In-Process Ultrasonic Cure Monitoring System for Defect Detection and Localization in Composites

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SAMPE 2021 Technical Conference
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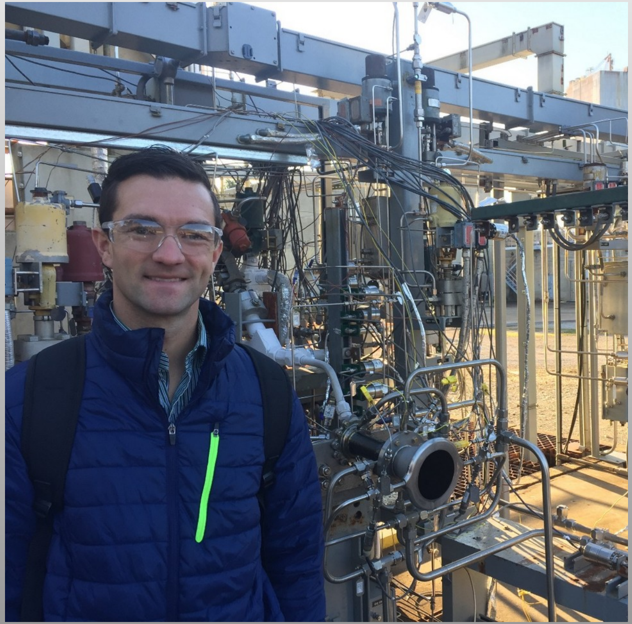
About Me – Presenter Bio

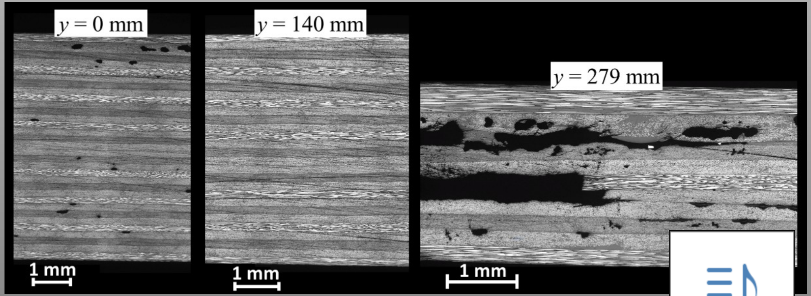
- Materials Research Engineer, NASA Langley Research Center (LaRC), 2018-Present
  - Research focus: Manufacturing and process monitoring of advanced aerospace composite structures
  - Projects within NASA Aeronautics Research Mission Directorate (ARMD) and Space Technology Mission Directorate (STMD)
- Graduate Research Assistant, National Institute of Aerospace (NIA), 2013-2017
  - Research performed on-site at NASA LaRC, 2014-2017
  - Ph.D. in Aerospace Engineering from N.C. State University, 2017



Challenge

- Composite materials offer many advantages to aerospace applications
- Defects (e.g., porosity) occur during the manufacture of composites, including cure
- Process models can predict cure defects
    - Example: Advanced Composites Project (ACP) Cure Defects Process Model (CDPM)[1,2]
- No direct validation of porosity during cure
    - Current validation method includes pressure sensors during cure and inspection/microscopy after cure

Image Credit: NASA/AFRC/Ken Ulbrich (https://images.nasa.gov/details-AFRC2019-0260-53)



1. Design of caul sheet misfit test: M. Roy, J. Kay, G. Fernlund and A. Poursartip (2015), *Porosity in Configured Structures*, Proceedings of SAMPE 2015, Baltimore, MD. (https://www.nasampe.org/store/ViewProduct.aspx?ID=4765959)
2. Porosity simulation using COMPRO applicable to those caul sheet misfit cases: C. Hickmott, A. Forghani, V. Hutten, E. Lorbiecki, F. Palmieri, B. Grimsley, B. Coxon, G. Fernlund, A. Poursartip (2019), *A Numerical and Experimental Approach for Modeling Porosity due to Entrapped Air and Volatiles Off-Gassing during Manufacturing of Composite Structures*. SAMPE 2019, Charlotte, NC. (https://ntrs.nasa.gov/citations/20200002678)

