Indian Society for
Non-Destructive Testing
Hyderabad Chapter

Proc. National Seminar on
Non-Destructive Evaluation
Dec. 7 - 9, 2006, Hyderabad

Flow Front and Cure Monitoring for Resin Transfer Molding Using Ultrasonic Guided Waves in Cylindrical Wires

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Abstract

The mechanical properties and quality of the RTM resin products depends highly on the complete filling and curing of resins in the mold. Hence, a method for monitoring the filling and curing of resins in mold has been a challenging problem in the field of RTM fabrication for a long time, particularly for thick components. In this paper, we describe a promising online method to monitor the flow and curing of RTM resins using ultrasonic guided waves in cylindrical wires. The reflection of the ultrasonic torsional guided waves at a boundary where a free cylindrical waveguide enters an embedded wire was investigated. An image processing algorithm was also developed for suppressing the unwanted signals from the kinks and other stationary signals. The time-of-flight of the reflected wave was used to determine the flow of resin and the amplitude of the reflected wave is used to measure the shear properties such as the viscosity of resin. From the viscosity changes, the curing of the resin can be monitored. The reflection of the lowest order torsional mode was considered as they are more sensitive to shear properties of the resin. Moreover, they are least attenuated and non dispersive in air providing an opportunity to place the sensor far away from the mold.

Keywords: *Torsional, Resin transfer molding, Resin, Flow front*

1. Introduction

Measuring the extent of flow and cure of resin inside opaque molds has been a very important parameter in determining the quality of products in process such as Resin Transfer Molding (RTM). Papadakis [1] in 1974 proposed two methods for determining the change in material properties during curing of the epoxy resin. While, one was based on the measurement of attenuation of both longitudinal and torsional modes in circular rods, the second one was based on measuring the reflection of the waves at the interface where the waveguide enters the epoxy resin. A U-bent wire in a through transmission arrangement was used by Li et al. [2], for monitoring the cure of epoxy resin in composite column wraps for highway applications. Further, Vogt et al. [3] provided these measurement techniques a theoretical foundation based on guided wave theory and numerical modeling.

However, very limited work has been done on methods to ensure complete filling of the molds with resin. Laser based flow sensor have been used for a very long time. The most common of them is laser Doppler velocimeter and laser time-of-flight velocimeter. However, these methods are useful only in transparent molds. Kim et. al.

[4] used a torsioanl waveguide of diamond cross section to sense the characteristics of the liquid as well as the liquid level. Since, thin wires are preferred (in order to reduce the inhomogenity in the resin product due to the presence of metal wire) making diamond cross section in these wires are very expensive.

Further, a novel technique for combining conventional Rhodes flow meter with advanced technology of fiber optic sensor was proposed in [5]. An idea for monitoring the flow front propagation of resin utilizing ultrasound transmission was proposed by Stoven et al. [6]. In this an acoustic pulse is sent out, moving perpendicular through stacks of fibers and is received by an ultrasound transducer at the other end. However, this technique requires considerable compactness between the fibers in the transverse direction for the wave to propagate through them.

In this paper an ultrasonic guided wave technique has been discussed for simultaneous monitoring of the flow and curing of resins inside opaque molds Apart from the usage of the sensor (discussed here) in RTM industries, it can also be used in industries where flow front measurement is required for viscous fluid. It has potential in various industries where it can be used as a leak/level indicator.

2. Theory

The main motivation for the work presented here is to develop a low cost but accurate sensor which overcomes the limitations of the existing sensors for monitoring proper filling and curing of the molds in real time. The sensor discussed here generates guided waves in a thin wire which acts as a waveguide. Because of the change in surface impedance at the point where the wire enters the embedding fluid the guided wave will get reflected and scattered through mode conversions. The time-of-flight of the reflected wave basically depends on the distance of the flow front from the transducer As the flow front moves, along the waveguide, the reflected signal also advances in time towards the initial pulses produced by direct interaction between the transducers. Thus, it is capable of providing information about the extent to which mold has been filled with resin. The distance of the flow front from the transducer can be got from equation (1).

$$t = \frac{2*d}{v_s} \tag{1}$$

Where t is the time taken for the reflected wave to reach the transducer, v_s is the shear wave velocity in the waveguide and d is the distance of the waveguide from interface. The velocity of the guided wave can be computed from the dispersion curves shown in Fig. 1, plotted using DISPERSE [7].

