Thermoplastic Joining Materials Guidance for Aircraft Design and Certification

Process Development & Scaling Studies

Waruna Seneviratne, John Tomblin, Jerome Teoh, Shafie Mohamed, Mark Walthers, Riley Ziegler, Zakk Lierman, Upul Palliyaguru, Akshay Tamala, and Lakshan Rubesingh

JAMS Technical Review
April 2023
Seattle, WA

Joint Centers of Excellence for Advanced Materials

CECAM center of excellence for composites and advanced materials

NIAR Wichita State University

ATLAS Advanced Technologies Lab for Aerospace Systems

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Research Team

NIAR

Waruna Seneviratne, PhD

John Tomblin, PhD

Jerome Teoh & Shafie Mohamed

Mark Walthers, Riley Ziegler, Zakk Lierman

Upul Palliyaguru, Akshay Tamala, Lakshan Rubesinghe

NIAR®
WICHITA STATE UNIVERSITY

FAA

Danielle Stephens, Technical Monitor

Larry Ilcewicz, PhD, Sponsor

Cindy Ashforth, Sponsor

Ahmet Oztekin, PhD

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Program Overview

Thermoplastic Bonding

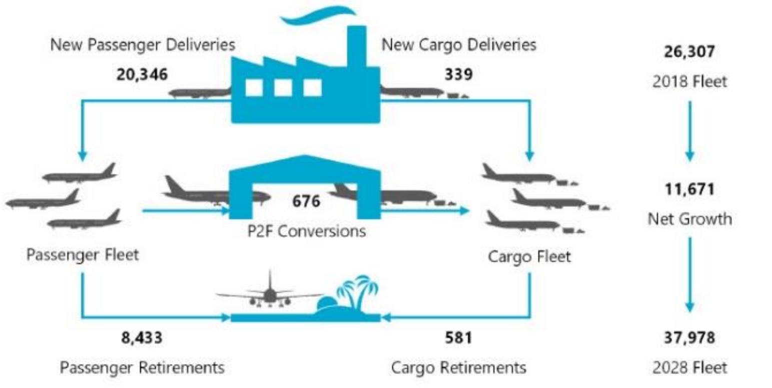
Thermoplastic Welding

Process Development

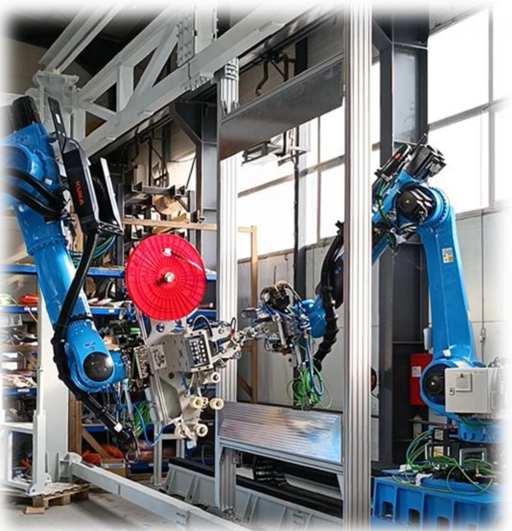
Performance Evaluation

Background

- Aircraft manufacturing processes will be required to undergo significant technology advancements to increase production rates.
- Thermoplastic material systems are being considered so that
    - Faster cycle time and manufacturing processes
    - Reversible process; thermoplastic materials can be melted and remolded without affecting the polymer's physical properties.
- Due to this capability, non-traditional joining approaches such as fusion bonding (welding) can be implemented in order to significantly reduce weight and cost over mechanical fastening and adhesive bonding.



Source: Oliver Wyman Global Fleet & MRO Market Forecasts



The primary goal of this task is to establish best practices for joining thermoplastic composite materials in order to reduce assembly time and cost of next generation structural components.
Process specifications and guidance materials are being developed to demonstrate joining techniques at scale.

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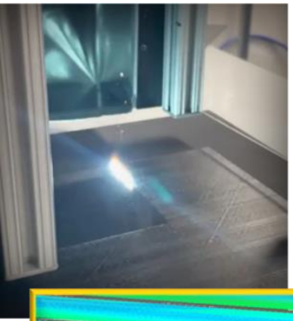
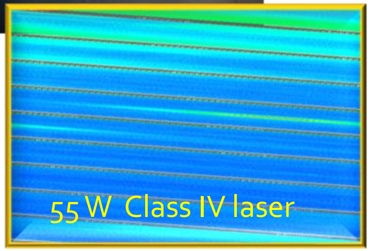
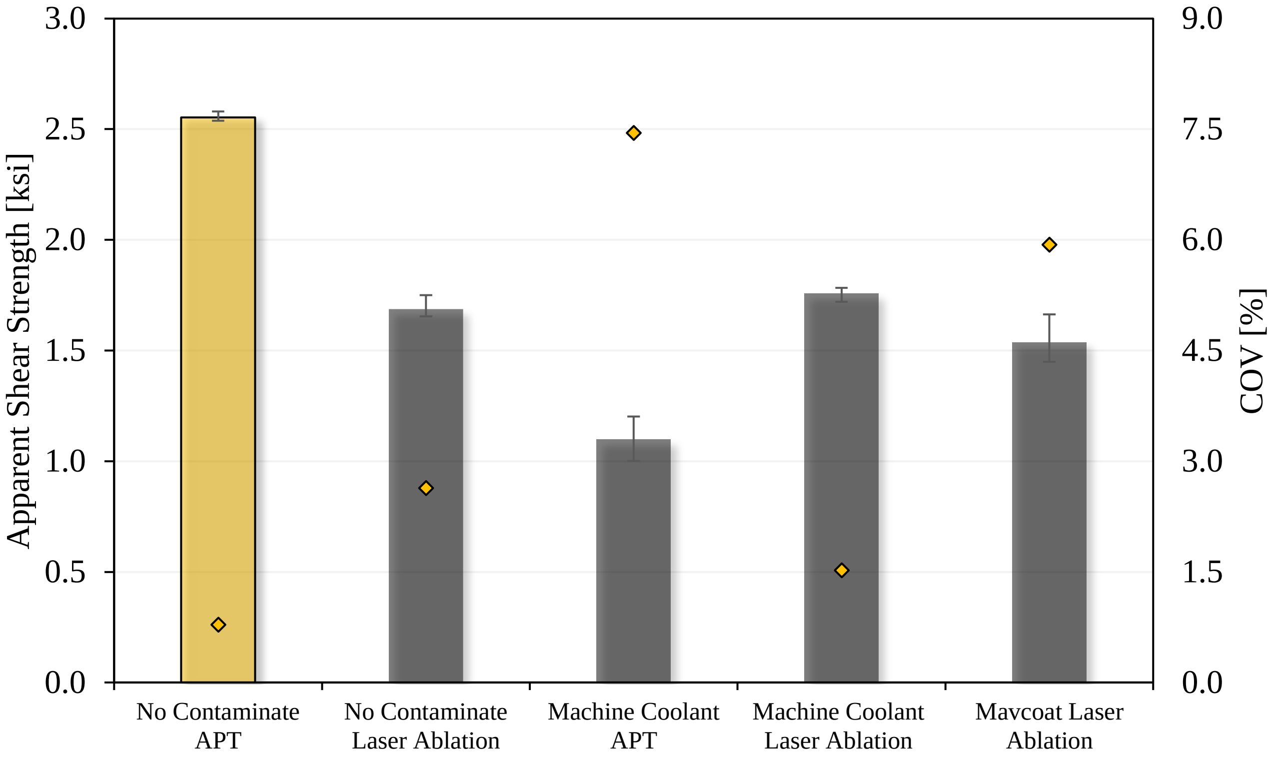
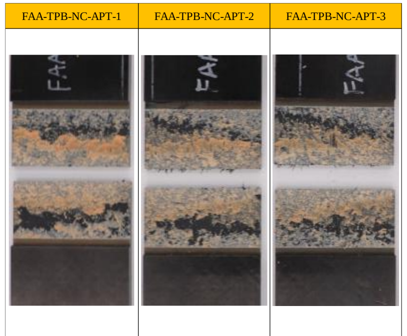
Thermoplastic Bonding: Contamination Study Results