Objectives

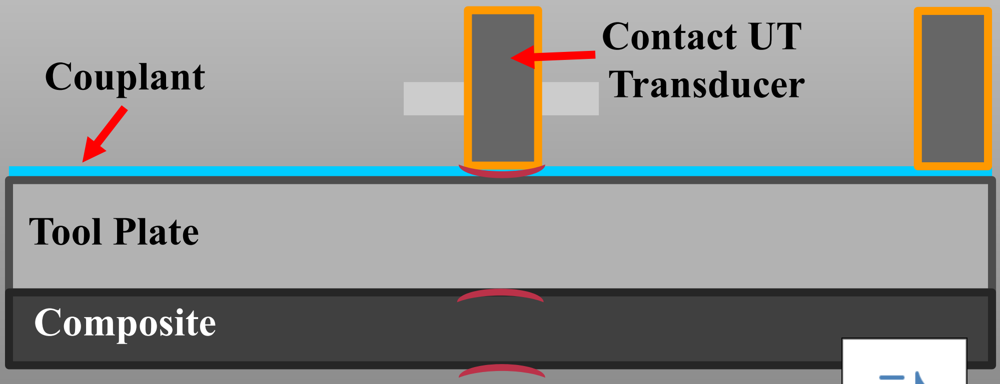
- Develop system to perform defect (e.g., porosity) detection, localization, and quantification during cure in oven and autoclave
- Why is this hard?
  - **Limited accessibility to composite part during cure**
  - **Small size of defects**
  - **Harsh environment of curing**
    - Current commercial-off-the-shelf inspection systems cannot withstand the elevated temperatures required to cure composites

Autoclave

Oven

Approach and Design

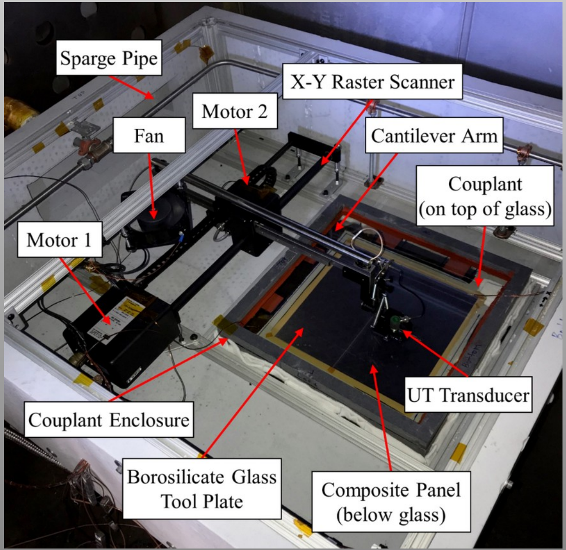
- Initial testing in oven, then transitioned to autoclave
- Scanner mounted inside insulated, unsealed cooling enclosure
  - Liquid nitrogen (LN_2) delivered from outside of oven/autoclave moderates the temperature inside enclosure
  - Oven/autoclave controls maintain temperature and pressure for curing
- High-temperature ultrasonic transducer (2.25 MHz) inspects composite part through the tool plate
  - Composite part vacuum bagged underneath tool plate (Other orientations possible)
- Ultrasonic waves reveal internal structure of composite panel



Prototypes

1st Version (Oven System)

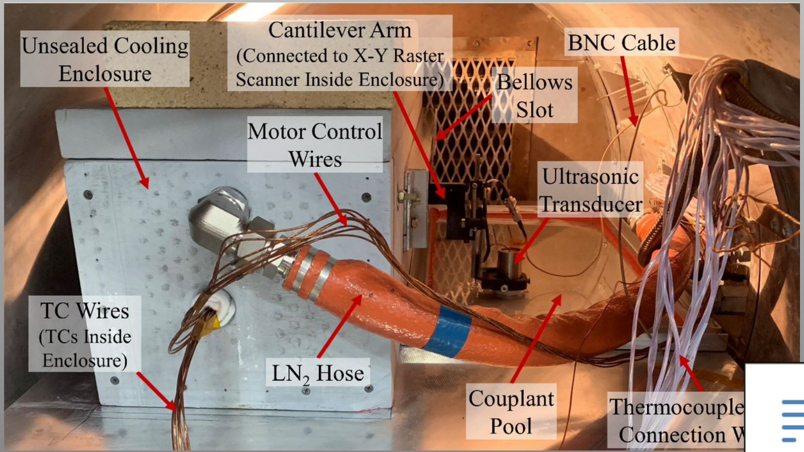
- No space concerns in oven so enclosure intentionally large
- X-Y raster scanner and ultrasonic transducer inside enclosure
- Composite panel vacuum bagged underneath low thermal conductivity tool plate (borosilicate glass)



Photograph of 1st prototype with lid removed to show scanner inside enclosure.