The presence of large number of waveguide modes complicates the data analysis and hence is not preferred. Hence, it was preferred to work with the frequencies where only fundamental modes are present. Secondly, for the application stated, the transducer has to be kept far from the actual location of the measurement and must provide a sufficiently strong signal from the air-fluid interface. Since, the fundamental torsional mode has low relative attenuation in copper wires and low dispersion (See Fig. 1), this mode was selected.

3. Experimental setup

A pair of 0.5 MHz piezoelectric shear transducers (Panametrics V151 Videoscan Y-Cut normal PZT shear wave probe) placed on either side of the waveguide was used for generating torsional mode in the wire waveguide. One of the transducers act as a transmitter while the other acts as a receiver. The transducer’s vibration direction was ensured to be perpendicular to

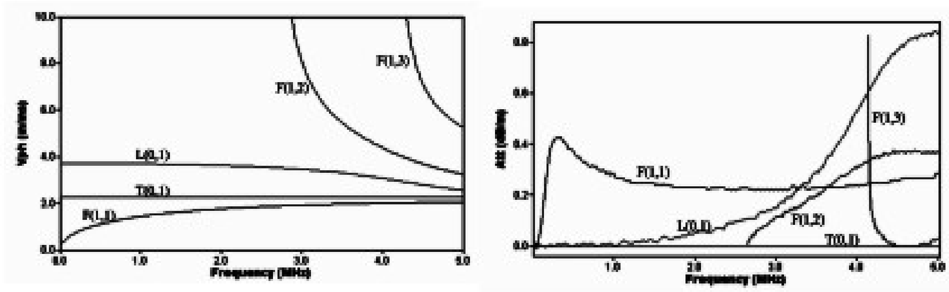


Fig 1: Dispersion curves for wave modes in copper wire of radius 0.25 mm in air plotted using DISPERSE

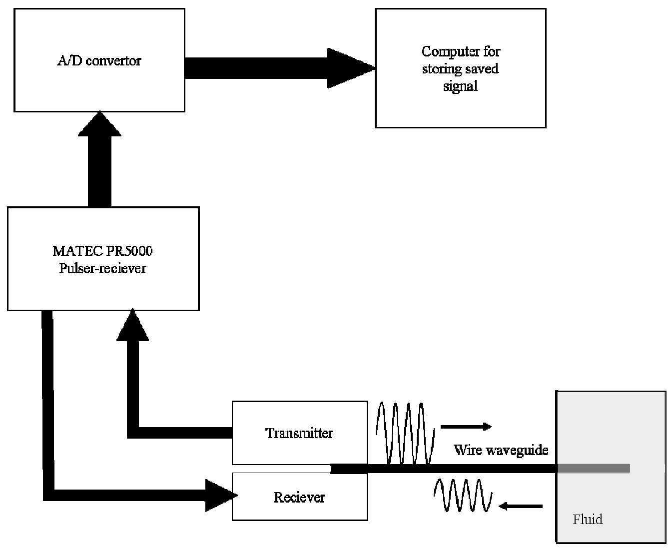
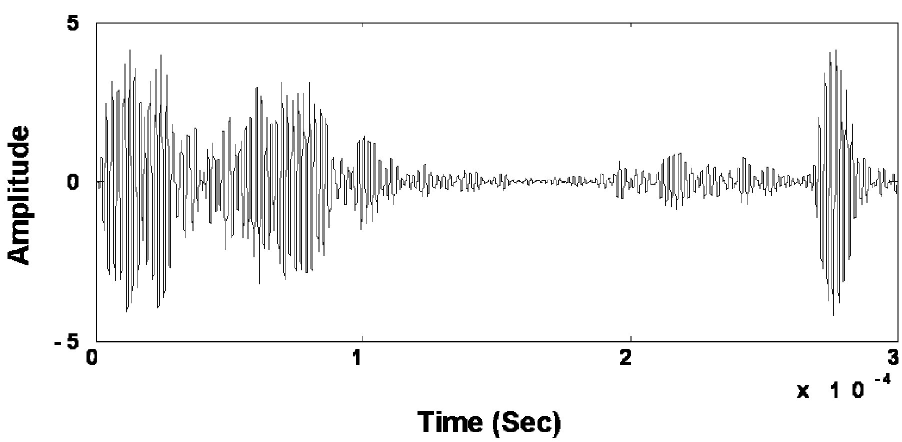
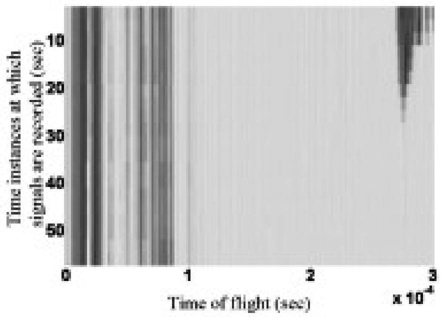


