ON-LINE MONITORING OF POLYMER ORIENTATION DURING INJECTION MOLDING

Russell Edwards, University of Utah, Salt Lake City, UT 84112
Charles L. Thomas, University of Utah, Salt Lake City, UT 84112
Anthony J. Bur, Polymers Division, NIST, Gaithersburg, MD 20899

Abstract

A non-invasive, on-line technique for monitoring the orientation of polymer in the mold cavity during injection molding is demonstrated. The propagation velocity of an ultrasonic shear wave can be used to detect anisotropic behavior in the mechanical properties of a solid. Thus, an ultrasonic shear transducer embedded in an injection mold produces a signal that is sensitive to polymer orientation. The technique is shown to be quite sensitive for semicrystalline polymers, but much less effective for amorphous polymers. Sensor results are compared to mechanical tests performed on plastic specimens.

Introduction

Molecular orientation has long been recognized as an important factor affecting the final properties of injection molded parts [1,2,3,4]. Therefore, techniques to detect and quantify this property have been of interest. Traditional methods used to measure molecular orientation include birefringence [1,2] and X-ray defraction [5,6]. Other methods relate anisotropy to mechanical properties of the plastic using common mechanical tests [2,5,9]. Most of these methods are laboratory measurements and therefore must be conducted off-line after the plastic has been fabricated.

Interest is now growing in measuring molecular orientation real-time. Pepper and Samuels have shown that orientation can be measured in-situ during tensile testing through the absorption of polarized IR light [7, 8]. This technique offers the advantage of studying the development of orientation while the polymer is deformed. Although effective for laboratory experiments, the technique is impractical for on-line orientation measurements.

Several research groups have studied the use of ultrasound to measure various polymer conditions while being molded [9, 10, 11]. This method is attractive because of the non-invasive nature of ultrasound, which has also proven fast enough for real-time, on-line analysis.

Researchers have also used ultrasound in a laboratory setting as a non-destructive method to detect anisotropic properties in oriented plastic. Treloar has proposed a method to measure orientation by converting longitudinal sound waves into shear waves [2]. This was accomplished by immersing a plastic specimen in a liquid bath and reflecting a longitudinal sound wave at an angle normal to the surface of the plastic. This produced a shear wave inside the plastic. By measuring the amplitude of the reflected wave at different angles, it was possible to determine the speed of sound of the shear wave, which could then be related to the shear modulus. By rotating the part and repeating the experiment, the shear modulus was plotted as a function of rotation angle. Konno et. al. used a more direct method to demonstrate the same results [9].

In this work an ultrasonic shear transducer was used to detect the change in axial and transverse shear velocities as a function of process time. The change in velocity could then be related to or defined as an orientation measurement.

Experimental Setup

The average sound velocity in a medium can be measured by sending a short sound pulse through a medium and measuring the time for the sound to travel a known distance. An arrangement as shown in Fig. 1 can be used to measure the sound velocity of an embedded object. Each internal interface is constructed to be parallel with the top surface. A sound pulse is sent into the materials and a reflection occurs at each interface. The echoes are then detected by the transducer. Conveniently, the time delay between the two echoes is independent of material surrounding the embedded object. By measuring the delay between the echoes and knowing the thickness of the object, the average sound velocity of the embedded material can be computed.

This arrangement was constructed in the mold as shown in Fig. 2 and 3. In this setup, the shear transducer was located on the backside of an aluminum insert housed inside a steel mold. A thin rectangular cavity was machined into the removable insert directly opposite of the location of the transducer. With the mold closed, the layered arrangement described previously was formed.

Fig. 2 shows a diagram of the equipment used in the experimental setup. A 50 ton injection molding machine was used to process the plastic. The transducer was driven by a repetitive high voltage spike, which was supplied by the pulser electronics. The receiver circuitry amplified and filtered the echoes, which were then digitized by a high-speed analog to digital converter. The binary encoded values were stored into a computers volatile memory and then displayed and transferred to secondary storage.

Although the waveforms were collected real-time, they were analyzed after the process was over for convenience. It is anticipated, however, that the orientation measurement could be calculated on-line and used in the process control of the injection-molding machine. It is estimated that the orientation data could be computed at a rate of 300 Hz, which is adequate for most mechanical and thermal control systems.

A more detailed view of the transducer and insert is shown in Fig. 3. The cavity (1x70x100 mm) was designed to be thin and long to produce the necessary shear stresses to orient the plastic. A large gate was used to fill the cavity uniformly. The transducer was located close to the intersection of the horizontal and vertical centerlines of the cavity. It should be noted that the orientation measurement described is an average measurement at the location of the transducer over an area approximately the same size as the transducer. The transducer was coupled to the back of the insert with a viscous epoxy allowing the transducer to be repositioned and still support a shear wave. By rotating the transducer, the particle vibration direction could be changed with respect to the plastic flow direction.