- Atmospheric plasma treatment (APT) shows resulted in the strongest bond.
- However, when contaminants are present, laser ablation is the most effective decontamination process.
- Mavcoat specimens decontaminated with the APT process did not survive machining.

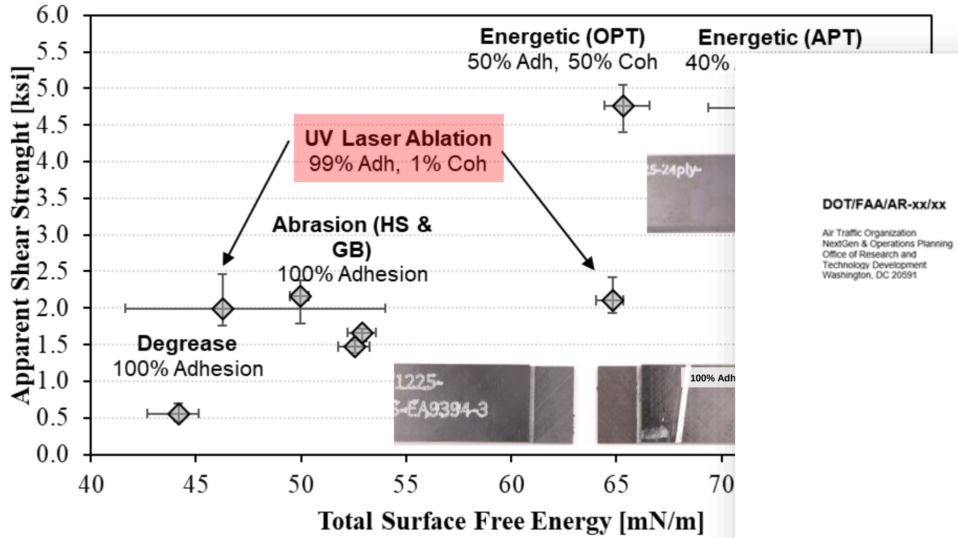








Effects Surface Preparation - Addition of Laser Ablation + CO_2 Cleaning



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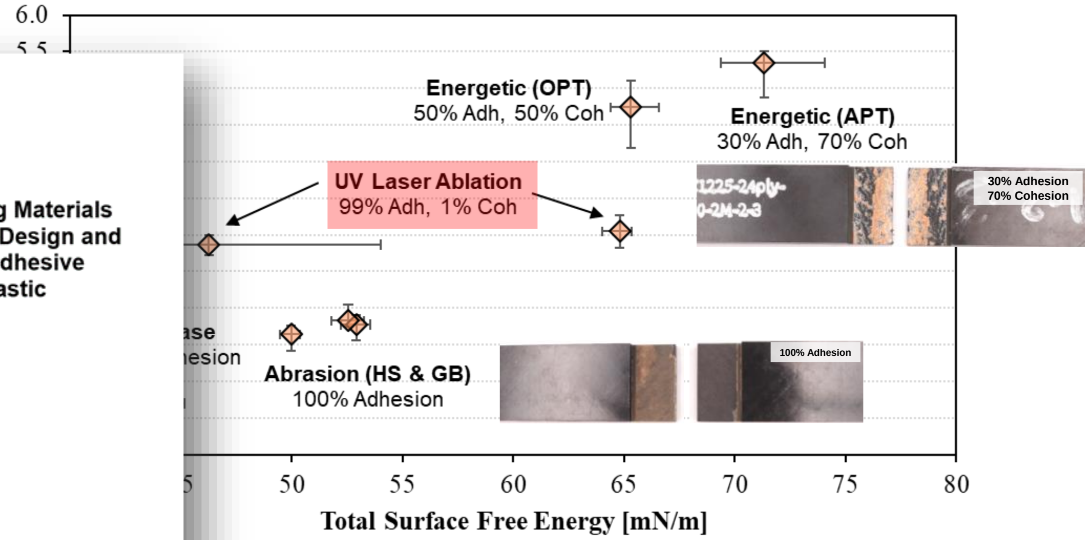
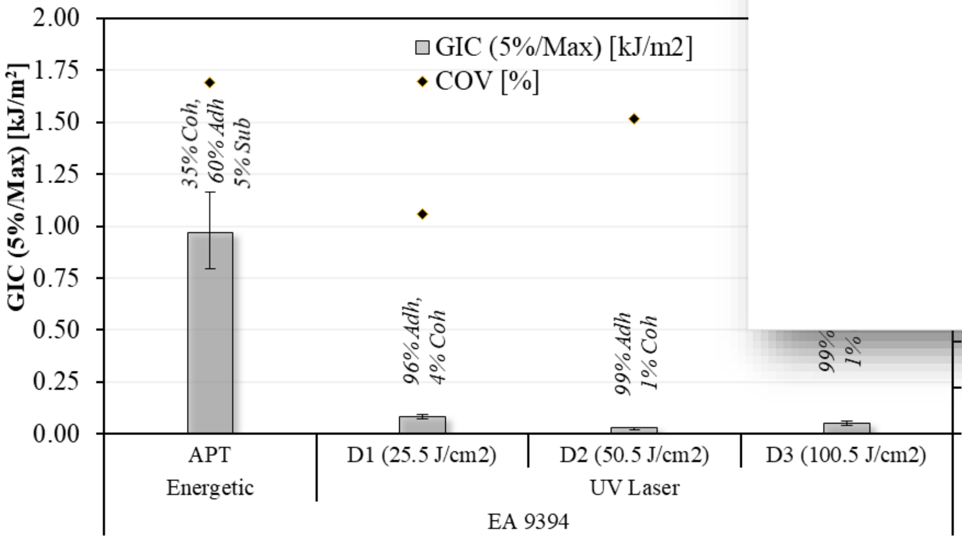
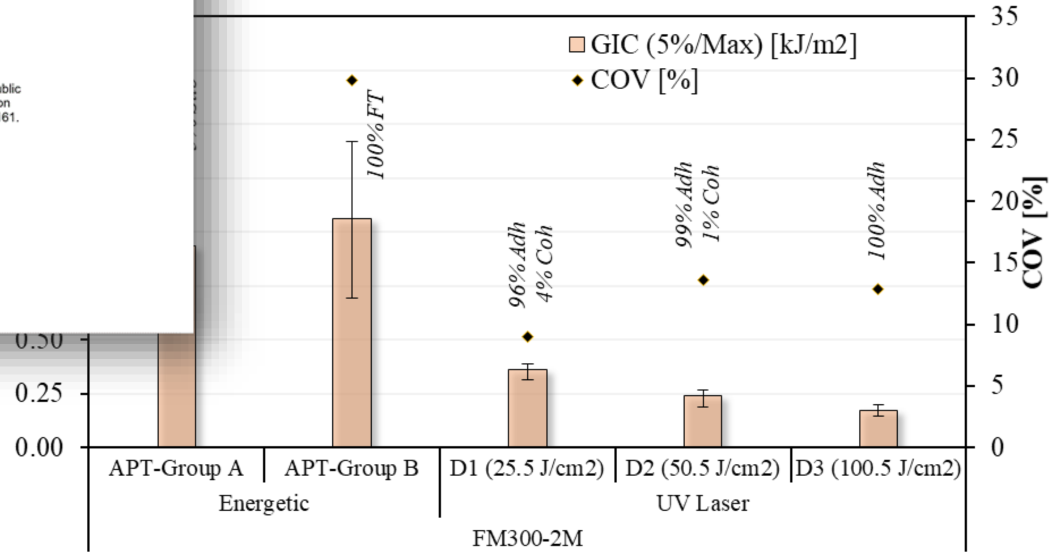


FM300-2M





DOT/FAA/AR-xx/xx

Air Traffic Organization
NextGen & Operations Planning
Office of Research and
Technology Development
Washington, DC 20591

Thermoplastic Joining Materials Guidance for Aircraft Design and Certification – Vol. I Adhesive Bonding of Thermoplastic Composites

