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A Real-time Ultrasonic Technique for Viscosity Monitoring during Polymer Processing

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Abstract. An experimental means has been designed for studying the possibility of using ultrasound to monitor melt viscosity change during polymer processing. The results have shown that not only ultrasound is capable of following melt viscosity change as results of temperature and flow rate variations, but also sensitive to material composition change. The sensitivity of ultrasound to both processing conditions and material composition makes ultrasound an excellent tool for the monitoring and control of polymer processes.

Keywords: ultrasound, viscosity.

INTRODUCTION

Ultrasonic diagnostic techniques usually make use of ultrasound velocity and attenuation in an evaluation material to gain insight about material composition, structure, morphology, and viscoelastic properties, etc. Being nondestructive in nature, sensitive and fast in response to material properties and processing conditions, ultrasound is gaining more and more acceptance as a cost-effective in-process monitoring tool for polymer processing [1-4]. The purpose of the present work is to study the possibility of using ultrasound to monitor melt viscosity change during polymer processing and compare the ultrasonic approach with the conventional pressure-based viscosity sensing approach. To this end, a special experimental means was designed and employed.

SENSING DESIGN

The sensing design is composed of two main components: a capillary rheometer and an instrumented slit die (Fig. 1). The slit die was fitted to the barrel exit of the capillary rheometer. The rheometer was used to heat polymer and control the flow rate of a polymer melt through the instrumented die slit. The slit die was equipped with two ultrasound sensors (UT_1 , UT_2) located in cross-section I, one pressure sensor (P_{II}) and one die temperature sensor (T_{die}) in cross-section II, one pressure sensor (P_{III}) and one melt temperature sensor (T_{III}) in cross-section III, and one pressure sensor (P_{IV}) and one melt temperature sensor (T_{IV}) in cross-section IV. The ultrasound sensors were axially aligned, but on the opposite sides of the slit. The cross-sections I, II, III, and IV were equidistantly located from the exit of the slit die. The slit die temperature was controlled with a wrapped-on heating jacket. The sensors and the thermocouple were mounted flush and perpendicularly to the wider surfaces of the slit. A 5-MHz center frequency acoustic pulse was generated by one of the two ultrasound sensors. The acoustic pulse was transmitted to the polymer and received by the other ultrasound sensor on the opposing side of the slit. By measuring the travel time τ of the acoustic pulse through the slit, the ultrasound velocity in the polymer melt was obtained as $v = d / \tau$, where d is the thickness of the slit. At the same time, temperatures and pressures at different locations were recorded. From the speed at which a polymer melt flew out of the slit die, the dimensions of the slit die opening, and the pressure differences between II, III, and IV locations, the viscosity of the melt was determined [5]. The pressure at ultrasound sensor location was estimated by extrapolating pressure readings at II, III, and IV locations.

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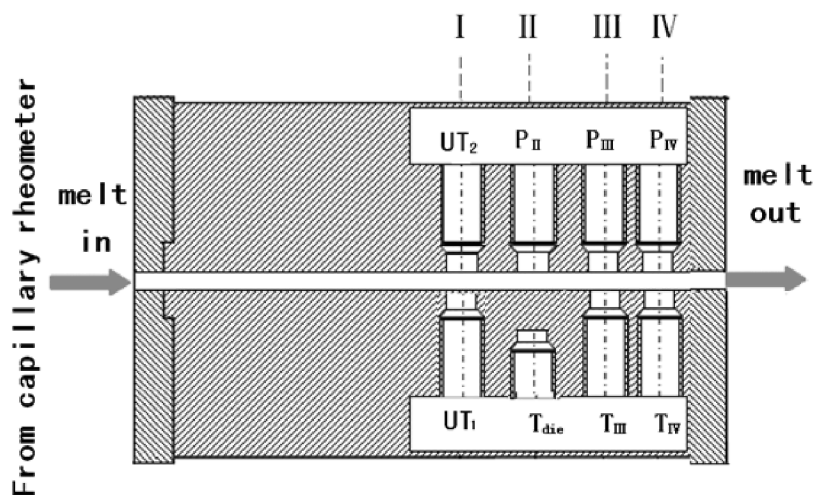


FIGURE 1. Schematic of the instrumented slit die used in the study.