The experiment was conducted by repetitively pulsing the transducer and collecting the reflected echoes while the plastic was injected. The procedure was repeated while the transducer was oriented parallel, perpendicular and 45 degrees to the plastic flow direction.

Experimental Ultrasound Data

Typical plots of the echoes collected after solidification of injection molded high density polyethylene (HDPE), are shown in Fig. 4 where each transducer orientation is represented. The amplitude of the echoes represent the power intensity of the sound. By viewing these plots, it was observed that the time difference between the echoes is shorter for the parallel transducer orientation which corresponds to a faster sound velocity in the axial direction. This indicates that the plastic has anisotropic properties since the speed of sound is a function of the direction of particle vibration.

An interesting result occurs when the transducer is placed between the transverse and axial directions. The energy in the sound wave decomposes into two discrete characteristic echoes with the same time delays found when the transducer was rotated parallel and perpendicular to the plastic flow. This result has practical importance since it is now necessary to have only one transducer in the mold to measure both characteristic sound velocities.

A different way to represent the waveform shown in Fig. 4 is to plot a scaled horizontal line with shades of gray representing the amplitude of the echoes. If a series of waveforms are collected as a function of time and then stacked next to each other, an image showing how the waveforms change can be visualized. This is known as an M-mode image. Three such images are shown in Fig. 5 for HDPE, where each plot represents one of the three transducer orientations as a function of process time.

Quantification of Orientation Measurement

To demonstrate that the change in velocity between the axial and transverse direction is related to the degree of orientation, a simple experiment was conducted. Several parts were molded to maximize and minimize orientation. This was accomplished by changing the processing conditions as explained by Fujiyama and Kimura [4,12,13]. They demonstrated that several processing variables changed the degree of orientation in the molded part. However, the dominating factor that influenced molecular orientation was the plastic melt temperature. For this experiment, the temperature was the only variable adjusted to vary the anisotropy in the molded parts. The HDPE was injected at two nozzle temperatures, 170 C and 260 C. Afterwards, the shear transducer was coupled directly to the plastic part and the echoes were recorded for the axial and transverse direction (see Fig. 6). The change in velocity proved to be much greater for the high oriented part in contrast to the low oriented part. This test demonstrated that the change in the sound velocity is sensitive to the degree of anisotropy.

Uncertainties do arise in the quantification of the ultrasonic orientation measurements. One problem may arise if the material is not uniformly oriented throughout the thickness. Most models suggest that orientation occurs in layers. Research has shown that for a rectangular plaque, the orientation occurs in a skin/core morphology with variable skin thickness where the bulk of oriented polymer is contained in the skin [5,6,12,13]. Since the ultrasonic wave travels through both skin and core, the change in delay times between the characteristic echoes represent an average orientation measurement over the cross section of the part.

Crystallinity is a factor in the sensitivity of the ultrasonic orientation measurement. The same hand test was conducted for amorphous general purpose polystyrene

(GPPS). This test showed that the changes in sound velocities for GPPS were almost undetectable. This is in agreement with Treloar [2]. The role of crystallinity in sound velocity is currently being investigated.

Verification of Anisotropic Behavior

To verify that the parts were oriented, the injection molded parts of the HDPE were cut into tensile specimens (see Fig. 7) and failed in tension. The load /deflection curves are shown in Fig. 8. The geometry of each specimen is assumed to be the same and therefore the curves represent the same trends as a stress/strain diagram.

It is interesting to note, that for small deflections, the stiffness does not change between the axial and transverse specimens. The anisotropy becomes most apparent at plastic deformation. High oriented specimens cut in the transverse direction shows the greatest change from the general trends shown in the other curves. This agrees with the ultrasonic test data shown in Fig. 6.

Estimation of Uncertainty

Sources of potential error in the ultrasonic orientation measurement are related to how accurately the sound velocity can be measured. Using a pulse echo technique, the sound velocity is measured by determining the time delay and thickness of the part. Flashing and shrinkage cause variations in the thickness. A dominant factor influencing the error of measuring the time of flight is the signal to noise ratio of the reflected echoes. Different plastics attenuate the reflected echoes while other mediums scatter sound to create acoustical noise. Each has the same effect by decreasing the apparent amplitude of the reflected echoes. Hand tests are more accurate than on-line measurements since more sound energy is reflected back to the transducer. For HDPE, it is estimated that +/- 10% of the maximum orientation value can be measured. For polymers with less sensitivity to the changes in velocity, uncertainty will increase.

Conclusions

An ultrasonic shear transducer was used to propagate sound waves through plastic while being processed. Two characteristic sound velocities were observed. The change in the characteristic sound velocities was shown to be sensitive to the degree of molecular orientation. This technique offers the advantage of real-time, non-invasive orientation measurements while on-line.