May 2023

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

U.S. Department of Transportation
Federal Aviation Administration

Program Overview

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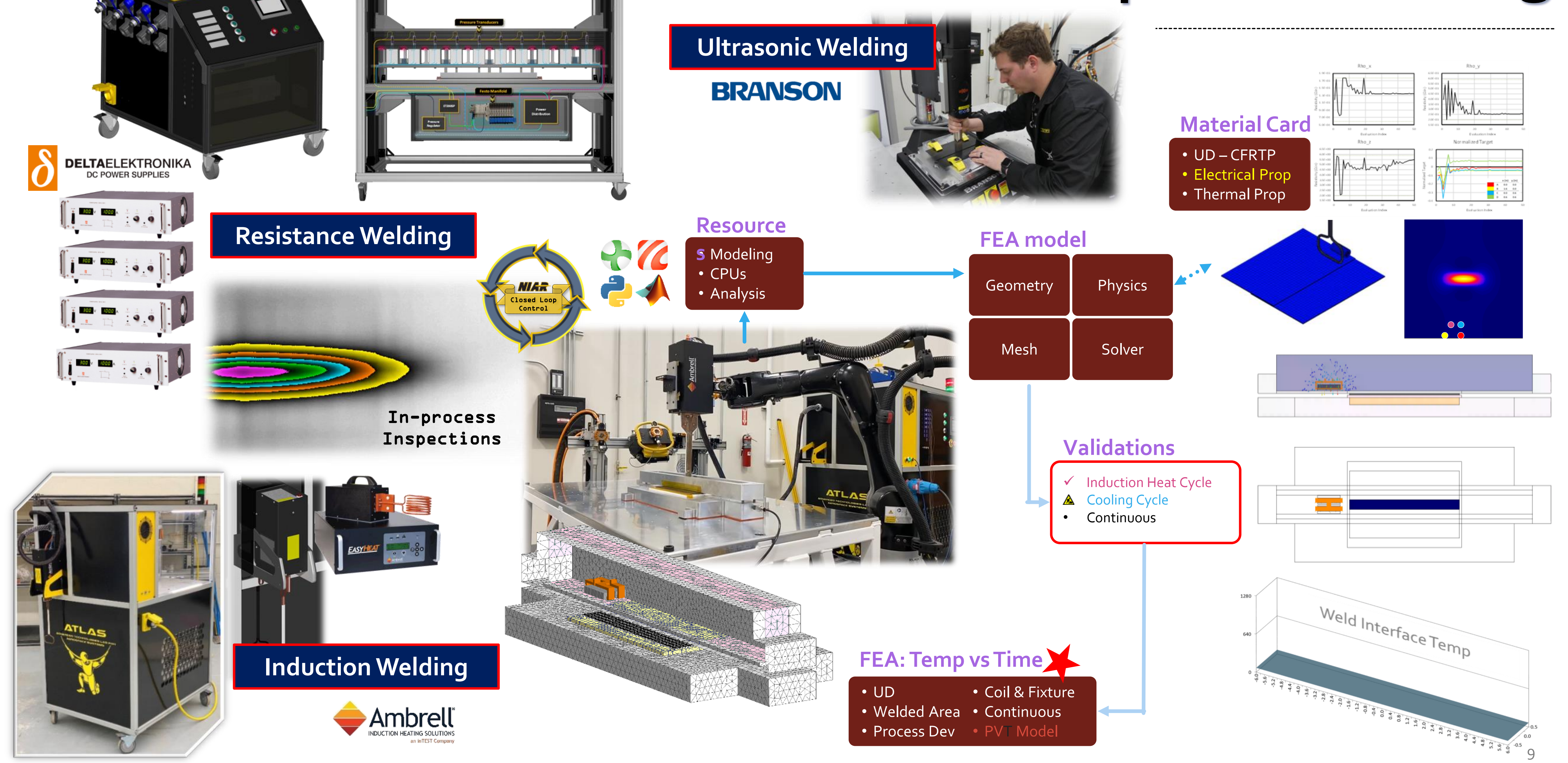
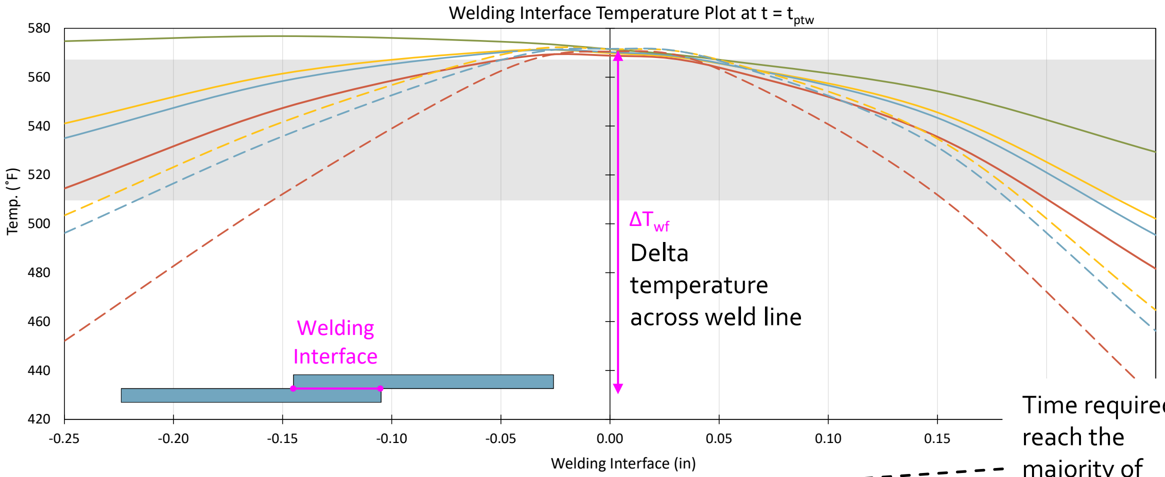
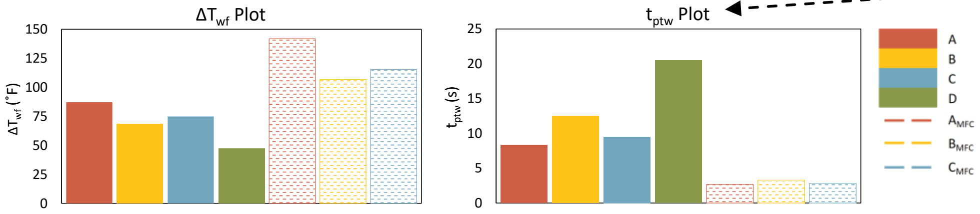
Thermoplastic Welding



Induction Welding Model Application

- Coil Design Analysis using 2D static model
  - Coil geometry and design will influence the shape and density of generated magnetic field, which in turn influences how the work piece is heated
  - FE model was employed to study the induced thermal distribution across the weld interface to design the NIAR induction coil

