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**REAL-TIME ULTRASONIC DIAGNOSTICS OF
POLYMER EXTRUSION AND INJECTION MOLDING PROCESSES**

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Abstract

Real-time and in-line ultrasonic diagnostics of polymer extrusion and injection molding processes together with the high temperature ultrasonic probes used are presented. For polymer extrusion, melt quality and filler concentration and dispersion monitoring are given as the example. Clad ultrasonic rod probes consisting of a core and a cladding fabricated by a thermal spray technique are used. For injection molding diagnostics, melt flow front, averaged flow speed, filling completion and solidification monitoring are illustrated for which sprayed high temperature ultrasonic thick film transducers integrated onto the mold inserts are employed.

1. Introduction

Presently, world market and international competition demands high quality products manufactured by efficient and cost-effective technologies. The technical specifications of products are increasingly advanced and precise. New materials and mass produced items, even those made from conventional materials, need continuous and automated quality control to ensure production efficiency and product superiority. Such quality control requires advanced instruments that diagnose the manufacturing and process and provide precise feedback on process parameters and materials properties during production. In this study real-time, in-line, non-invasive and non-destructive diagnostics methods will be introduced to monitor the polymer extrusion [1,2] and injection molding (IM) [3,4] processes which are two popular mass production technologies for plastic products and of interest here.

Ultrasound, due to its capability to probe inside materials nondestructively, is an attractive diagnostic approach to satisfy these requirements. Recently, in-line or in-situ ultrasonic monitoring of polymer extrusion [5-11], foam extrusion [12,13] and IM processes [14-19] has been demonstrated with the potential of process optimization. Since these polymer production processes are operated at elevated temperatures, e.g. 100 to 350°C, the ultrasonic sensors should operate at such elevated temperatures. Here, piezoelectric ultrasonic transducers (UTs) are considered because of their simplicity, high sensitivity and cost-effectiveness. In addition to high temperature (HT) operation, these UTs are also required large bandwidth and high signal-to-noise ratio (SNR).

In the process monitoring and diagnostics, ultrasonic parameters such as ultrasonic velocity and attenuation in the polymer melts, scattered ultrasonic signals, for instance, due to fillers in the polymer melts, and reflected ultrasonic signal from the probe-polymer melt interface, etc can be used to characterize melt properties such as viscosity [5,8], filler concentration [5,6,10], filler dispersion [5,6,10], melt and mixing quality [5], residence time distribution [7,11], filling completion [15,18,19], flow front arrival [16,17], solidification [17], polymer degradation [6,19], etc and process parameter such as temperature [9,14,17]. All the experiments presented in this study were conducted in ultrasonic transmission mode for polymer extrusion and in pulse-echo mode for IM. The ultrasonic data acquisition system was composed of two pulser-receivers, two 12-bit dual-channel digitizing boards with a sampling rate of 50MHz for each channel and one personal computer.

2. Diagnostics of Polymer Extrusion Processes

Polymer extrusion [1,2] is one of the most used industrial mass production processes of plastic products. In the process, polymer pellets are fed into the feed hopper, transported, melted, mixed and blended by screws in the heated barrel section under elevated temperatures (normally about 150°C ~

220°C), and then converted into the melt at the extruder exit die that shapes the product. The shapes can be rods, tubes, films, sheets, filaments and pipes. In the process additives such as colorants and fillers, etc, which are also in pellet form, may be added. At the feed hopper polymer pellets enter into the extruder barrel and come into contact with the screw. The rotating screw or screws force the pellets forward into the barrel which is heated to the desired melt temperature. In most processes, a heating profile is set for the barrel in which three or more independently controlled heaters gradually increase the temperature of the barrel from the feed hopper to the die exit. This allows pellets to melt gradually as they are pushed through the barrel and lowers the risk of overheating which may cause degradation in the polymer. Extra heat is contributed by the intense pressure and friction taking place inside the barrel.

At present, single screw extruders dominate the extrusion field. However, twin-screw and multi-screw extruders can achieve improved dispersion and mixing [1,2]. Polymer extrusion is also a main part of IM, blow molding, micromolding, etc. Therefore it is highly desired to have real-time in-line diagnostic capability to evaluate the performance of each segment of the extruder and all extrudates. Here ultrasonic probes which can be installed from the feed hopper to die exit [11,20] will be illustrated to monitor the melt quality and filler concentration and dispersion.

2.1 Ultrasonic probes for the polymer extrusion monitoring

For the experiments the ultrasonic probes used were composed of a steel clad buffer rod [20] and a longitudinal (L) wave piezoelectric UT attached to the UT end of the probe. The probing end of one type of probes had the same external diameter and threads as conventional Dynisco pressure and temperature probes as shown in Fig.1 and could be installed at any ports designed for hosting Dynisco probes from feed hopper to the die exit. The probe was made of a 130.9mm long clad buffer rod consisting of a steel core and a 1mm thick stainless steel cladding. The probing end was of 7.7mm diameter. In this approach, the probing end of this rod was in contact with molten polymers whereas its UT end could be cooled by air or water, or coated with HTUT without any cooling. If cooling is used, commercially available ambient temperature piezoelectric UTs and couplants can be readily used, and the temperature of the probing end can be up to more than 600°C. Therefore such probe is suitable for diagnostics of all polymers during processing.

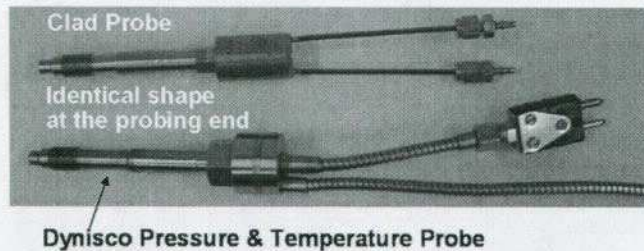


Fig.1 A clad ultrasonic buffer rod probe having the same external probing end diameter and thread as conventional Dynisco pressure and temperature probe. The probing end is of 7.7mm diameter.

