In-process Inspection of Pultruded Tubular products using Air-Coupled Ultrasound

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Abstract

Pultruded products offer many excellent properties, particularly high strength, low weight and excellent corrosion resistance. However their acceptance into many critical applications has been adversely affected by the inability to guarantee 'defect-free' quality. Common problems such as voids and delaminations will greatly reduce the strength of the finished product, but until now there has been no effective means of verifying their absence during manufacture.

The water coupling required for conventional ultrasonic inspection is unacceptable during the pultrusion process. Manual inspection of finished products is very time-consuming, and runs the risk that an unrecognized production problem could result in large quantities of scrap product being produced.

Air coupled ultrasonic Inspection has been proven over a number of years in critical applications such as inspection of honeycomb composite panels for space applications. Developments of the technique have been applied to in line inspection of pultruded products, using both scanning and surface wave approaches. For tubular products a surface wave technique can be used, applied from the outside of the tube only, immediately near the mandrel, while the tube is still at a temperature around 80 ºC. Transducers can be positioned up to a metre apart, giving very rapid inspection.

Experience has been gained in the USA developing a multi channel technique on pultruded tubes intended for support pole applications, It has proved possible to find critical defects which might otherwise have compromised the safety of the finished product. The system also provides immediate feedback for process control, and allows a central data connection facility. This will allow the US based head office to monitor production at plants all over the world, allowing 'discrepancies' between produced and shipped product quantities to be identified.

Introduction

In this paper I will attempt to describe some work carried out by QMI Inc. in California during the last year. This has resulted in the development of a technique, currently being implemented, which gives cost-effective 100% in-line inspection of pultruded materials.

The Pultrusion Process

The pultrusion process for continuous manufacturing of composite material profiles has been in use for many years but is still finding new applications. As the name suggests, pultrusion is a combination of 'pulling' and 'extrusion'. Extrusion relies on pressure to force a heated material through a die, with pultrusion the material is pulled through the process.

Reinforcing fibres, typically carbon or glass, are saturated in a resin bath then, formed to shape and passed through a heated die. The heat cures the resin and produces a finished material at the desired dimension. The process is typically capable of making continuous lengths of material in a wide range of sizes. Because of the need to ensure proper wetting of the fibres and curing in the die the process is relatively slow, typical line speeds are of the order of 50cm per minute.

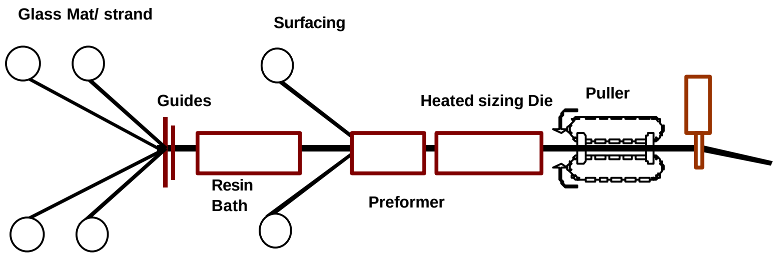


Figure 1 : schematic diagram of typical pultrusion machine

Pultruded materials have a number of distinct advantages over either metals or conventionally manufactured composite materials. These include:

Strength	Glass reinforced pultruded materials can have Flexural, tensile and impact strengths around three times that of steel [i]
Weight	Typical density 2-3 g/cm^{3},
Corrosion resistance	This is dependent on the resin properties, with suitable selection of materials pultruded tubes are usable for strong acid or alkali at ambient or moderately elevated temperatures.
Insulating properties	Like most plastics, Pultruded materials are good electrical insulators. For some applications conductors can be incorporated into the material during manufacture. Thermal insulation is typically good.
Machinabilty	Most pultruded materials can be easily cut, drilled or machined.
Ease of manufacture.	Pultrusion machines are typically simpler, lighter and relatively low cost compared to systems for producing similarly sized metal products. The raw materials are lightweight reinforcement and liquid resins. In consequence it is easy to set up a manufacturing operation close to where the product is required, thus minimizing difficulties in transporting long finished products. As an extreme example of this a study[ii] explored the feasibility of setting up a pultrusion machine in orbit for manufacture of space station components

Because of their properties, Pultrusions are used in a wide variety of applications, for example

- Piping, storage and process equipment in industries such as chemicals, fuel and sewage processing
- Structures such as bridges, buildings, support poles, ladders, and a variety of offshore uses.
- Various requirements for strong light rods such as tool handles and fishing rods
- Transportation applications as diverse as floors for railway wagons and bicycle frames.