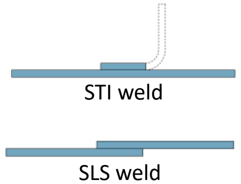


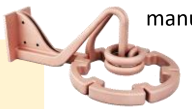


Time required to reach the majority of welding interface to process window

Coil Design

Weld Configuration | Fabrication Method



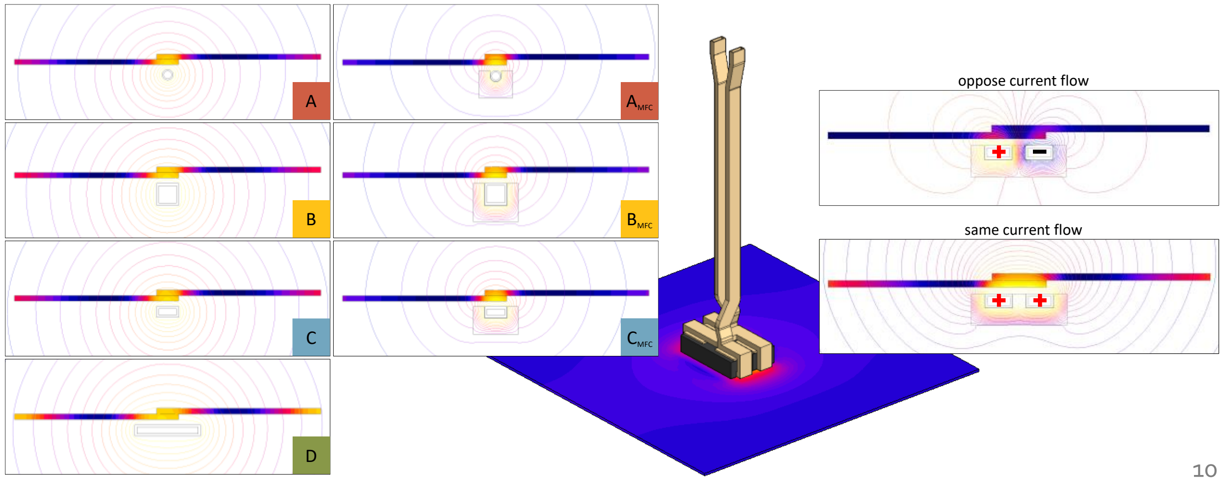


Additive manufacturing

Using factory's standardized tube

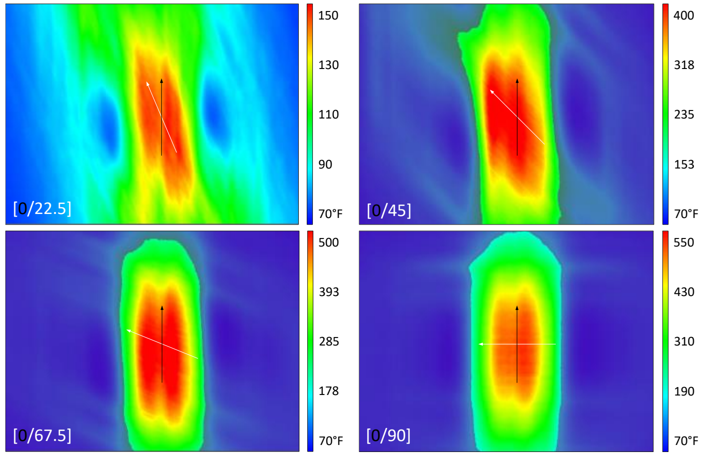
Coil Geometry	MFC Geometry
Number of Turns	Wall-to-wall Distance

Screening & Scoring
- Thermal Distribution
- Heating Efficiency

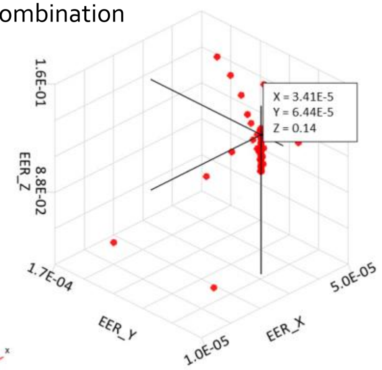


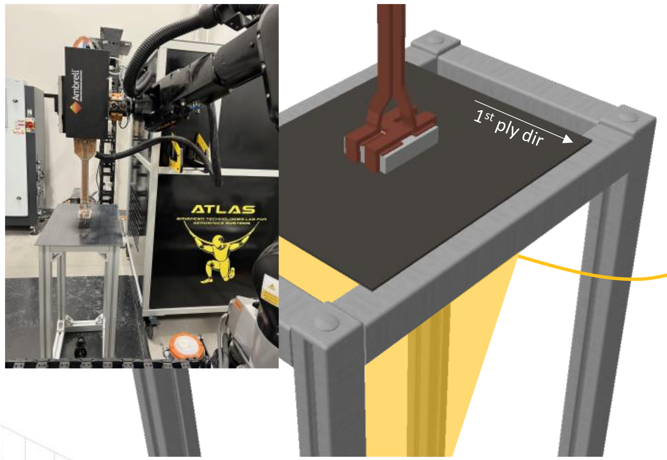
Induction Welding Model Application

- Material properties analysis and anisotropy electrical characterization model for simulation inputs
  - Heating efficiency knockdown at the inter-ply region need to accounted in characterizing

