In-Situ Detection of Process-Induced Porosity During Cure of Out-of-Autoclave Composites

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ABSTRACT

Composite materials offer unique benefits in aerospace applications, including high strength-to-weight ratio, and are becoming increasingly used by industry manufacturers. Current manufacturing and processing methods can lead to defects in the composites, which are identified after fabrication using inspection methods. This study utilized a high-temperature ultrasonic inspection system to detect process-induced porosity in an out-of-autoclave (OOA) composite panel during cure.

In order to perform ultrasonic scans in-situ during cure, the system needed to be able to operate at oven temperatures up to 200 °C. There are no commercially available ultrasonic scanning systems that can operate continuously at these temperatures, so an enclosure was fabricated to insulate the ultrasonic system in the curing oven. The enclosure housed a MISTRAS® motorized X-Y raster scanner and contact transducer (Olympus® X2002). The Olympus® X2002 contact transducer is a continuous high-temperature delay line transducer with a center frequency of 2.25 MHz. In order to prevent the inside of the enclosure from reaching high temperatures, a sparge pipe inside the cooling enclosure was connected to a liquid nitrogen (LN2) tank outside of the oven via insulated hoses. The cooling system was automatically controlled by a temperature controller that was programmed to open a solenoid valve along the hose at 31 ℃ and close at 28 ℃ inside the cooling enclosure. When the solenoid valve was open, LN2 would flow from the LN2 tank and vaporize prior to reaching cooling enclosure. A U-shaped sparge pipe had holes drilled along its length to uniformly introduce cold nitrogen gas into the cooling enclosure. This prevented the motors from ever reaching the maximum desired operating temperature of 38 ℃. In the bottom of the enclosure, the tool plate was placed with the composite facing the outside of the enclosure, exposing it to the temperatures of the oven. The tool plate was 63.5 mm thick borosilicate glass, which was chosen for its low ultrasonic attenuation and moderate thermal conductivity. A thin layer of ultrasonic couplant was placed on the tool plate. The transducer sent and received ultrasonic waves through the tool plate into the composite.

A MISTRAS® Remote UT System performed all wave generation, analog to digital conversion, and data acquisition and processing. The transducer was connected directly to the Remote UT System via a high-temperature BNC cable (CD International, RG-316). Polyimide insulated copper wire was used to connect the scanner to a 2-axis motor drive, which was connected to the Remote UT System. The motor drive and Remote UT System were located outside the industrial oven. A diagram of the ultrasonic system is shown in Figure 1.



Figure 1: Diagram of ultrasonic in-situ defect detection system.

In this study, a porosity gradient was introduced into the carbon fiber reinforced polymer (CFRP) composite through a misfit of the part and caul plate. A 24-ply quasi-isotropic ([0/90, ±45]12S) composite panel was laid up using Newport® AS4C-M/NB321 out-of-autoclave (OOA) plain weave (PW) prepreg (42% resin content, 195 g/m2). The first 16 plies were 203 mm × 203 mm. Ply drops were incorporated into the panel by decreasing the length of plies 17-24. The sizes of each ply are included in Table 1. All plies were centered along their length (*x*-axis) creating a trapezoidal type cross-section.

Table : Ply sizes

|  |  |  |
| --- | --- | --- |
| Plies | Length (mm) | Width (mm) |
| 1-16 | 203 | 203 |
| 17-18 | 102 | 203 |
| 19-20 | 85 | 203 |
| 21-22 | 68 | 203 |
| 23-24 | 51 | 203 |

A 15-5 stainless steel caul plate (Size: 203 × 203 × 1.2 mm) was placed on the laminate. The composite and caul plate were vacuum bagged to the tool plate. Per the product datasheet, Newport 321 can be cured between 121 °C and 149 °C, depending on service temperature, with a hold for 90-120 minutes. Based on prior thermal testing of the cooling enclosure, the desired composite temperature cycle could be attained when the air temperature of the oven was ramped to 160 °C at a rate of 1.7 °C/min with a 3 hour hold. The extended hold was not necessary to cure the composite, but did allow for additional scans at the cure temperature during preliminary testing. The composite panel was under vacuum pressure for the entire cure cycle. Under vacuum, the caul plate deformed causing high and low pressure regions. The low-pressure regions formed high porosity in the composite part.

The ultrasonic data collected showed that the inspection system was able to monitor the evolution of porosity within the composite throughout the cure cycle. Fifty scans of a 203 mm × 51 mm (8 in. × 2 in.) area of the composite were completed throughout the cure cycle. The scan speed was set to 43 mm/s in the *x*-direction and 36 mm/s in the *y*-direction, with a 1.0 mm/pixel resolution in both directions. Each scan took approximately five minutes to complete. Figure 2 shows C-scan amplitude data (top view) from one scan during the cure cycle. The color map indicates the maximum amplitude (%) measured with a time gate that contains reflections from the back surface (furthest from the transducer in contact with the caul plate) of the composite. Because porosity in the composite increases the ultrasonic attenuation in the composite part, a higher amplitude (red) indicates low porosity and a lower amplitude (blue) indicates high porosity. The regions where the caul plate was applying increased pressure (center and ends of the panel) resulted in reduced porosity, whereas the ply drop regions had reduced pressure and thus had higher porosity.



Figure 2: Amplitude C-scan (top view) of OOA composite from one scan during the 160 °C temperature hold. Higher amplitude (red) indicates low porosity. Lower amplitude (blue) indicates high porosity.

A B-scan is a two-dimensional image plotting the ultrasonic signals from a single *y*-position at every *x*-location of the composite panel. The travel time (μs) of the ultrasonic wave (representing the through-thickness location) is plotted along the *y*-axis, and the ultrasonic wave signal is represented as a contour map. Based on the B-scan data, the location of the defects with respect to the composite thickness was able to be determined. The ply drop regions had high porosity near the front (tool plate) surface of the composite (Figure 3).



Figure 3: B-scan (cross-section view) of OOA composite from one scan during the 160 °C temperature hold.

Using the data obtained from amplitude C-scans and B-scans throughout the cure cycle, the high and low porosity regions within the composite laminate were detected and localized with high spatial resolution. This paper will discuss the evolution of porosity content in the OOA composite during cure. OOA tests aided the transition of this system to an autoclave, which is the primary method of curing aerospace-grade thermoset composites.