In particular, their excellent strength to weight ratio makes pultruded materials of particular value in the aerospace industry. Two particular applications where pultrusions have been used include an Air to surface missile, where the body is a single glass reinforced pultruded tube approximately 5m long and 40cm diameter, and in paper designs for cargo-carrying airships, where a huge framework, uses pultruded materials to minimize the weight.

Inspection requirements

Inherent in any manufacturing process is the possibility of defects, in the case of pultrusions the most likely problems result from inadequate filling of the reinforcement by the resin, resulting in problems such as porosity, voids and delaminations. These will reduce the strength of the finished product.

For many applications conservative design techniques can be used and the ultimate strength is not required, In other cases the risk of failure and its probable consequences are not too serious. For these applications inspection is purely a cost/benefit issue, If the cost of inspection is less than the probable consequences of warranty claims, lost customer good will and wasted material through failures then it is worth doing. In other applications such as gas piping or aerospace applications the consequences of failure are much greater. Here it is necessary to implement an effective inspection process to ensure that the material used conforms to the requirements.

In either case an inspection can be carried out on or off-line. It is desirable to implement inspection on-line for a number of reasons, particularly so as to minimize feedback time and avoid production of large quantities of non-conforming product.

Possible approaches to inspection

Water coupled Ultrasonics, normally using a through transmission technique, is the standard approach for inspection of composite materials. It provides good resolution of delaminations and internal voids. Detection of porosity depends on its extent. Conventional UT requires a scanning approach to cover the entire surface. For off-line inspection of tubular products this is normally achieved by rotating the part. Water coupled ultrasonics is not acceptable for use on a pultrusion line as the water can adversely affect the curing process,

Air coupled through transmission ultrasonics avoids the problems with water but still requires a scanning approach. For a tubular product it is very difficult to arrange a through transmission system since access is only to the out side of the tube. For open profile pultruded products such as sheets this approach can work well,.

Mechanical impedance Ultrasonic approaches can work well, but again a scanning approach is required.

Real-time X-ray systems can give good resolution of voids and porosity, but are normally very poor at detecting delaminations. Effective interpretation of the results from tubular products normally requires a computed tomography system, which is very expensive. There are also health and safety considerations which make in-line use of an X-ray system somewhat impractical.

Lastly penetrant inspection can give good detection of surface porosity problems, again it is not really suitable for an in-line inspection. Unless the post-inspection cleaning is very thorough it also has the disadvantage of making minor blemishes very apparent to the customer!

Application of Air-coupled UT to Pultruded Products

Air coupled ultrasonics[iii] has become a well established technique, particularly for through transmission inspection of composite materials . By using high power tone burst pulsers, resonant transducers and sensitive amplifiers it is possible to overcome the extreme signal losses which are inherent in using air as a couplant and to resolve defects which are typically 2-3mm across.

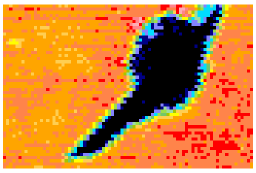


Figure 2 : Air coupled C-scan of impact damage

The example shown is impact damage in a carbon fibre laminate. The air-coupled technique is very suitable for this application, as water tends to conceal delaminations in the material.

As well as the though transmission configuration it is also possible to use air coupled transducers to generate plate waves in the material. The absence of water, which would attenuate plate waves , means that is possible to propagate them over some distance. Discontinuities in the material between transmit and receive probes cause a detectable variation in received signal.

Plate waves have a number of major advantages for our purposes:

Because we are testing a strip of material rather than a spot scanning is not necessary, it is therefore possible to achieve much greater inspection rates.

The technique is particularly suitable for inspection of tubular products because it can be configured with both probes on the same side of the material as shown.

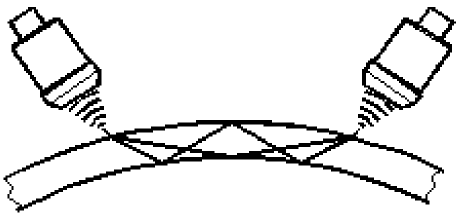


Figure 3 : Generation of plate waves

Method Development

To investigate the possibilities of the technique a number of samples were obtained from a manufacturer All samples were approximately 300mm square, cut from large diameter pultruded tube of 5-6mm wall thickness. The manufacturer, without assigning any details to the specific samples declared the quality as good to inferior. Especially, no reference was made as to what parts are considered porous (low resin content), containing delaminations or leakers.

All 300 x 300mm samples were dyed with liquid penetrant to test for porosity and leakers. After the process, one sample showed a surface full of red spots, 1-5 mm in diameter, indicative of porosity and leakers. All other samples did not reveal any spots and were considered not porous.