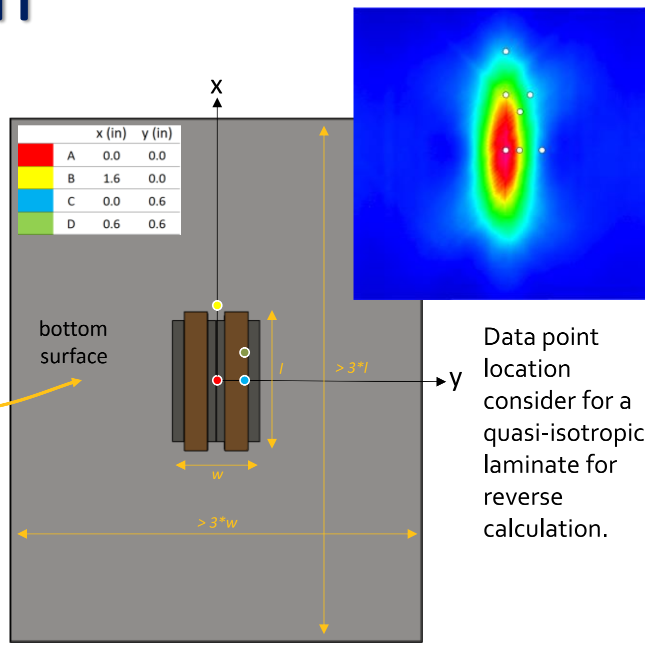


Anisotropy resistivity combination

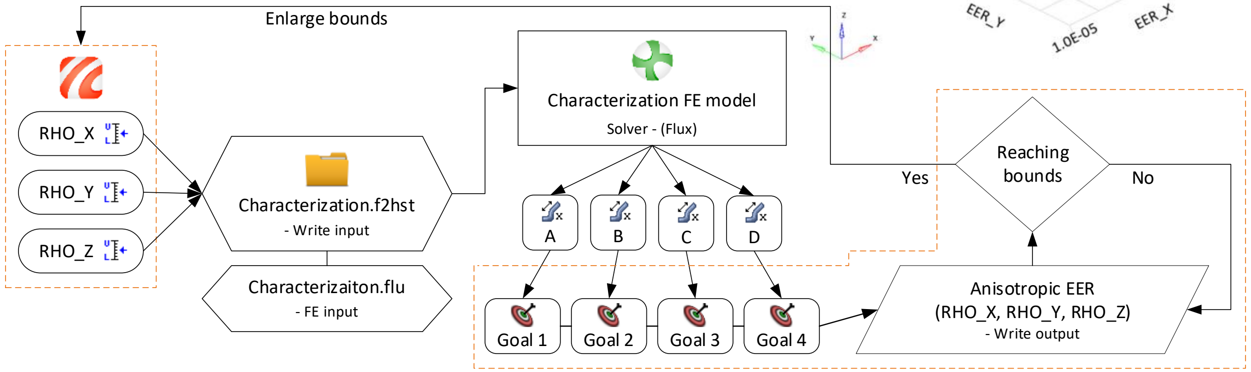




Infrared camera

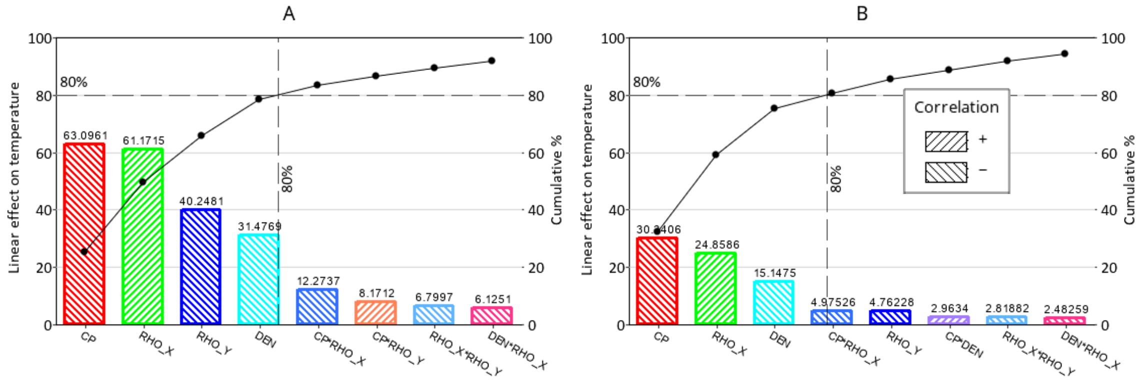


Data point location consider for a quasi-isotropic laminate for reverse calculation.