Figure 2a shows a schematic diagram of a setup with two ultrasonic buffer rod probes, which can be the one shown in Fig.1, operating in the transmission mode at an extrusion die. The probing end of the probes was flush with the inner surface of the exit die. Let the length of the probe be d and the gap of the exit die be h , which is also the thickness of the polymer melt during extrusion at the die. The ultrasonic wave was transmitted from the transmitting UT, propagating through the buffer rod with a length d , the thickness h of the melt and another buffer rod with a length d , and then reached the receiving UT. This signal is designated as L_A . L_B and L_C were the signals traveled through the melt thickness two and four more times, respectively than L_A . The time delays of these three signals are illustrated in Fig.2b. The ultrasonic L wave velocity in the melt can be obtained as $V_{\text{melt}} = 2h/t_{2h}$. The amplitude reduction of the signals which is associated with the ultrasonic attenuation in the melt can be expressed as $\alpha_{\text{melt}} = 10 \{ \log (|L_A|/|L_B|) \} / h$, where $|L_A|$ and $|L_B|$ are the amplitude of the L_A and L_B signals, respectively.

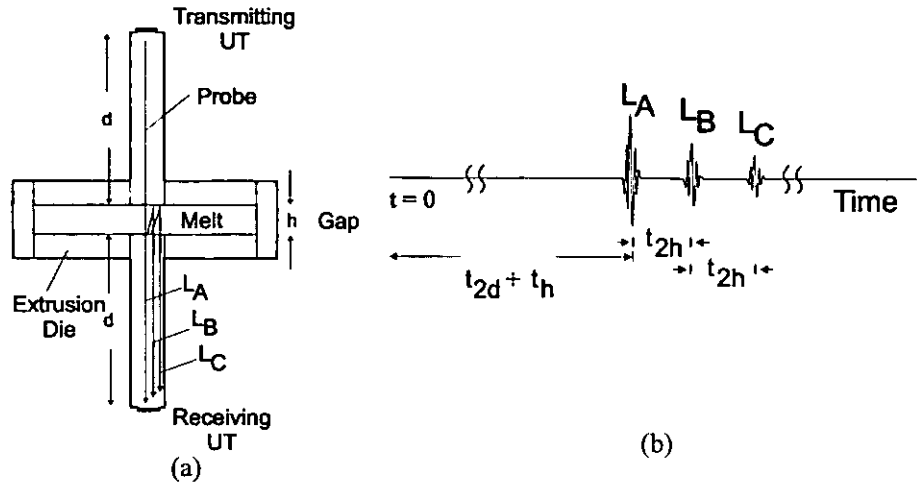


Fig.2 (a) Schematic diagram of a setup with two ultrasonic buffer rod probes operating in the transmission mode at an extrusion die and (b) time delays of transmitted ultrasonic signals.

Figure 3 shows reflected L wave signals (echoes) at an ultrasonic frequency of 5MHz from the probing end of the probe shown in Fig.1 and operated in the pulse-echo mode. L^1 and L^2 were the 1st and 2nd round trip echoes. One can see that the SNR of the reflected L^1 signal was above 35dB. It is known that the SNR of the signals obtained in the transmission mode are higher than those obtained in the pulse-echo mode. This is an advantage of the transmission mode [20]. The drawback of the transmission mode is the requirement of two probes with proper alignment and cannot be used at barrel section when screw is present. The dimensions of the probe shown in Fig.1 were chosen to achieve high SNR and small size. Higher is the SNR, the higher is the sensitivity to monitor the fluctuation of the V_{melt} and α_{melt} both in reflection or transmission modes. In this investigation only L wave signals were used. The ability of ultrasound to diagnose the melt polymers is realized if enough ultrasonic energy is propagated through the polymer melts received by the receiving UT. In the pulse-echo mode the transmitting UT is also used as the receiving UT.

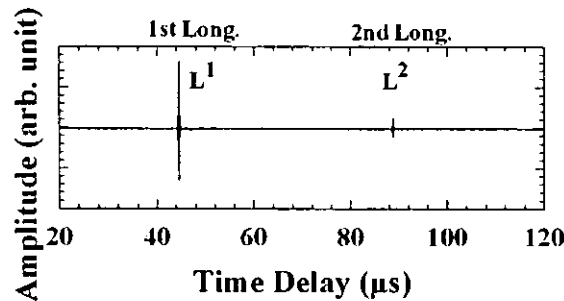


Fig.3 Reflected 5MHz L wave echoes from the probing end of the probe shown in Fig.1.

Since the α_{melt} due to absorption in melts is normally proportional to the square of the operating ultrasonic frequency, for thicker polymer melts and those having higher α_{melt} the operating ultrasonic frequency needs to be lower, and this needs to use a clad rod having a larger diameter [20].

2.2 Melt quality monitoring

Because each manufacturer desires to enhance the productivity of polymers in a given extruder by maximize the extrusion rate (tons/hr), and then a part of pellets may not be properly melted due to excessive production speed. Also, the extruders produced by different machine builders perform differently with regard to various polymers or same polymers supplied by different suppliers at different extrusion rate. Therefore there is a need to have an instrument which can maximize the production rate

and maintain or enhance the quality of extruded polymers. Below a demonstration will be made to illustrate how and why ultrasonic technology can be used for this purpose.