All the samples were c-scanned in through-transmission with water squirters at 2.25 MHz to establish a baseline. Three parts were selected as representative examples and scanned with identical parameters, especially with the same gain:

Airscan transducers operating at 400kHz were mounted on the same side (outside) of the cylinder and aligned for plate wave generation in three different directions: plate waves running along the surface parallel to the cylinder axis, along the circumference, and having components in both these directions.

A sound barrier (foam) was mounted between the transducers for short sound paths (3-5 cm). The plate waves traveled 3 - 10 cm between the transducers, depending on the transducer configuration..

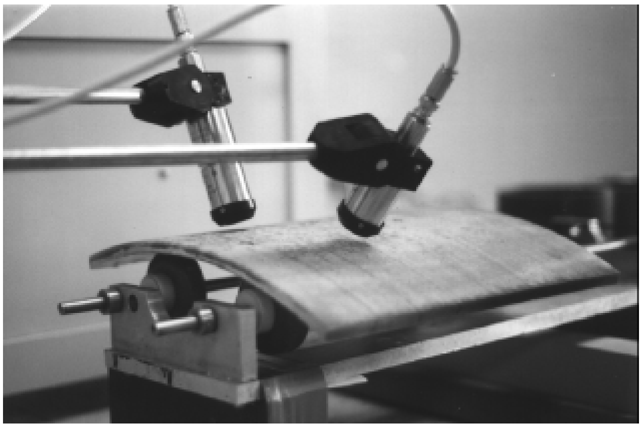


Figure 4 : Experimental arrangement

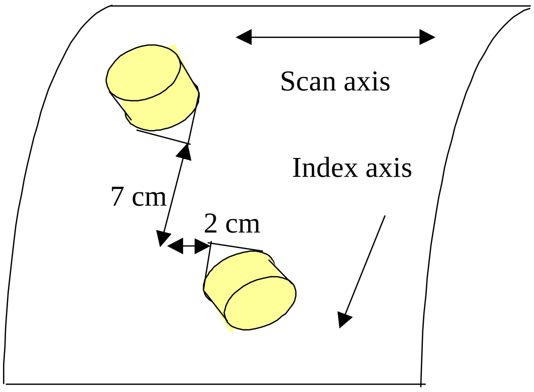
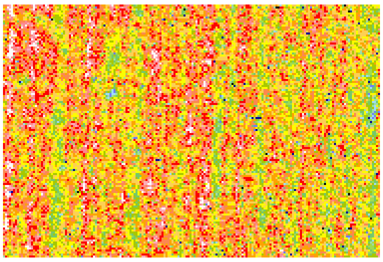


Figure 5: optimum probe positioning

Results

Best overall results, i.e. best discrimination, without insignificant variations, were obtained with a sound beam path of 7 cm along the circumference, and 2 cm along the cylindrical axis (see figures 4 and 5).

All the Airscan C-scans were imaging the amplitude only. No frequency analysis was performed.



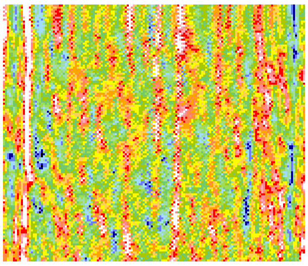
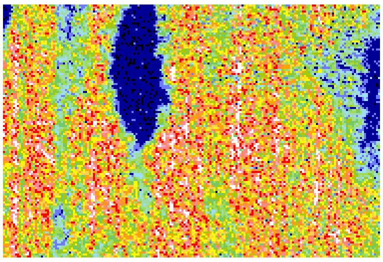


Figure 6: Most homogeneous part, with no gross defects

Figure 6a) shows a c-scan section of 12 cm by 18 cm, scanned with water squirters in through-transmission. Note the very regular and homogeneous structure.

Figure 6b) shows a c-scan section, scanned with airscan plate waves. Note the overall regular structure. The blue areas are regarded as of minor importance.



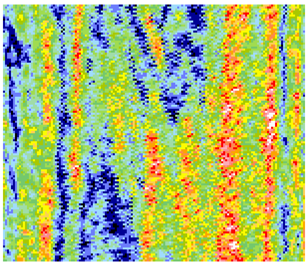
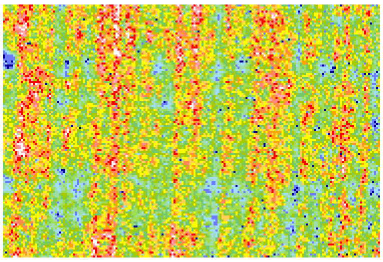


Figure 7: Three flawed areas in water through transmission

Figure 7a) shows a c-scan section of 12 cm by 19 cm, scanned with water squirters in through-transmission. Note the distinct large dark area, most likely indicative of delaminations. At left and right borders are similar areas.