2nd Version (Autoclave System)

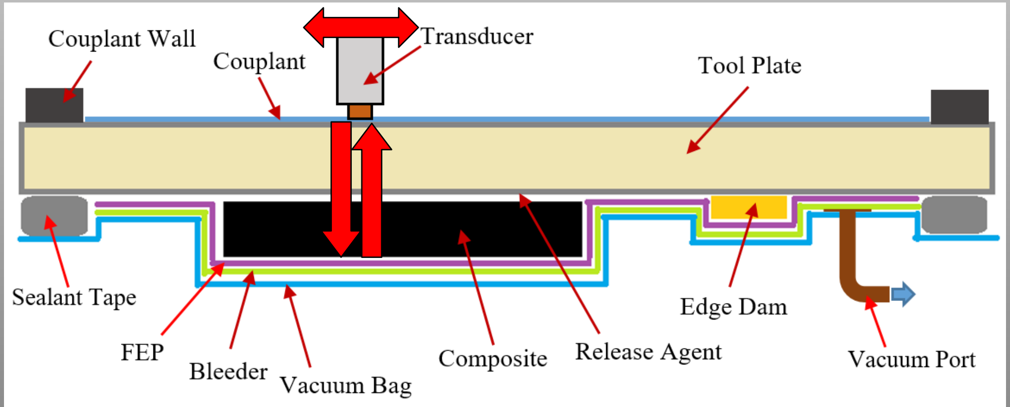
- Backwards compatible to oven
- Reduced footprint
- Ultrasonic transducer outside enclosure
- Improves processing
  - No thermal gradient in part
  - Nearly identical to traditional processing
- Results published in Composites Part A
  - T.B. Hudson, P.J. Follis, J.J. Pinakidis, T. Sreekantamurthy, and F.L. Palmieri, “Porosity detection and localization during composite cure inside an autoclave using ultrasonic inspection.” *Composites Part A: Applied Science and Manufacturing*, 106337, 2021. https://doi.org/10.1016/j.compositesa.2021.106337



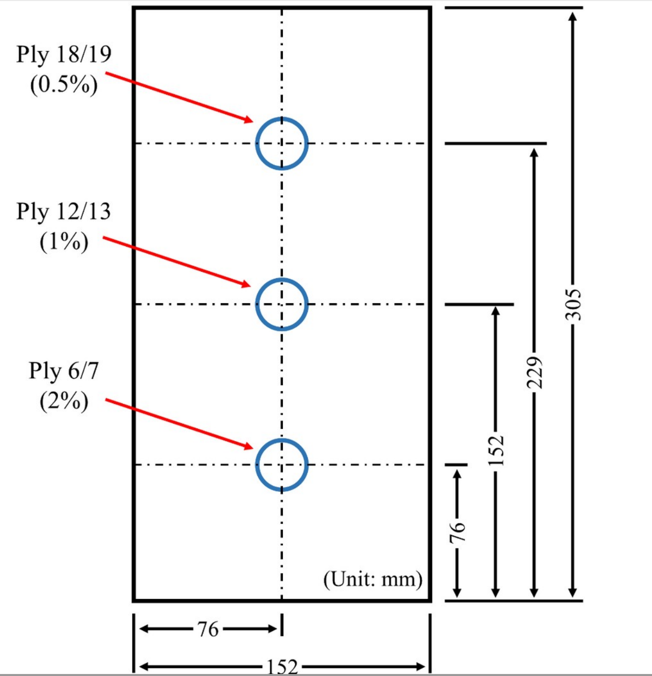
Photograph of 2nd version inside autoclave prior to cure

Intentionally Embedded Porosity

- Porosity simulated by hollow glass microspheres introduced during layup of out-of-autoclave (OOA) composite.
  - **Material: Newport® AS4C-M/NB321 OOA plain weave (PW) prepreg (42 wt.% resin, 195 g/m²)**
  - **Layup: 24-ply quasi-isotropic ($[0/90, \pm45]_{6S}$)**