Figures 4a and 4b show the outer and inner look, respectively of three extruded polymer pipe samples having an outer diameter of 57.15mm and a wall thickness of 6.35mm obtained with low, medium and high extrusion speed. In Fig.4b there are no visible un-melted pellets for the sample obtained with low extrusion speed and this sample is designated as "good". However, visible un-melted pellets can be seen from the samples obtained with medium and high speed designated as "fair" and "bad" samples, respectively, in Fig.4b. There were more and large un-melted pellets in "bad" than those in "fair" sample. Clearly Fig.4a shows that the optical surface examination technique was not sensitive to monitor the melt quality of the samples presented here.

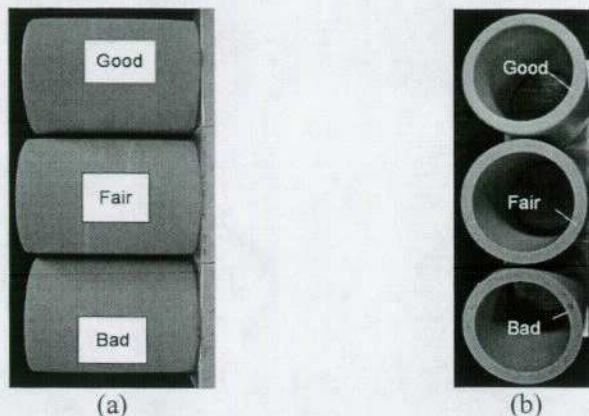


Fig.4 (a) Outer and (b) inner look, respectively of extruded polymer pipe with low (good), medium (fair) and high extrusion speed (bad). The outer diameter of the pipe was 57.15mm and wall thickness 6.35mm.

To evaluate the effectiveness of the ultrasonic monitoring, two clad ultrasonic probes having the Dynisco shape as shown in Fig.1 were used for the real-time and in-line diagnostics of polymer melt quality at the die exit here. These two probes shown in Fig.5 were operated in the transmission mode. In addition, temperature and pressure probes were also installed at the same location but in different angular positions.

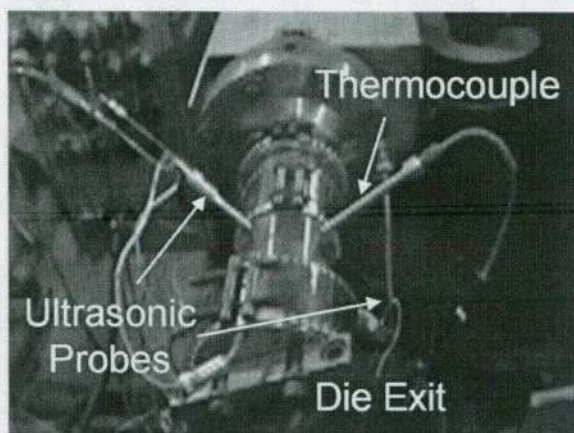


Fig.5 Two ultrasonic clad probes shown in Fig.1 are used for the polymer melt quality monitoring at the die exit in a transmission mode

Figure 6 shows a demonstration that during the extrusion of polypropylene (PP) with the addition of several nylon pellets of higher melting temperature than PP the ultrasonic probe could sense the un-melted nylon pellets real time due to the instantaneous reduction of the transmitted ultrasonic signal as shown in Fig.6. The reduction was caused by the acoustic impedance mismatch between the hard nylon pellet and the PP melt where acoustic impedance is defined by the product of the material density and

ultrasonic L wave velocity in the material. Figure 6 also indicates that pressure and temperature probes are not sensitive to detect the un-melted pellets.

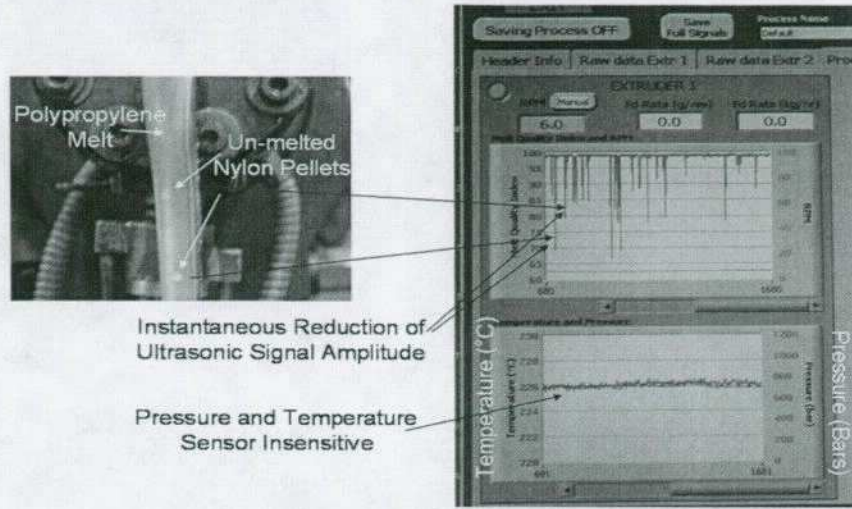


Fig.6 Sensitivity of ultrasonic, pressure and temperature probes for real-time and in-line detection of the un-melted nylon pellets in PP melt.

At an industrial 120mm single screw extruder the ultrasonic sensors have been setup as shown in Fig.5. The extruded materials were PP. The thickness of the melt between two probing ends of the two aligned clad ultrasonic probes was 33mm which was also the gap size of the die exit. The extrusion throughput was nearly 400kg/hr. The upper center plot of Fig.7 shows the reduction of the transmitted ultrasonic signal strengths (amplitude) which correlate to the melt quality index according to the experience of the extrusion. The optical images of the samples extruded at the 29%, 36%, 43%, 50%, 57% and 64% of the maximum throughput of this extruder are also given in Fig.7. It can be seen that when the throughput rises, the un-melted pellets increases and the ultrasonic signals obtained real-time and in-line accurately and timely indicate such property. It is noted that if the extrudates in Fig.7 were in pipe shape, the un-melted pellets may not be seen as indicated in Fig.7. In Fig.7 the small variations of melt quality index versus throughput may come from the fluctuations in size distribution and dispersion of the un-melted pellets. It is noted that this extruder and/or the conditions were not effective to extrude PP because of the indication that the melt quality of PP was good only when the extrusion throughput was nearly 30% of the maximum rate. This also means that the ultrasonic diagnostic technology can evaluate and improve the extruder including screw design for extrusion of particular polymers.