Experiment Data Feed In

DoE analysis on the UD material properties



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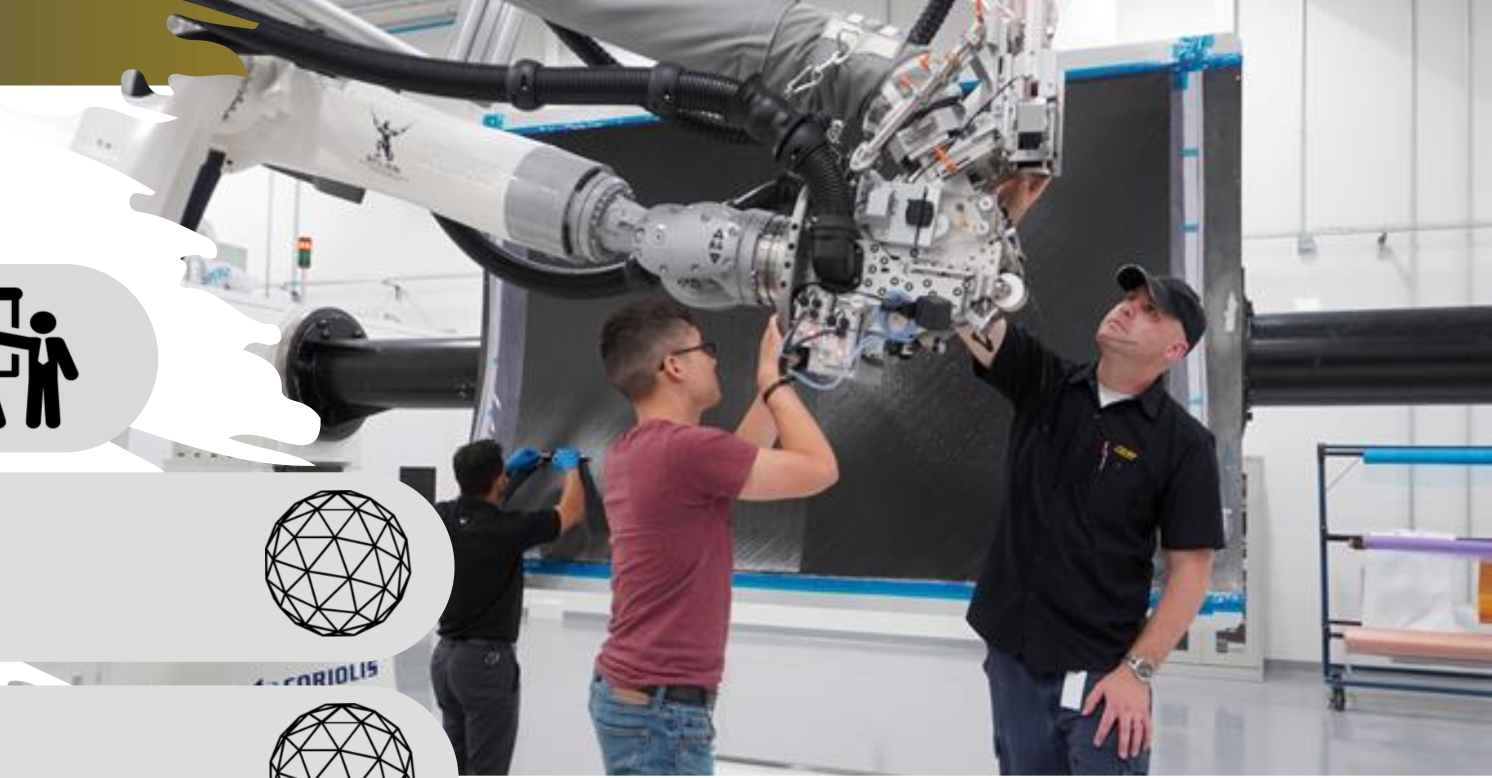
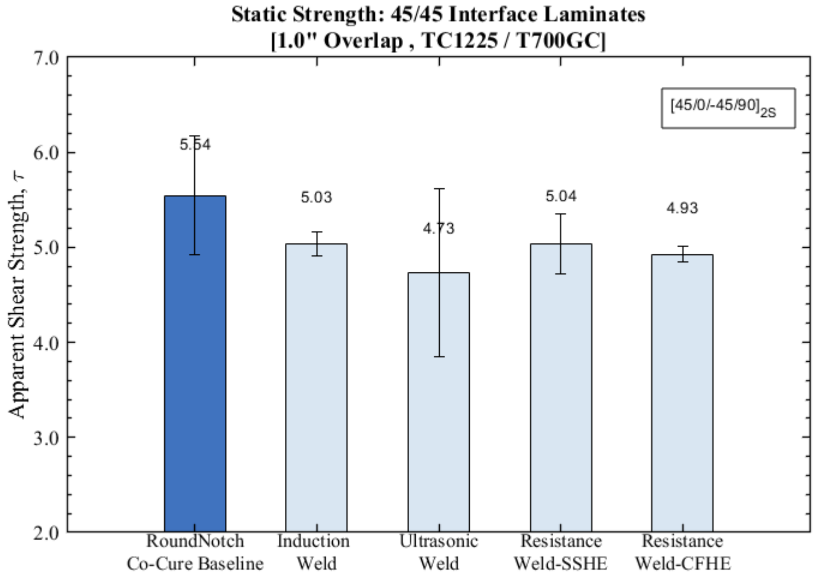
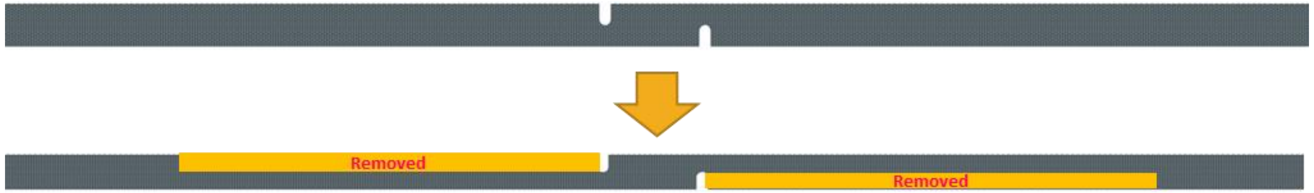