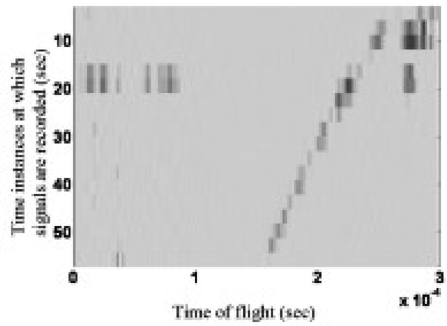
Fig 2: Schematic representation of the experimental setup used in the experiment



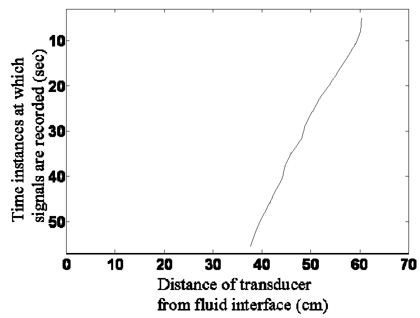
3: A- scan signal of the reflection from Vinyl ester resin interface



(a)



(b)



(c)

Fig 4: Images for vinyl ester resin. (a) Raw unprocessed B-scan image (b) Processed B-scan image (c) Flow front profile

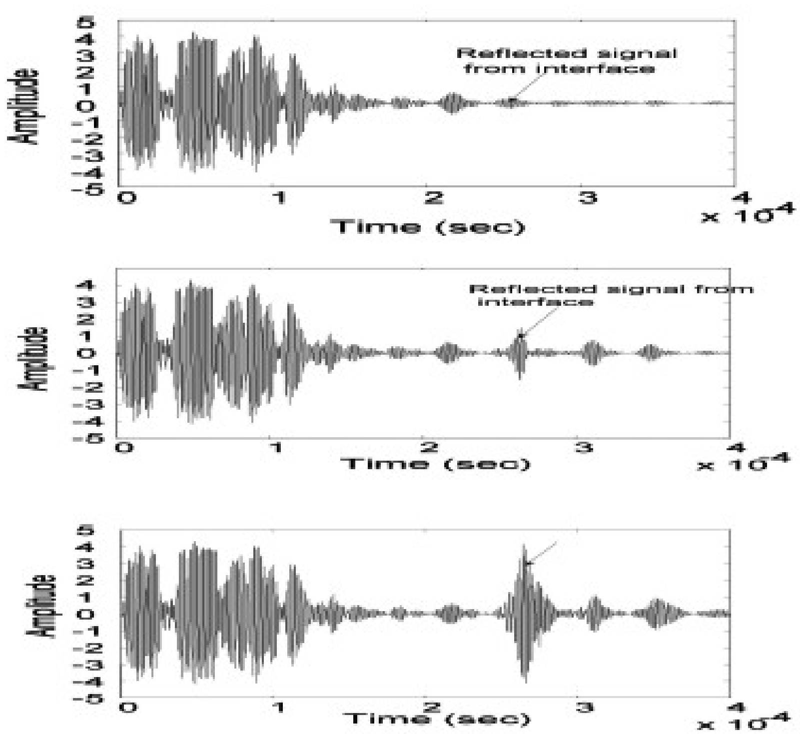


Fig 5: A-scan signals while vinyl ester resin is curing at different time instances of time (a) 9 minutes, (b) 11 minutes, (c) 15 minutes