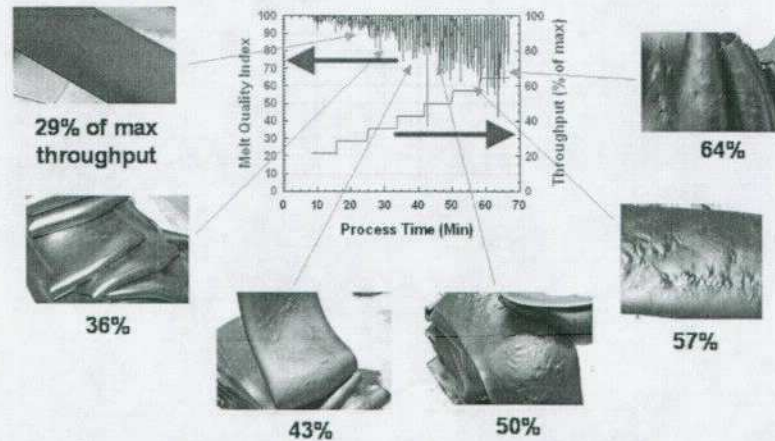


Fig.7 Real-time and in-line ultrasonic monitoring of melt quality index with corresponding optical images of the extruded PP with different amount of un-melted pellets due to different extrusion throughput.

2.3 Filler concentration and dispersion monitoring

PP resins of different viscosities are used for numerous applications of plastic products. One common way to achieve different viscosities is to add calcium carbonate (CaCO_3) as fillers with various quantities into PP. Monotonic dependency has been obtained for both ultrasonic velocity and attenuation in CaCO_3 added PP with respect to the concentrations of CaCO_3 , which can then be used as calibration curve for the determination of filler concentration, for a given attenuation or ultrasonic velocity value. Since ultrasonic attenuation is less sensitive to the fluctuation of pressure and temperature during extrusion [6], it is used in this investigation to monitor the CaCO_3 concentration and dispersion in PP.

A single screw extruder with an internal barrel diameter of 63.5mm was used for the experiments. Two ultrasonic probes were installed in an instrumentation die in a similar fashion as that shown in Fig.5. The pellets of PP with different CaCO_3 concentrations were obtained from the output of a twin-screw extruder. Step changes in the feeding rate of the CaCO_3 filler were made while maintaining constant that of PP in order to obtain several concentration levels allowing one to derive a calibration curve for the ultrasonic characteristics as a function of CaCO_3 concentration. In all experiments, the averaged levels of attenuation were determined for each step change of the CaCO_3 feeding rate. For each concentration level, the extrudate was sampled and actual concentration was obtained from pyrolysis (ashing). The results are shown in Fig.8.

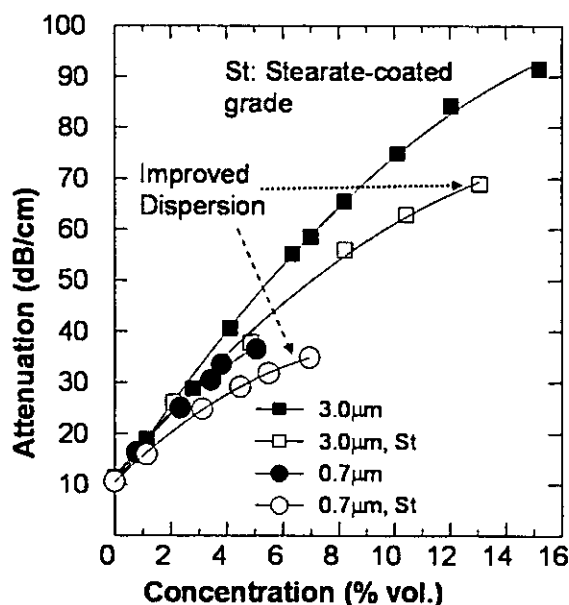


Fig.8 Variation of ultrasonic attenuation in PP as a function of CaCO_3 concentration.

To illustrate specifically the impact of CaCO_3 particle dimension on ultrasonic attenuation, two CaCO_3 samples were used with two mean particle diameters: 3.0 μm (Camel-Wite) and 0.7 μm (Camel-Cal). The curves for these two particle dimensions are clearly distinct, the smaller diameter leading to a lower attenuation at a given concentration. Figure 8 also shows results for stearate-coated grades known to impart improved particle dispersion for both 3.0 μm and 0.7 μm mean diameter CaCO_3 in PP. This stearate-coated grade gave lower attenuation than non-treated one, indicating that the apparent diameter in the latter case was larger, due to agglomeration of particles. It thus implies that a specific calibration curve of ultrasonic attenuation versus CaCO_3 concentration could be obtained for each different grade of CaCO_3 , with respect to particle size and dispersion.

3. Diagnostics of Polymer Injection Molding (IM) Process

Conventional polymer IM [3,4] is a process of forcing melted polymer into a mold cavity having a unique shape for a designed production parts. Each IM machine is equipped with a polymer extrusion section which will convey the polymer pellets, melt and mix them and collect them into the nozzle. Then the typical IM cycle can be described as: (i) the polymer melt is injected into the cavity of a mold through a gate from the nozzle; (ii) the cavity is completely filled with the material and the additional melt is forced into the cavity under high pressure until the gate is frozen in order to compensate for the shrinkage due to the continuous cooling. Then, the part is further cooled until it is sufficiently solidified; (iii) the mold is opened and the part is detached from the immobile mold; and (iv) the part is ejected from the cavity of the mobile mold by the ejection pin. Then the mold is closed and the entire cycle, (i)-(iv), is repeated.