Comparison of Weld Single lap Shear Strength (1” OL)

	TC1225 / T700GC			
	Category	Average Apparent Shear Strength [ksi]	COV [%]	% Difference
TC1225-Baseline- Round Notch	MASC-BL-AC-TC1225	5.54	11.30	
TC1225-IW	MASC-IW-TC1225	5.03	2.51	-9.24%
TC1225-UW	MASC-UW-TC1225	4.73	18.70	-14.65%
TC1225-RW-SS	MASC-RW-TC1225	5.04	6.27	-9.12%
TC1225-RW-CFHE	MASC-RW-TC1225	4.93	1.68	-11.13%

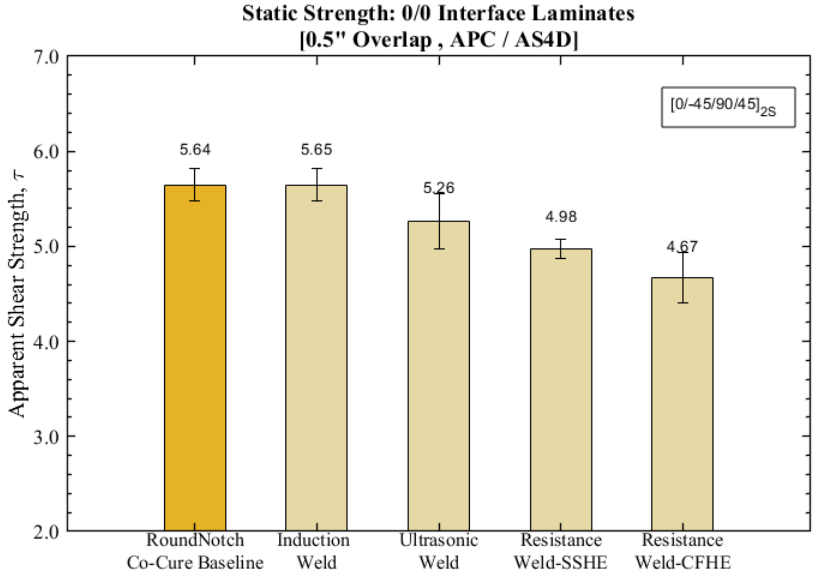
45/45 interface
TC1225 / T700GC





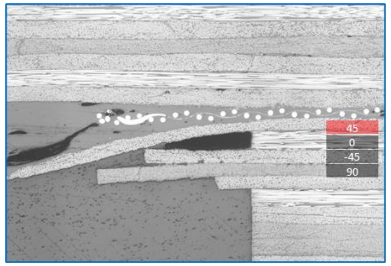
	APC / AS4D			
	Category	Average Apparent Shear Strength [ksi]	COV [%]	% Difference
APC-Baseline- Round Notch	MASC-BL-AC-APC	5.64	3.03	
APC-IW	MASC-IW-APC	5.65	2.99	0.06%
APC-UW	MASC-UW-APC	5.26	5.58	-6.75%
APC-RW-SS	MASC-RW-APC	4.98	1.98	-11.82%
APC-RW-CFHE	MASC-RW-APC	4.67	5.63	-17.26%

0/0 interface
APC / AS4D



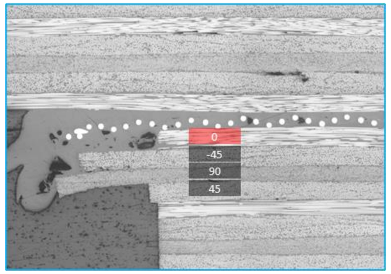
Resistance Welding: Temperature & Pressure Dependance (0.5” OL)

