variation of the ultrasonic velocity in LLDPE with time during dynamic-packing injection molding. The mobile-plate temperature is 43°C, the stationary-plate temperature is 110°C, the melting temperature is 200°C, and the injection pressure is 40 MPa.

cussed previously, the iPP crystallites that form during solidification equally cause ultrasonic attenuation. The quantitative relationship between ultrasonic attenuation and phase separation and crystallization should be separately investigated later.

Ultrasonic characterization of dynamic-packing injection molding

During the process of dynamic-packing injection molding, the injected melt is forced to move repeatedly in the cavity by two reversibly moving pistons with the same frequency. Thus, the pressure in the cavity and the rate of the melt flow vary with the periodic vibration of the pistons. Figure 14 shows that the periodic vibration of the pistons causes the fluctuation of the pressure at the same frequency. However, the amplitude of the fluctuation with time is characterized by small–large–small phenomena, which are related to the resistance to the flow of the melt influenced by solidification. The specific process is discussed later.

As mentioned previously, the cavity pressure affects the ultrasonic velocity. Presumably, the periodic fluctuation of the pressure causes corresponding undulations of the ultrasonic velocity, and this is verified by Figure 15. However, the overall variation trend of the velocity with time is ascending, and this can be ascribed to further solidification with time. The to-and-from flowing of the polymer melt will change the melt viscosity and correspondingly give rise to the vibration of ultrasonic attenuation, as shown in Figure 16. At the same time, more time is needed for polymer solidification during dynamic-packing injection molding because the melt at a high temperature is repeatedly pushed into the cavity and

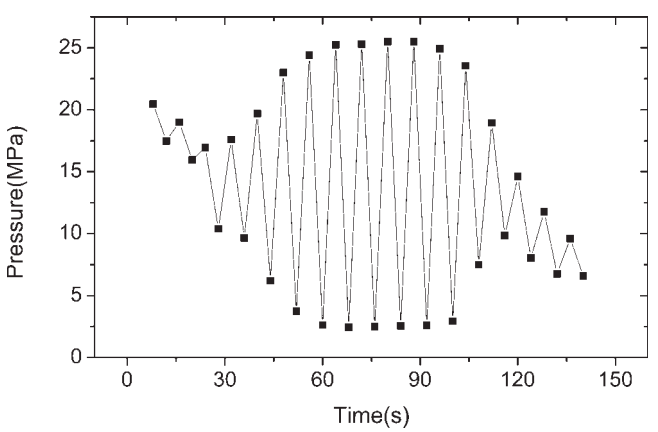

Figure 14 Variation of the cavity pressure with time during dynamic-packing injection molding of LLDPE. The mobile-plate temperature is 43°C, the stationary-plate temperature is 110°C, the melting temperature is 200°C, and the injection pressure is 40 MPa.

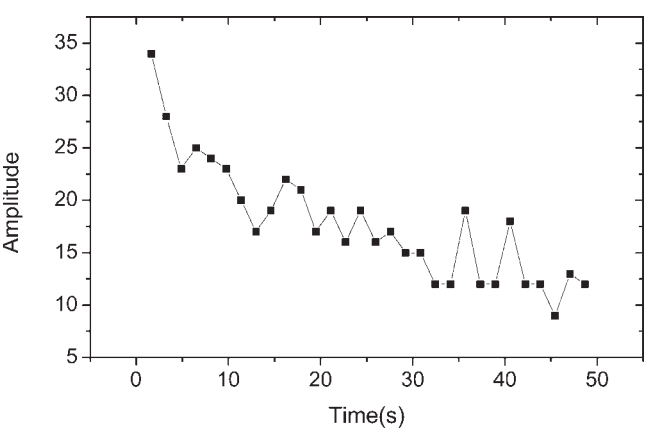

Figure 16 Variation of the amplitude of the echo signal for LLDPE with time during dynamic-packing injection molding. The mobile-plate temperature is 43°C, the stationary-plate temperature is 110°C, the melting temperature is 200°C, and the injection pressure is 40 MPa.

more heat arises during the shear flow, and this results in a high temperature in the cavity.

CONCLUSIONS

The complicated process of polymer injection molding can be monitored in real time with an ultrasonic technique. Some important information, such as the filling, solidification, and detachment from the mold, can be obtained by the determination of the changes in the ultrasonic velocity and attenuation. Processing variables, including the temperature and pressure, influence the filling and solidification process of a polymer during injection molding and can be reflected by the variations of the ultrasonic velocity and attenuation. Crystalline LLDPE and noncrystalline PMMA have different ultrasonic behaviors ascribable to the scattering attenuation caused by crystallites that form during solidification for LLDPE. Additionally, the periodic movement of pistons during the process of dynamic-packing injection molding can also be monitored by corresponding vibrations of the ultrasonic velocity and attenuation.

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