In-situ Inspection Setup for OOA Panel During Cure

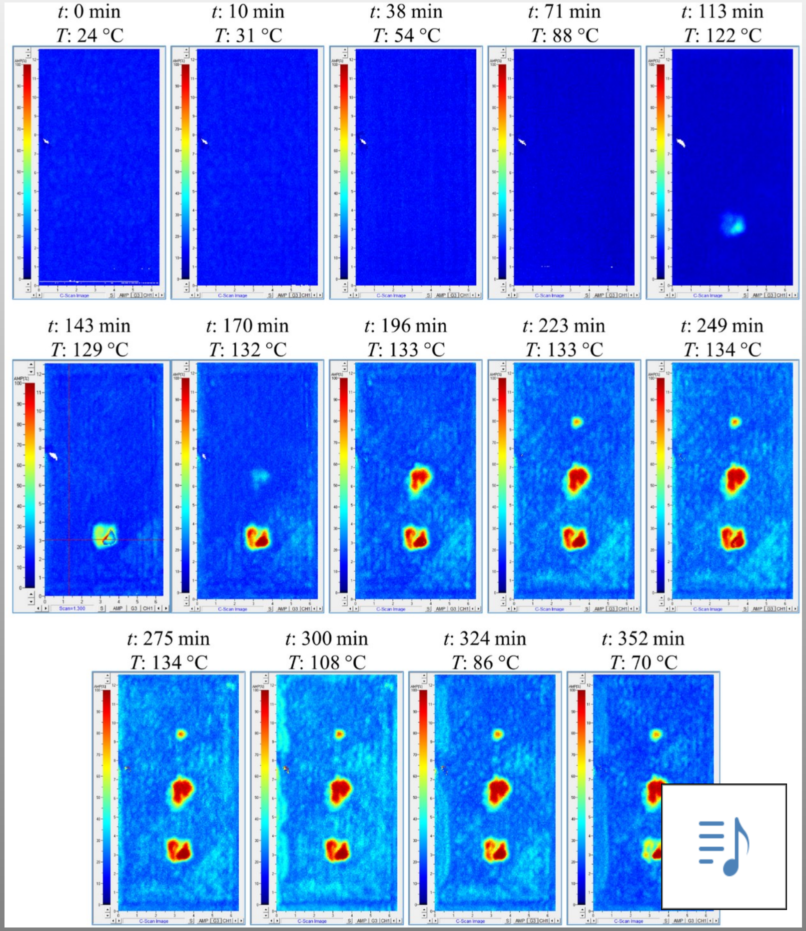


Embedded Defect Panel Diagram

Results

1. T.B. Hudson, P.J. Follis, J.J. Pinakidis, T. Sreekantamurthy, and F.L. Palmieri, “Porosity detection and localization during composite cure inside an autoclave using ultrasonic inspection.” *Composites Part A: Applied Science and Manufacturing*, 106337, 2021. https://doi.org/10.1016/j.compositesa.2021.106337
2. Sloan, J. "Out of autoclave processing:< 1% void content." (2015) Retrieved from https://www.compositesworld.com/articles/out-of-autoclave-processing-1-void-content.