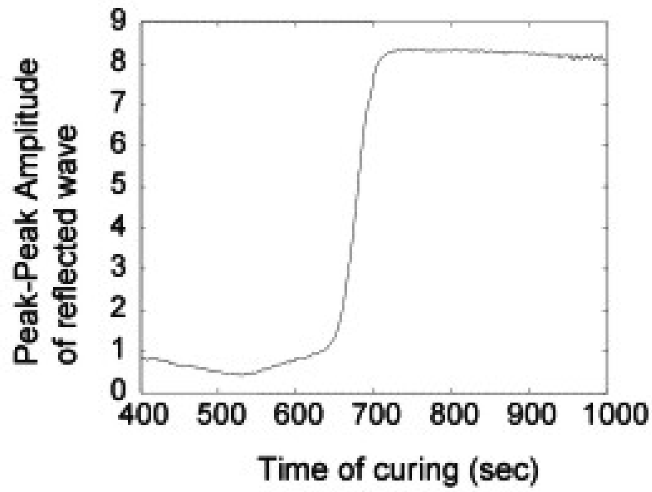


Fig 6: Peak-Peak amplitude of the reflected wave from the vinyl ester resin interface as the resin cures

the axis of the waveguide, in order to predominantly generate torsional modes in the waveguide. A three cycle Hanning window tone burst signal was used to excite the transducer. The frequency of the shear transducers were chosen to be 0.5 MHz so that only the fundamental modes were generated in the rod as shown by the dispersion curve in Fig. 1.

Next, a 0.5 mm diameter copper wire (density=8900 kg/m^3, shear wave velocity=2330 m/s, longitudinal velocity=4660 m/s) is used as the waveguide for transmitting torsional mode. The strength of the reflected signal from the air-fluid interface depends on the both the viscosity, density, waveguide diameter, and the frequency of operation. During the experiments, 700 mm long wire was used**.** The torsional wave was generated in both directions, one towards the viscous fluid and other in the opposite direction. If this other end is a free end, the reflected guided waves from this end overlaps with the useful reflected signal coming from the fluid interface. In order to avoid this interference, the other free end of the wire was covered with a material having high damping capabilities.

A MATEC PR5000 Pulser-receiver was used for exciting the transmitter transducer and for receiving the signal from receiver transducer. For the experiments performed a three cycle pulses were generated using the pulser. The received analog signal was digitized using a National Instruments PCI 5102 20 MHz analog to digital converter for converting the analog signal received into a digital form so that the signals can be stored and processed in a computer. A Labview program capable of collecting and storing the signal at fixed intervals time was also developed. A schematic diagram of the experimental setup is shown in Fig 2.

4. Post-processing

A typical A-scan signals obtained using vinyl ester resin (viscosity=275 cps and density=1030 kg/ m^3) is shown in the Fig 3. Due to low viscosity of the resin the amount of energy reflected from the interface is less. This results in the useful signal getting masked by the noise and the reflections from unavoidable kinks in the thin waveguide. The very weak nature of the reflected signal from the interface of low viscous fluids calls for the development of a post-processing algorithm for enhancing the interface reflected signal and suppressing the unwanted stationary signal.