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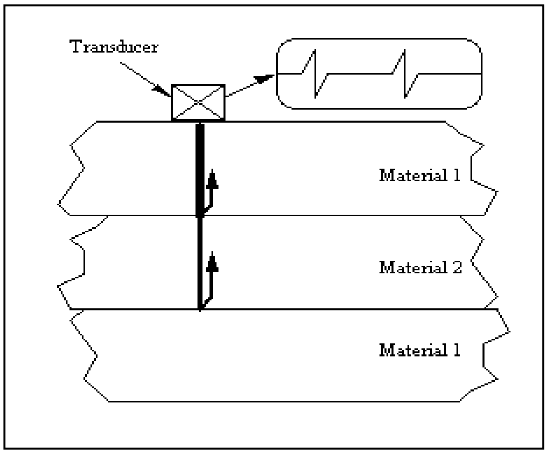

Figure 1. General arrangement for ultrasonic velocity measurement.

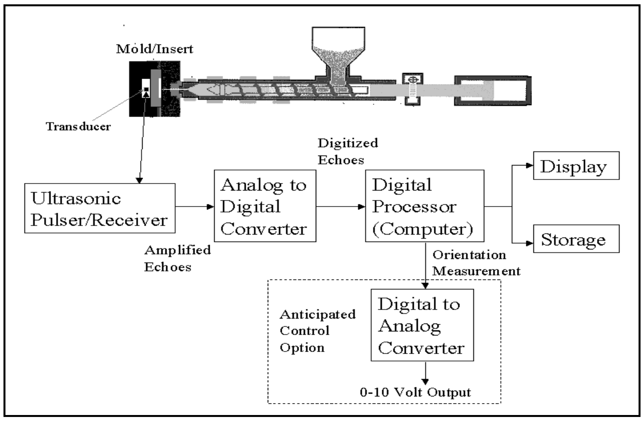

Figure 2. Block diagram of on-line orientation

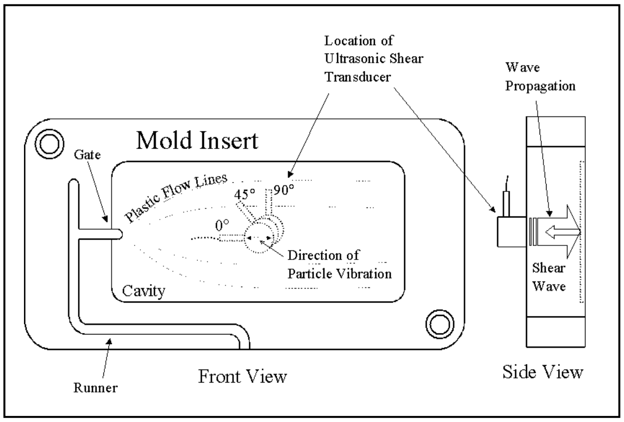

Figure 3. Transducer location and orientation with respect to the insert.

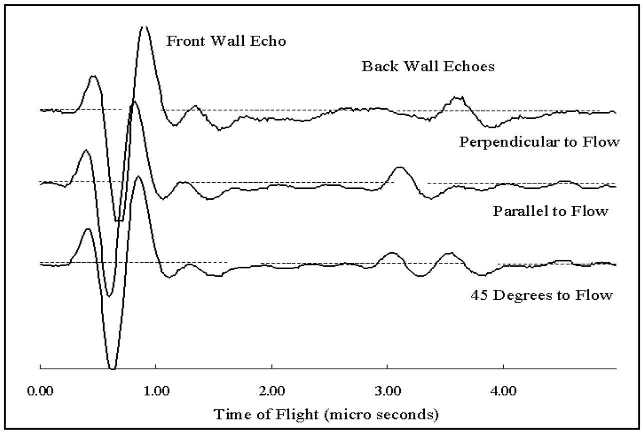

Figure 4. Amplitude waveforms of ultrasound shear echoes for three different transducer orientations.