Due to the requirement of high speed, high efficiency and cost-effective production, in-line diagnostics technology is desired. Although the pressure, temperature and positioning sensors are equipped for the machine control effectively but since the material properties of the part are not known, process control was not achieved by the machine manufacturers. Ultrasonic diagnostics technology is introduced here to illustrate the feasibility of process control because part properties may be obtained from the ultrasonic parameters such as ultrasonic velocity and attenuation in the part, reflection and transmission coefficient at the mold-part interface and ultrasonic scattered signal in the part, etc. In order to provide varieties of the products, co-IM [21], gas [22] and water assisted IM [22], powder IM [23] and micromolding [19] have been developed. In this study only ultrasonic diagnostics of convention IM is given as an example.

3.1 Integrated ultrasonic sensor inserts for IM diagnostics

In order to monitor the behavior of the polymer inside the mold cavity during all types and sizes of IM processes, integrated ultrasonic sensor inserts approach was adopted. Thick film HTUT sensors were fabricated onto small size steel inserts by a sol-gel spray technique [18,24] and then embedded into the mold insert of proper size. Multiple mold inserts of various sizes are commonly used by injection molders, in particular, for multi-cavity molding processes. Figure 9 shows the HTUT sensor inserts with (right) and without (left) an electrical connection. The HTUT sensors can operate up to more than 400°C [24] which can cover all polymer IM processes. These sensors do not require ultrasonic couplant and can be coated onto curved sensor inserts. Teflon insulated coaxial cables were used for electrical connection between the top electrode and the pulser-receiver used. The maximum operating temperature of this coaxial cable was 200°C. For applications at temperatures higher than 200°C, a ceramic insulated coaxial cable can be used as an electrical cable.

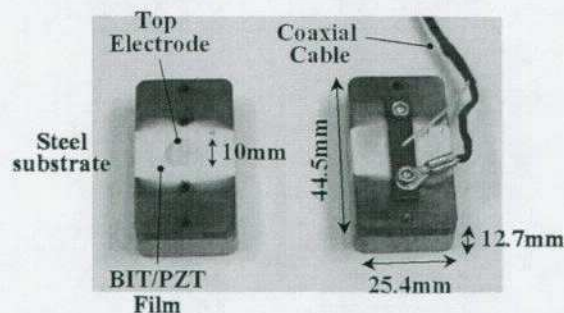


Fig.9 HTUT sensor inserts with (right) and without (left) an electrical connection used for monitoring of injection molding process

Figure 10 presents a cross-sectional view of the mold (mobile and immobile), mold insert and molded part (polymer) with four HTUT sensor inserts (UT1-4). The HTUT sensor inserts were embedded into the mold insert, which also demonstrates that sensor array configuration is feasible. The mold, mold insert and sensor inserts were made of steel. The mold insert had dimensions of 76mm-width, 165mm-length and 21mm-thickness, which was 1mm thinner than the mobile mold so that a rectangular part with dimensions of 76mm-width, 165mm-length and 1mm-thickness could be molded for the study. By replacing the mold insert, the shape and dimensions of the molded part can be easily modified to meet the customer's demands. The bottom surfaces of the integrated HTUT sensor inserts were flush with the mold insert surface (cavity surface), as seen in Fig.10. The UTs were aligned vertically on the center line of the mold cavity. A distance between the center of the UT1 and UT2 (UT3 and UT4) was 34.9mm and that of the UT2 and UT3 was 44.5mm. All the HTUTs had almost the same ultrasonic performance, which indicated that fabrication of the HTUTs was consistent. Their ultrasonic center frequency and the 6dB band width were 9-11MHz and 6-8MHz, respectively.

Polymer melt was injected into the cavity of the mold through the gate at the center of the immobile mold in Fig.10. For comparison purpose with ultrasonic data, a Kistler temperature and cavity pressure sensor, whose sensing end had circular shape with a diameter of 4mm and was flush with the internal surface of the immobile mold, was attached to the immobile mold. This Kistler sensor probing end was facing to the UT1 as shown in Fig.10. L^n ($n=1,2,3,\dots$) represents n -th round trip ultrasonic echoes propagating in the HTUT insert and reflected at the insert-polymer interface, and L_{2n} ($n=1,2,3,\dots$) represents those in the polymer and reflected at the polymer-immobile mold interface.

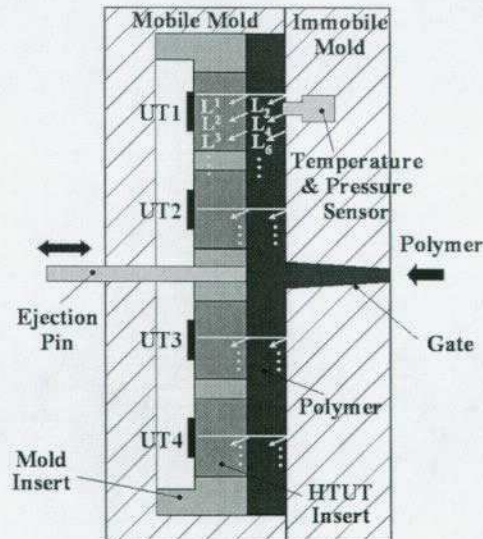


Fig.10 Cross-sectional view of the mold (mobile and immobile), mold insert and molded part (polymer) with four HTUT sensor inserts (UT1-4). L^n and L_{2n} ($n=1,2,3,\dots$) represent n -th round trip ultrasonic echoes propagating in the HTUT insert and those in the polymer, respectively.