The A-scan signals at different time instances are combined to form a B-scan image S(i,j), where 'i' represents discrete time of flight data of the signal and 'j' represent each instant of data recording during mold filling, as shown in Fig 4(a). The S(i,j) matrix is plotted in the form of intensity plot, as a grayscale image. The method takes advantage of the fact that except for the signal reflected from the moving flow front all the other signals including the ones from the kinks remain stationary (unchanged) during the filling process. Hence, an iterative process of subtracting the time signal at time instant t_{i-1} from the signal at time instant t_i was performed on the signals collected by the data acquisition system as shown in equation (2).

$$S^1(i,j) = S(i,j) - S(i-1,j) \qquad (2)$$

This results in suppressing the strong stationary signal to some extent without affecting the weak moving reflected signal from the flow front. However, the results could be further improved by estimating the stationary signal by taking the mean of the signals at time instant t_{i-1} and at time instant t_{i+1} is used as shown in equation (3). This is due to the fact that the amplitude of the stationary signals keeps changing due to the attenuation in the viscous fluid. The processed B-scan images are shown in Fig 4(b).

$$S^2(i,j) = S(i,j) - \frac{S(i+1,j) + S(i-1,j)}{2} \qquad (3)$$

From the processed B-scan images, the flow front profile was extracted by first obtaining the time-of-flight of the maximum of the signal in each row (representing the reflected peak of the A-scan at any time instance). Since, in some of the B-scan, the signal to noise ratio was low, all of these maxima may not necessarily correspond to the peak of the reflected signal. Hence, the median of the time-of-flight of these maximum was taken as the seed. Using this seed as a starting point, the maximum in the adjacent rows were obtained by confining the search only to the near vicinity of the previous found maxima. This was carried out in both vertical directions. Finally, these maximum points in each row were joined in order to visualize the flow front profile. From the flow front profile, which is essentially the time-of-flight data, the distance of the flow front from the transducer was calculated as shown in Fig 4(c) using Equation (1), using the velocity of the fundamental torsional mode in the waveguide.

5. Cure monitoring

The change in amplitude of the transient reflected wave was used for monitoring the cure or changes in the viscosity of the resin after the completion of the mold filling. For instance, during the cure of resin, a change in both the density and viscosity of the resin can be observed. The torsional wave due to its shear nature is very sensitive to changes in viscosity and density of the surrounding fluid. Hence, with curing, the amplitude of the energy reflected from the interface where the rod enters the resin increases. Even though, the reflected wave at the interface is more representative of the interface properties, it is reasonable to extend it to the entire volume provided uniform mixing of hardener and resin has taken place. Moreover, once the resin has cured the wire waveguide gets attached to it. Hence, the use of thin wire is preferred since it is easy to either remove the wire after the curing process or to snap the wire and leave it in place in the finished product.

The experimental setup is same as the one described above for flow front monitoring. The experiment was conducted on a poly vinyl ester resin mixed with suitable hardener. The A-scan signals of the torsional modes generated in the wave guide at various instances of time are shown in Fig 5. Initially the amplitude of the reflected wave is small and it slowly increases with the curing. With curing, the viscosity and density increases, thereby increasing the acoustic impedance of the resin leading to a higher fraction of energy getting reflected. Finally it reaches the maximum value indicating that it has fully cured. The peak-peak amplitude of the reflected wave can be taken as a measure for monitoring the cure of resin. The peak-peak amplitude at various time instances, during the curing of the polyester resin, has been plotted in Fig 6.

6. Conclusions

A waveguide sensor for monitoring the flow front and curing of resins inside a mold has been developed and tested. The time-of-flight of a transient fundamental torsional mode, that is supported in a very thin wire and is reflected from the air-fluid interface (at the point of entry of the wire into the fluid) while the fluid front approaches a stationary transducer was used to measure the flowfront. Due to the low viscosity of the fluid, the strength of the reflected signals were weak when compared to the other reflected signals. Hence, a post processing algorithms (based on time domain analysis) was developed for enhancing the weak transient reflected signal from the interface and suppressing the other stationary reflections and noises. This method showed an significant improvement in enhancing the contrast of the interface reflected signal. The computational simplicity of the methods provides an opportunity to implement it in real time. The post processed B-scan images were then used to plot the flow front profiles for different fluids. While, this sensor has been shown to work for vinyl ester resin, this approach can be used in many other applications such as level sensing, and high temperature process monitoring and may be used for a wide range of fluids.

The use of the sensor for monitoring the cure of the resins has also been discussed. Usage of thin wire reduces the adverse effect of foreign materials present in the resin products. The curing curves showing the capability of this sensor has also been presented.

7. References

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