RESULTS AND DISCUSSIONS

Two homo polypropylenes with melt flow indices (MFI) of 12 (PP1) and 2 (PP2), respectively, and a polystyrene (PS) with a MFI of 3.5 were tested. Figure 2 shows typical behaviors of melt pressure, temperature, and ultrasound velocity during a test of PP1 carried out at a set temperature of 220 °C and a shear rate of 12.5 s⁻¹. Upon engaging the piston of the capillary rheometer into pushing a polymer melt through the slit (at about 13 seconds into the recording), both pressure and ultrasound velocity increased sharply, then leveled off. The melt temperature increased also. The abrupt increase in ultrasound velocity is caused by fast pressure change, given that ultrasound velocity is a function of mass density and elastic modulus of the melt and both of which are affected by pressure. The increase in melt temperature is believed to be caused by shear heating. As can be seen in the figure, the evolution of ultrasound velocity does not follow exactly that of pressure. This is because ultrasound speed is also a function of temperature. The slight departure of the ultrasound velocity curve (ripples in the curve) from that of pressure is indeed accounted for by melt temperature variation. After the piston stopped, the melt pressure decreased quickly, so did the ultrasound velocity as a consequence of pressure drop. Figure 3 displays evolution of melt pressure versus melt viscosity change for different materials and at selected temperatures. For a given material and at a given temperature, melt pressure decreases with an increase in melt viscosity. This is because, due to shear thinning effect, smaller viscosity values were obtained at higher shear rates and the latter were achieved by increasing piston speed thus creating higher melt pressures. Owing to this obvious monotonic dependence of melt pressure on melt viscosity, melt pressure has long to be used as a means to gauge viscosity change. Figure 4 shows evolution of ultrasound velocity versus melt viscosity change. The ultrasound velocity values were those obtained when the pressure stabilized. Similar to melt pressure, ultrasound velocity also manifests a monotonic dependence on melt viscosity. In other words, ultrasound velocity can also be used in a similar way that pressure is used for viscosity monitoring or measurement. However, compared with pressure, ultrasound velocity does demonstrate its superiority in making distinction among different materials. For example, in Fig. 3, at 220 °C, the pressure measurement makes almost no distinction between PP2 and PS, whereas the difference of the two materials is seen unambiguously by ultrasound in Fig. 4. In other words, in addition to its capability of sensing pressure change, ultrasound also offers a means to monitor material composition change during a process. This makes ultrasound a preferred monitoring tool when processing easily degradable materials, or when batch-to-batch variation in material properties can compromise the quality of products.

CONCLUSIONS

Ultrasound velocity in a polymer melt could be used in a similar way a pressure sensor is used for monitoring melt viscosity change during polymer processes. Since ultrasound velocity is also conditioned by the physical composition and structure of a material, it can be used to monitor material composition or structure change as well.

This particularity of ultrasound of being sensitive to viscosity variation and material composition change at the same time makes it a valuable choice as monitoring tool for a variety of polymer processes.

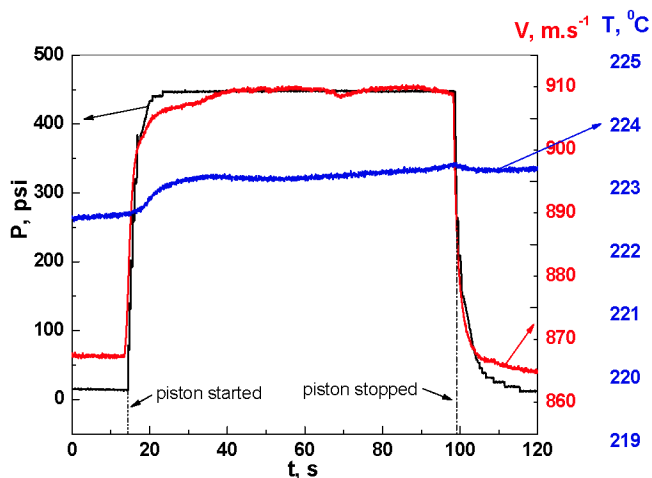


FIGURE 2. Evolutions of ultrasound velocity (V), melt temperature (T), and melt pressure (P) during a test of PP1 carried out at a shear rate of 12.5 s^{-1} .

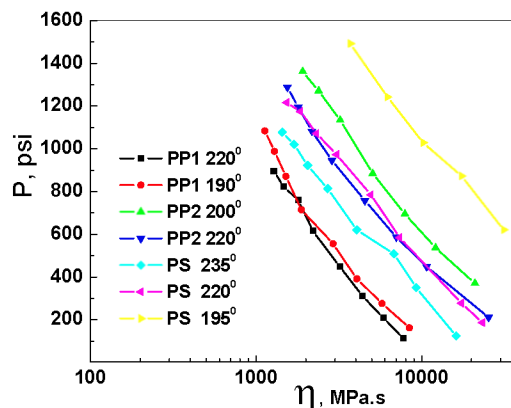


FIGURE 3. Evolution of melt pressure versus melt viscosity change for different polymers and temperatures.

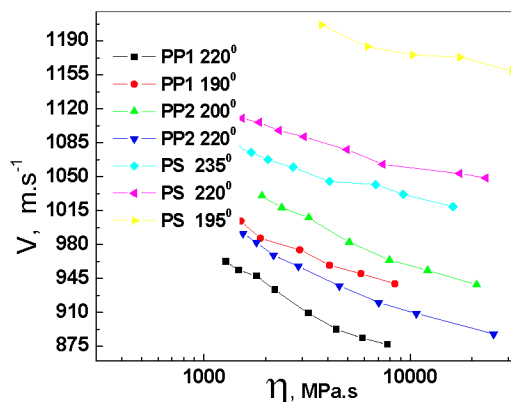


FIGURE 4. Evolution of ultrasound velocity versus melt viscosity change for different polymers and temperatures.

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