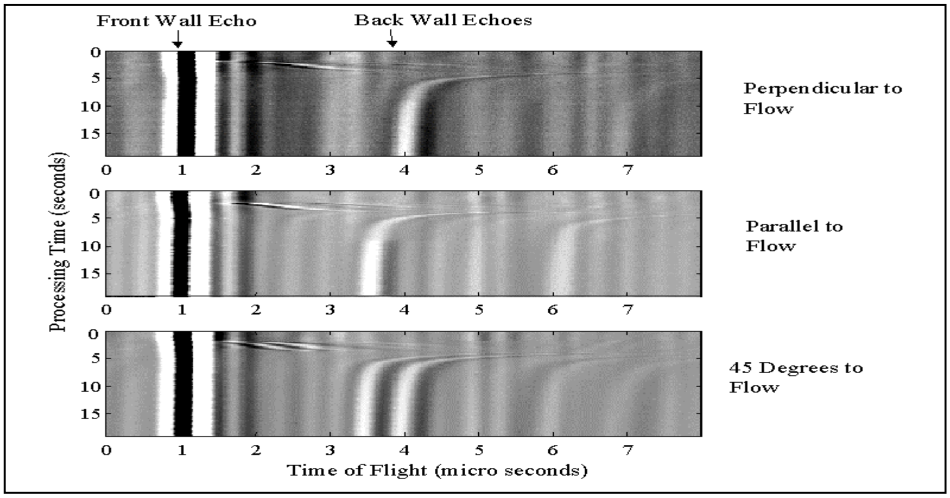

Figure 5. M-mode plots of ultrasonic echoes as a function of process time. The time delays for the transducer oriented perpendicular and parallel to flow can be observed. The double echo from the 45-degree orientation is also shown.

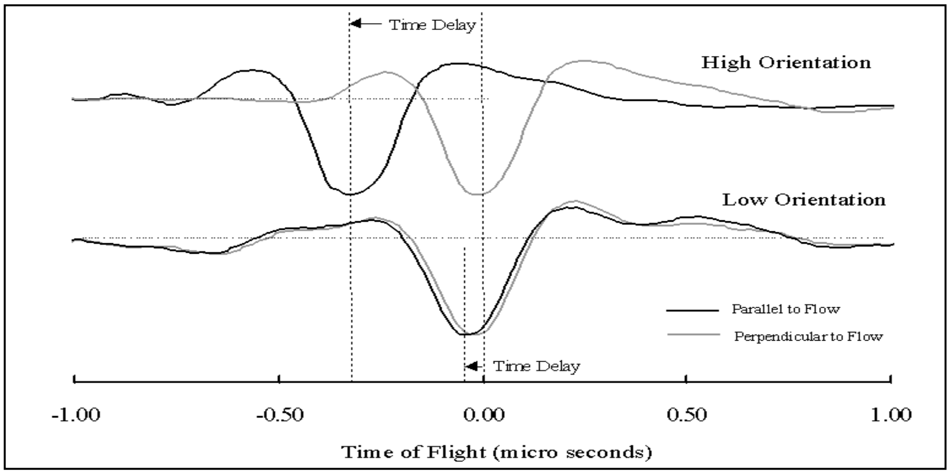

Figure 6. Time delays of axial echoes with respect to transverse echoes in high and low oriented HDPE.

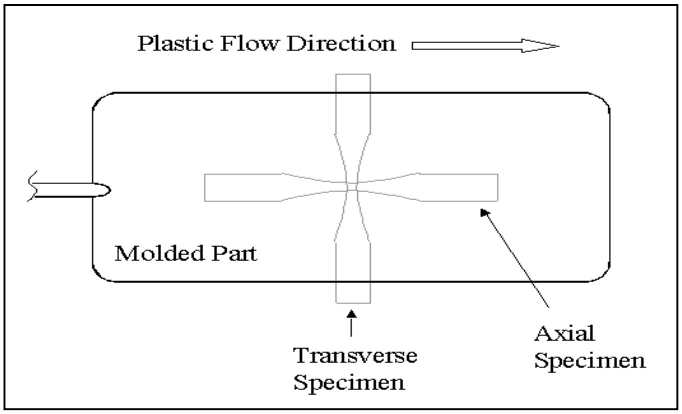

Figure 7. Location of cut tensile specimens with respect to molded part.

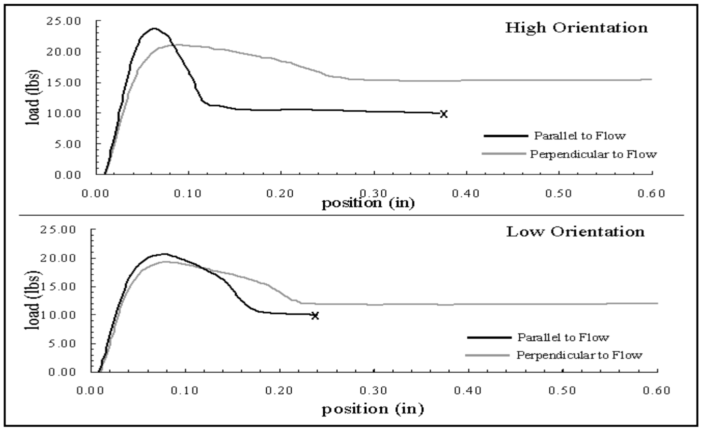

Figure 8. Load/Deflection curves of high orientated and low orientated HDPE tensile specimens.

Key Words: Injection Molding, Ultrasound, Orientation, Anisotropy