The experiments were carried out using a 150-ton injection molding machine. A material employed was an injection grade polycarbonate, which is amorphous thermoplastic. The molding conditions were set as follows: melt temperature was 320°C; mold temperature was 120°C; and injection (plunger) speed was 110mm/sec. The total cycle time was about 30sec. The data acquisition rate was 10Hz unless particularly mentioned.

3.2 Ultrasonic measurement results

Figure 11 shows a typical result of acquired signals with the UT1 during the injection process. Although the signals were acquired during whole cycle (30sec) in time delay range from 4 μ sec to 24 μ sec covering from the L^1 to L^5 echoes, only the signals at the beginning (from 4sec to 9sec) and the end (from

22sec to 27sec) of the process in the time delay range from $4\mu\text{sec}$ to $9.6\mu\text{sec}$ are shown in Fig.11. One can see the L^1 and L^2 echoes reflected at the insert-polymer or -air interface depending if the polymer existed at the UT location or not. S^1 represents the first round trip shear wave echo reflected at the insert-air or -polymer interface. When the polymer melt arrived at the UT1 location at the process time of 5.8sec, the L_2 and L_4 echoes propagating in the polymer started to appear. At this moment, the L_6 and L_8 echoes were out of the time delay range shown in Fig.11. At the process time of 25.5sec, the L_2 , L_4 , L_6 and L_8 echoes vanished, which indicates that the molded part was detached from the UT sensor insert.

In order to investigate further the correlation between ultrasonic signals observed and the process cycle, the amplitude values of the L^4 and L_2 echoes with respect to the process time were obtained using the signals measured with the UT1. Here the L^4 echo was chosen instead of the L^1 echo since, in principle; higher-order round trip echoes of L^n can lead to higher sensitivity to the UT insert-polymer interface condition because of more reflections at this interface [2]. The results are presented in Fig.12a. Temperature and pressure values measured by the Kistler sensor are also presented in Fig.12b. It is noted that the ultrasonic data shown in Fig.12a were acquired with a different cycle from that for the data shown in Fig.11. Hence the process time at which the L_2 echo appeared or disappeared in Fig.12a was different from that shown in Fig.11. At the process time A, the polymer melt arrived at the UT1 and the Kistler sensor locations simultaneously. The amplitude of the L^4 echo suddenly decreased and the L_2 echo started to appear as seen in Fig.12a due to the fact that a part of the ultrasonic energy was transmitted into the polymer through the UT1 insert-polymer interface and then reflected back at the polymer-immobile mold interface.

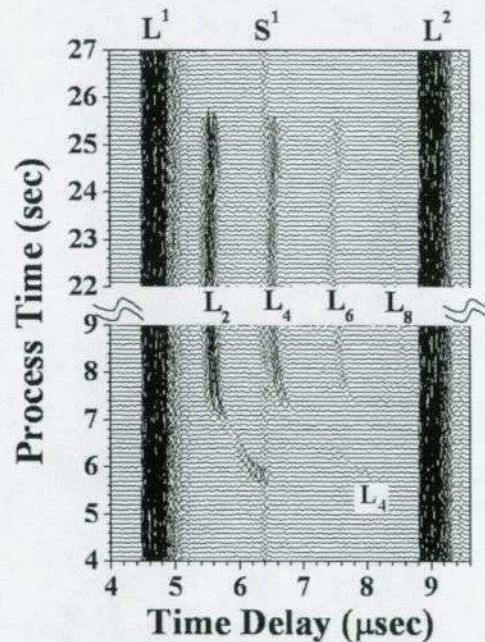


Fig.11 Typical signals measured with the UT1 during injection process

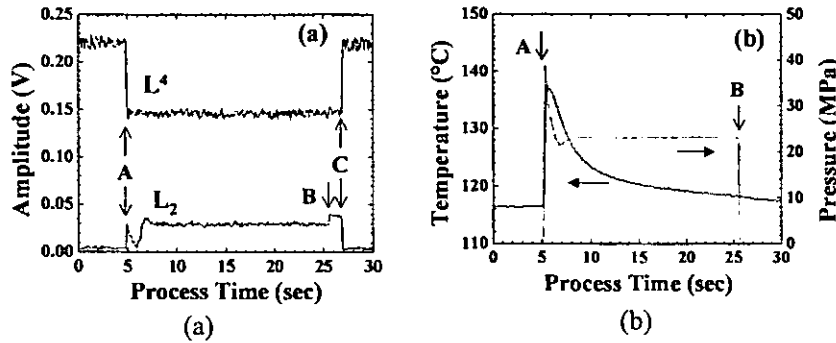


Fig.12 (a) Amplitude variations of L^4 and L_2 echoes measured with UT1, and (b) temperature (solid line) and pressure (dotted line) variation measured with Kistler sensor during injection process. Arrows A, B and C indicate the time for flow front arrival at UT1 location, mold open and part ejection, respectively.

At the time A, the pressure and temperature raised up sharply from zero to 40MPa and from 116 $^{\circ}\text{C}$ to 137 $^{\circ}\text{C}$, respectively, as shown in Fig.12b. It should be noted that the pressure sensor has a threshold in its response, resulting in a slight time delay comparing with the ultrasonic data ($\sim 0.1\text{sec}$ with our experimental conditions). In addition, the measured temperature was smaller than the melt temperature of 320 $^{\circ}\text{C}$ since it was not the melt temperature but “contact (or surface)” temperature of the part, which is significantly affected by the interface condition between the sensor and the polymer.