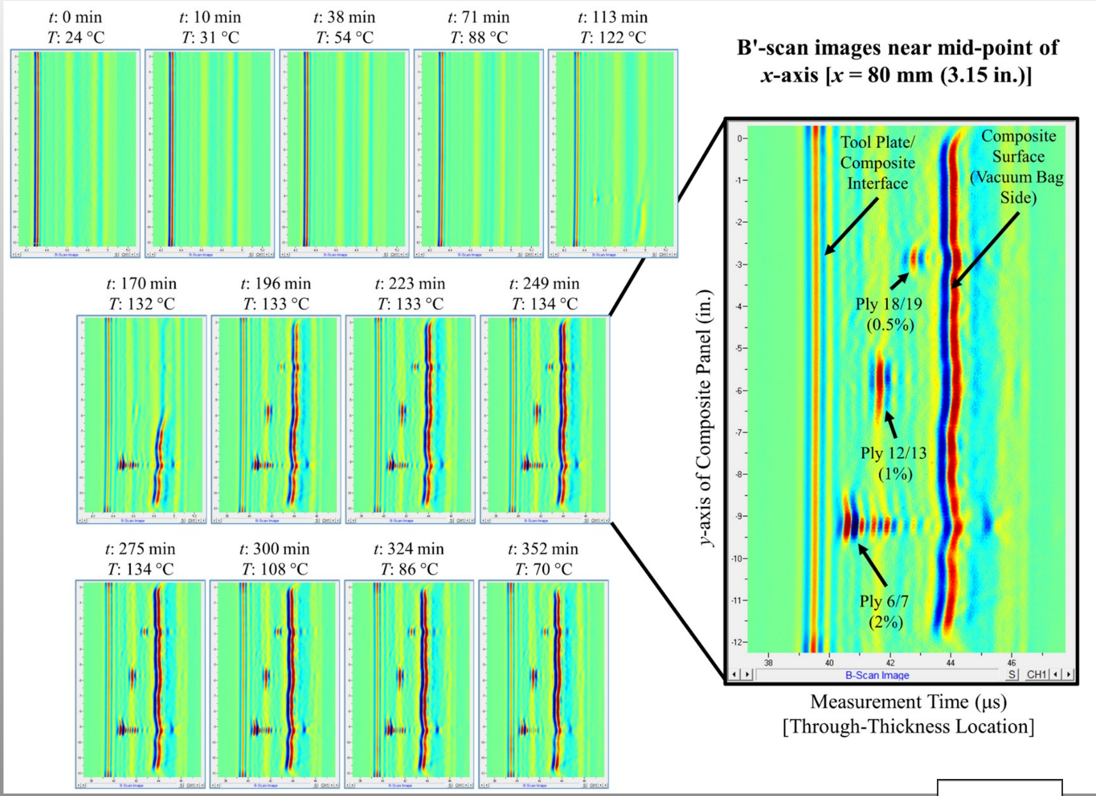
- Scans performed every ~15-20 minutes throughout cure cycle
  - **Scan area: 165 mm × 318 mm**
  - **Scan resolution: 1 mm × 1 mm**
  - ***Scan time can be significantly reduced by optimizing scanning parameters***
- C-scan images of ultrasonic amplitude of reflections within the composite
  - **Porosity causes a reflection**
  - **Higher value (red) indicates porosity/defect present**
- Three porosity defects clearly visible
- First detection later in cure cycle for OOA material than during autoclave testing[1] (not shown)
  - **OOA preforms have high porosity before processing because they are only partially impregnated. Partial impregnation provides path for entrapped air to escape when vacuum is applied during cure before full consolidation[2]**
  - **Much lower pressure applied (101 kPa compared to ~690 kPa autoclave)**



Key Result: Demonstrated defect detection and localization (in-plane) during cure.

Results *(cont.)*

- B'-scan: 2-D image that provides a through-thickness "slice" of the composite
- Three porosity defects clearly visible (between plies
  1. 25% through the thickness (Ply 6/7 interface)
  2. 50% through the thickness (Ply 12/13 interface)
  3. 75% through the thickness (Ply 18/19 interface)



Key Result: Demonstrated defect detection and localization (through-thickness) during cure.

Summary

- System developed that performs defect detection and localization during cure in oven and autoclave[1].
- Features:
  - High spatial resolution cure monitoring of resin state and material properties (in addition to defect detection).
  - Scalable from research and development to existing production lines.
  - No change required to current part design and limited changes to processing equipment (with current system).

1. T.B. Hudson, P.J. Follis, J.J. Pinakidis, T. Sreekantamurthy, and F.L. Palmieri, “Porosity detection and localization during composite cure inside an autoclave using ultrasonic inspection.” *Composites Part A: Applied Science and Manufacturing*, 106337, 2021. https://doi.org/10.1016/j.compositesa.2021.106337

Impact

- Impact:
  - Real-time knowledge of porosity (or other defect) location and quantity during cure.
  - Validation of process models and/or processing parameters during certification.
  - Control of processing parameters during cure based on real-time measurements.
  - Results in more efficient process development, shortened certification time, reduction in off-spec parts, and increased production throughput.
- Applications:
  - Aircraft, launch vehicles, satellite buses, automotive, wind turbine blades, etc.
- Users:
  - OEMs, Tier I/II suppliers, inspection equipment manufacturers, inspection service companies, processing equipment (e.g., autoclaves) manufacturers, government agencies, universities, research labs.

Acknowledgements

- **Composite Fabrication and Testing:**
  - Hoa Luong and Sean Britton
- **System Design:**
  - Eric Burke, Jeff Seebo, and Jamie Shiflett

National Aeronautics and Space Administration

Questions?

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