Figure 7b) shows a c-scan section, scanned with airscan plate waves. Note the dark areas of the delaminations identified in figure 7a), which are now geometrically distorted due to the plate wave configuration.



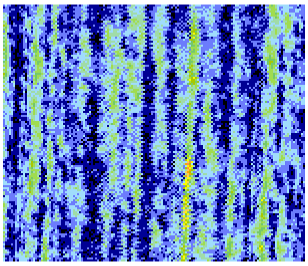


Figure 8: Porous/leakers with liquid penetrant

Figure 8a) shows a c-scan section of 12 cm by 19 cm, scanned with water squirters in through-transmission. Note the homogeneous appearance, although a few and small dark areas are present.

Figure 8b) shows a c-scan section, scanned with airscan plate waves. Note the dramatic difference as compared to the through transmission results.

The recording of the plate wave amplitude alone, regardless of the frequency spectrum, is already able to detect more details and features than any of the through-transmission configurations (water or air-coupled). The geometrical localization and sizing of imaged features would be more cumbersome than in through-transmission. A precise determination of the location would need some mathematical reduction (deconvolution). However, this is not considered necessary for production control.

Recording the amplitude only, while disregarding any frequency changes, is considered a reliable method for the above-detected flaws and especially for detecting porous material.

Implementation

The technique is currently being implemented for a manufacturer of glass reinforced pultruded tubes which are employed as utility support poles. The company manufactures these products in a number of plants around the world.

To make matters more complicated the poles are not cylindrical, but are of octagonal cross section, the inside surface being circular as shown in Figure 9

It was found that the corners resulted in some attenuation of the sound path, and to get acceptable sound transmission a lower frequency was used (200kHz). With this it was possible to inject the sound at the centre of one face, propagate a plate wave around two corners, and detect the sound again at 90 degrees to the injection point.

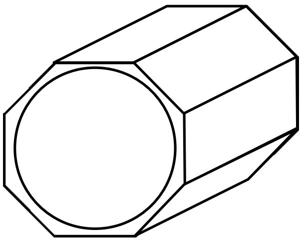


Figure 8 : Support pole cross section

To get complete coverage of the product four channels are used with eight transducers in a configuration as shown in figure 10.

To avoid interference between the channels it is necessary to alternate the tone bursts on adjacent probes.

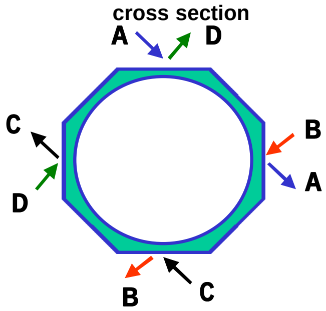


Figure 8: Probe configuration for octagonal tube

The system has now been tried out on-line in a production plant, mounted immediately after the die. At this point the tube temperature is around 100 Celsius.

Preliminary results have been very encouraging. With the ‘good’ signal set to approximately 80% of full screen height the variation with ‘normal’ product is only a few dB. Problems such as porosity result in greater than 20dB signal drop.

Further work is continuing to quantify detectability of various defects.

Future developments

The intention is to integrate the air-coupled testing into a complete process monitoring system. The system will give ‘real time’ feedback to the manufacturing process and allow deterioration in product quality to be immediately investigated and corrected.

The intention is that the system will be used in a variety of plants around the world, with direct reporting of results to the US head office. Interlocks will prevent production of faulty or untested product.

Issues that the system will address go beyond ‘merely’ product quality. Apparently there is a long standing concern with some plants that raw material used and product sales reported don’t match. The obvious suspicion is that material is being stolen and sold unreported. However this is almost impossible to prove. Since the enhanced system will report precise lengths of good and scrap material produced, and will neither allow the production of excessive scrap, nor allow the machine to run with testing switched off, the problem should be greatly reduced

References

[i] Information on typical pultrusion characteristics obtained from **Teel Plastics** web page

[ii] “The Potential for on-orbit manufacturing of Large space structures using the pultrusion process”, M.L.Wilson, I.O. MacConochie, G.S. Johnson, NASA/SAWE, 1987.

[iii] “Principles and Applications of Air-Coupled Ultrasonics” Joe Buckley, Presented at BINDT transducer seminar November 1997, to be published in a future issue of INSIGHT.