Just after the time A, the amplitude of the L_2 echoes decreased and increased during a few seconds in the time range between 5sec and 7sec, which might reflect the variation of ultrasonic attenuation in the polymer because of its solidification. This will be discussed further later. At the process time B, the mold was opened and the molded part was detached from the immobile mold. Consequently, the amplitude of the L_2 echo increased due to the almost total reflection at the polymer-air interface, and the pressure dropped to zero. In addition, the phase change of 180 $^{\circ}$ was observed on the L_2 echo at the time B since acoustic impedance of the polymer is smaller than that of the steel mold but larger than that of air, resulting in the change of sign of reflection coefficient at this interface from plus to minus. Such phase reverse of the L_2 echo is also a good indication of the part detachment from the immobile mold. At the time C, the amplitude of the L^4 echo recovered to its initial value and the L_2 echo disappeared, indicating that the part was detached from the UT1 insert due to the part ejection. Hence, the times of the flow front arrival, mold open and part detachment were clearly observed on the ultrasonic echoes as indicated by the arrows A, B and C, respectively, in Fig.12a.

3.3 Discussion

3.3.1 Flow front arrival and flow speed monitoring

During the filling stage, the flow front advancement and flow front speed are critical information. The flow front position can be used to control the plunger speed so as to allow smooth transition from the filling to the packing/holding stages, to avoid part flashing and mold damage due to high impact. As mentioned previously, the amplitude of the L^4 echoes steeply decreased at the time A as seen in Fig.12a, which indicates the melt flow front arrival at the UT locations. Therefore, the average flow front speed, V_f , between the UT1 and UT2 (UT3 and UT4) can be obtained using the time A of each UT.

In this experiment, the signals were acquired every 3msec (333Hz) for higher time resolution. The V_f was calculate to be 306mm/sec by using $V_f = L/\Delta t_f$, where L ($=34.9\text{mm}$) was the distance between UT3 and UT4, and Δt_f ($=114\text{msec}$) was the difference of the time A between the UT3 and UT4.

3.3.2 Filling completion monitoring

Filling completion of the mold with the materials is the most critical requirement for the molding process since the incomplete part must be rejected. Figure 13 shows one incomplete (#1) and three complete (#2-4) parts molded successively under the same molding conditions. Accidentally the part #1 had defects on both bottom edges as indicated by the arrows in Fig.13. The volume filling rate for the part #1 was calculated to be 99%. Figure 14 presents the amplitude of the L_2 echoes, obtained during the cycles for the parts #1-4 shown in Fig.13, with the UT1-4, whose locations are indicated in Fig.13. Even

though the part was filled at UT3 and UT4 locations for the part #1, one can see that the L_2 echoes measured with the UT4 appeared for a few seconds only at the beginning of the cycle. In addition, the amplitude of the L_2 echoes measured with the UT3 gradually decreased to noise level before the mold opened at time B. These are due to the fact that the part detachment at the UT3 and UT4 locations occurred before the mold opened because of shrinkage of the part caused by the lack of enough filling pressure. The L_2 echoes measured with the UT2 for the part #1 appeared in the entire time range between A and B, however the amplitude was a little smaller comparing with those for the part #2-4. It is concluded that the presented ultrasonic method has the ability to monitor the incomplete filling of the part even with filling rate of 99%.

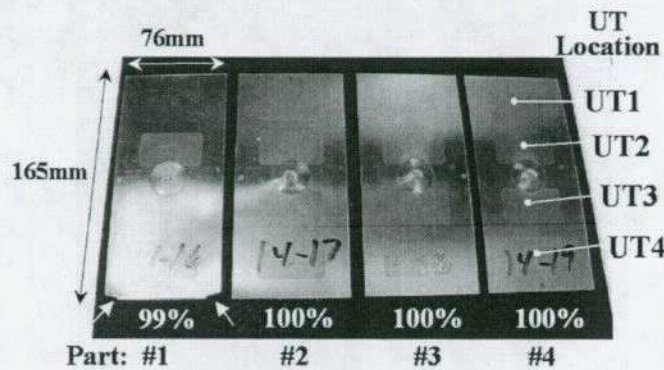


Fig.13 One incomplete (#1) and three complete (#2-4) parts molded successively under the same molding conditions. Filling rate of part #1 was 99%

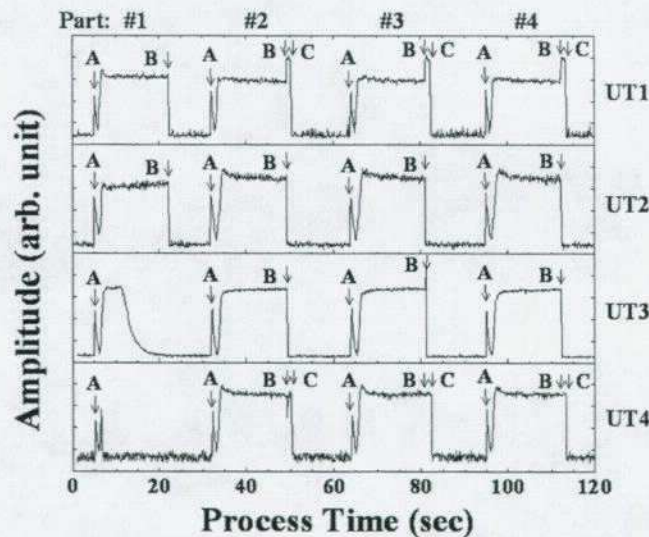


Fig.14 Amplitude variation of L_2 echoes measured during injection cycles for the parts #1-4 shown in Fig.13.

It is noted that the part ejection time C was not observed on the L_2 echoes measured with the UT2 and UT3 for the part #2-4 in Fig.14. This is due to that the part detachment at the UT2 and UT3 locations had already occurred at time B because the part in the gate area was weakly pulled towards the immobile mold when the mold was opened, resulting in the slight bending of the part. The part in the gate area was cut from the molded parts after the ejection, hence it is not seen on the parts shown in Fig.13.

3.3.3 Solidification monitoring

Ultrasonic velocity and attenuation inside the molded parts are strongly related to the physical properties of the molded part. Therefore, solidification of the molded part may be monitored with the velocity and attenuation during the process. They can be determined using the time delay and amplitude variations of the L_{2n} echoes propagating in the polymer, as shown in Fig.11, provided that the echoes have sufficient SNR. The ultrasonic velocity, V , is determined by $V = 2l / (t_4 - t_2)$, where l is the thickness of the mold cavity measured at the UT location by a micrometer, and t_2 and t_4 are the time delay of the L_2 and L_4 echoes, respectively. It is difficult to estimate the acoustic properties such as acoustic impedance of the UT insert and the mold during the process due to their temperature change, which is necessary to calculate the ultrasonic attenuation in the molded part. Hence the attenuation, α , of the amplitude of the L_{2n} echo, which is associated with the ultrasonic attenuation in the molded part, is calculated by $\alpha = 10 \{ \log (|L_2|/|L_4|) \} / l$, where $|L_2|$ and $|L_4|$ are the amplitude of the L_2 and L_4 echoes, respectively.

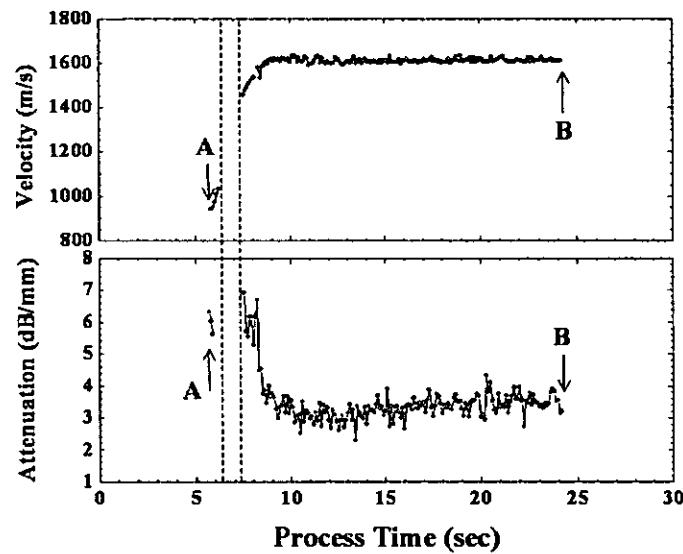


Fig.15 Ultrasonic velocity in the molded part and attenuation of L_{2n} echo obtained using L_2 and L_4 echoes measured with UT2.

Figure 15 presents the ultrasonic velocity and the attenuation of the L_{2n} echo obtained at the UT2 location. At the process time between 6.3sec and 7.2sec, indicated by the dotted lines in Fig.15, the data are missed, since the ultrasonic attenuation in the polymer was so high due to the solidification [16] that the L_4 echoes didn't have sufficient SNR to determine its time delay and amplitude. The measured velocity inside the polymer varied from 950m/s to 1600m/s and the attenuation from 6dB/mm to 3dB/mm due to the variation of the elastic properties of the part, such as elastic constants, viscosity and density, indicating a transformation of the polymer from the molten state to solid state [5].

4. Conclusions

Real-time and in-line ultrasonic diagnostics of polymer extrusion and IM processes together with the high temperature ultrasonic probes used were presented. For polymer extrusion, clad ultrasonic rod probes consisting of a core and a cladding fabricated by a thermal spray technique were used [20]. This type of probe has the advantage of high SNR which is necessary for diagnostics to achieve high sensitivity. For the demonstration two ultrasonic probes operated in the transmission mode and installed at the exit die were used to monitor the melt quality of extruded PP and CaCO_3 filler concentration and dispersion in PP. For the melt quality the fluctuations of the transmitted ultrasonic signals were used to quantify the amount of un-melted pellets. The monitored results showed that the ultrasonic diagnostics system could be used to maximize the production throughput and in the meantime obtain the accepted

extrudate quality. In addition, ultrasonic attenuation variation was also demonstrated to be able to monitor the concentration amount and dispersion of CaCO₃ in PP.

Thick film HTUTs were successfully deposited on steel substrates by a spray technique [18,24] to develop integrated ultrasonic sensor inserts for polymer IM process diagnostics. The center frequency of ultrasonic signals generated by these HTUTs was around 10MHz and a SNR was more than 30dB in the pulse-echo mode at 400°C. For IM process diagnostics, the polymer behavior in the mold cavity was monitored using the multiple HTUTs sensor inserts embedded in the mold insert of proper size at different locations. Multiple mold inserts of various sizes are commonly used by injection molders, in particular, for multi-cavity molding processes. Utilization of sensor inserts in the mold insert allows us to monitor the injection process with molds of all sizes. The material employed was injection grade polycarbonate and the molded part had a rectangular shape. Flow front arrival and average flow front speed of the polymer inside the mold cavity was determined using the amplitude variation of the echo reflected at the UT sensor insert-air or -polymer interface. This echo was also used to detect the time of the opening of the mold. The amplitude and/or phase variations of the echoes propagating in the molded part were used to detect the part ejection and to monitor the filling completion of the mold cavity with the polymer. The amplitude of the echoes was sensitive to the part detachment from the mold so that uncompleted part with filling rate of 99% could be detected. The solidification monitoring of the molded part was performed by measuring the ultrasonic velocity and attenuation in the molded part using the multiple echoes propagating in the part. The variation of ultrasonic velocity and attenuation were reflecting the elastic properties of the part, such as elastic constants, viscosity and density, during the solidification.

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