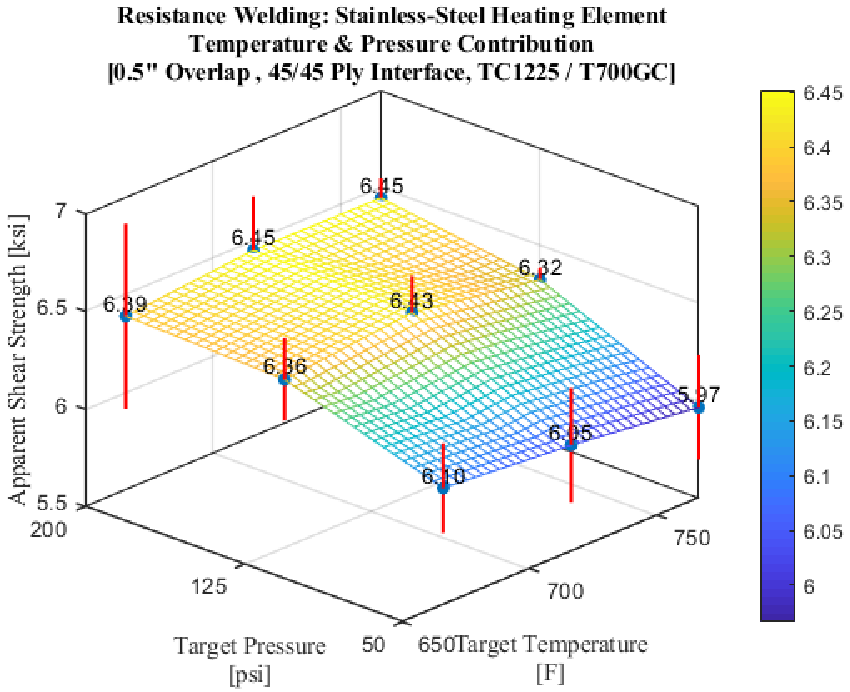
TC1225 / T700GC

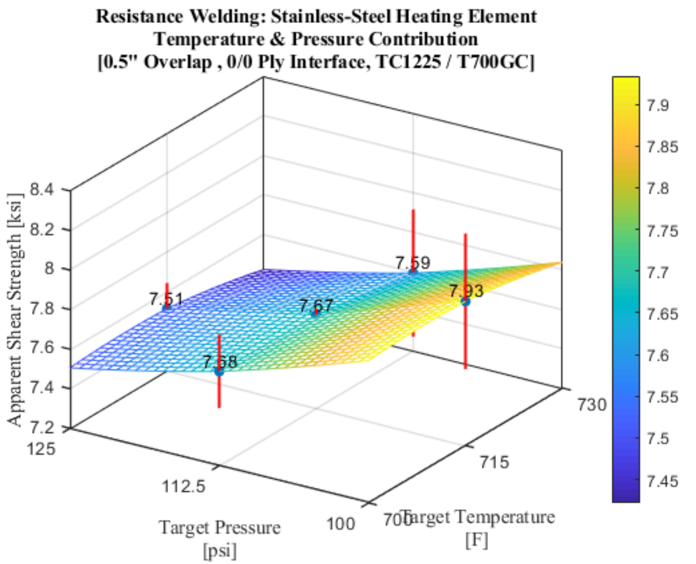


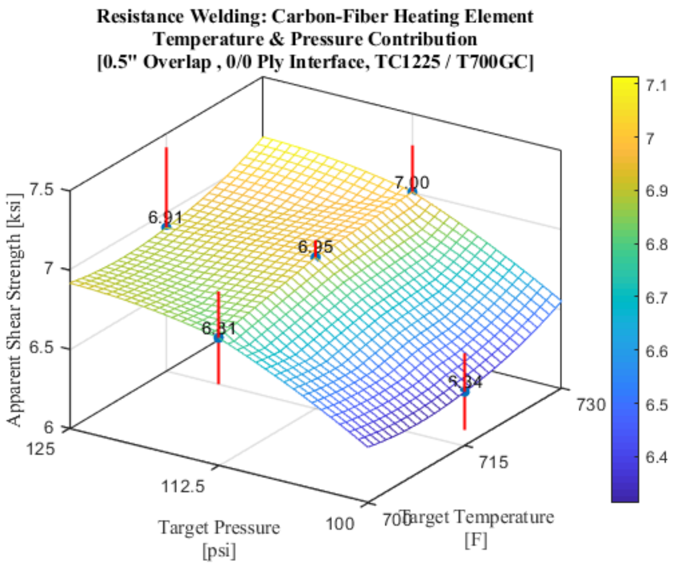
Initial Assessment Ranges (large range) Evaluated with 45/45 interface

Finalized Range (smaller operational range) Evaluated with QI o/o interface









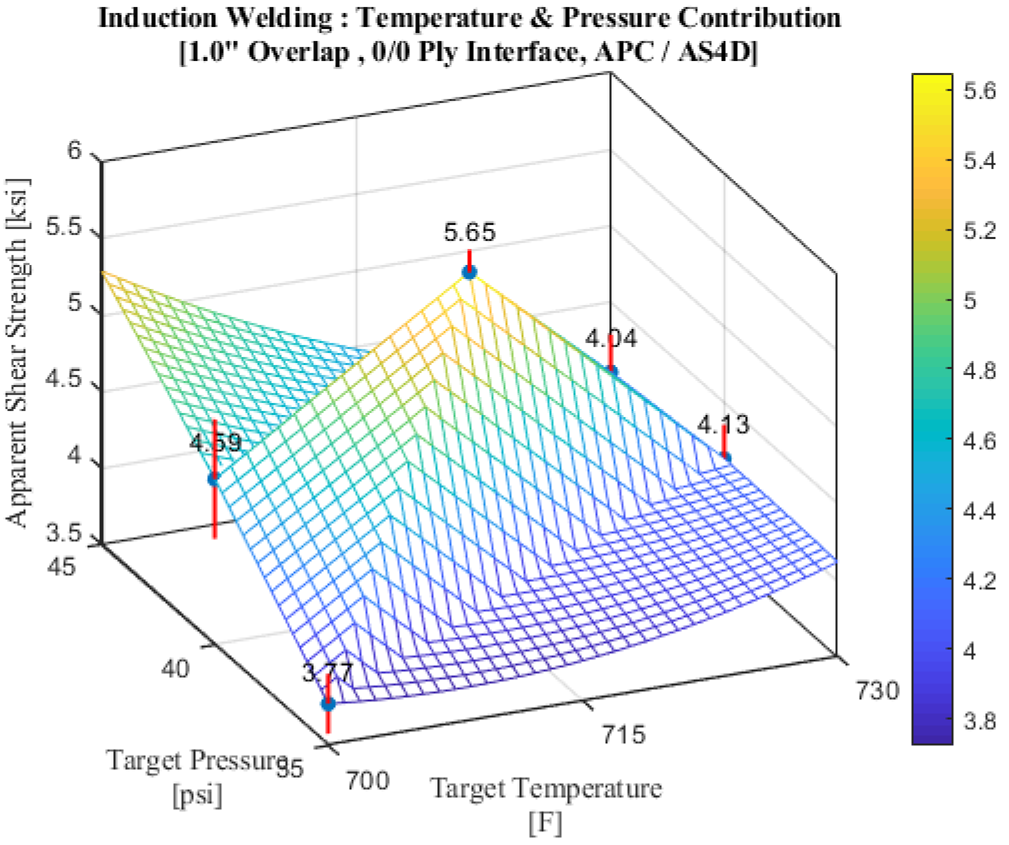
Stainless-Steel Heating Element — *45/45 interface*

Stainless-Steel Heating Element — *o/o Interface*

Carbon-Fiber Heating Element — *o/o Interface*

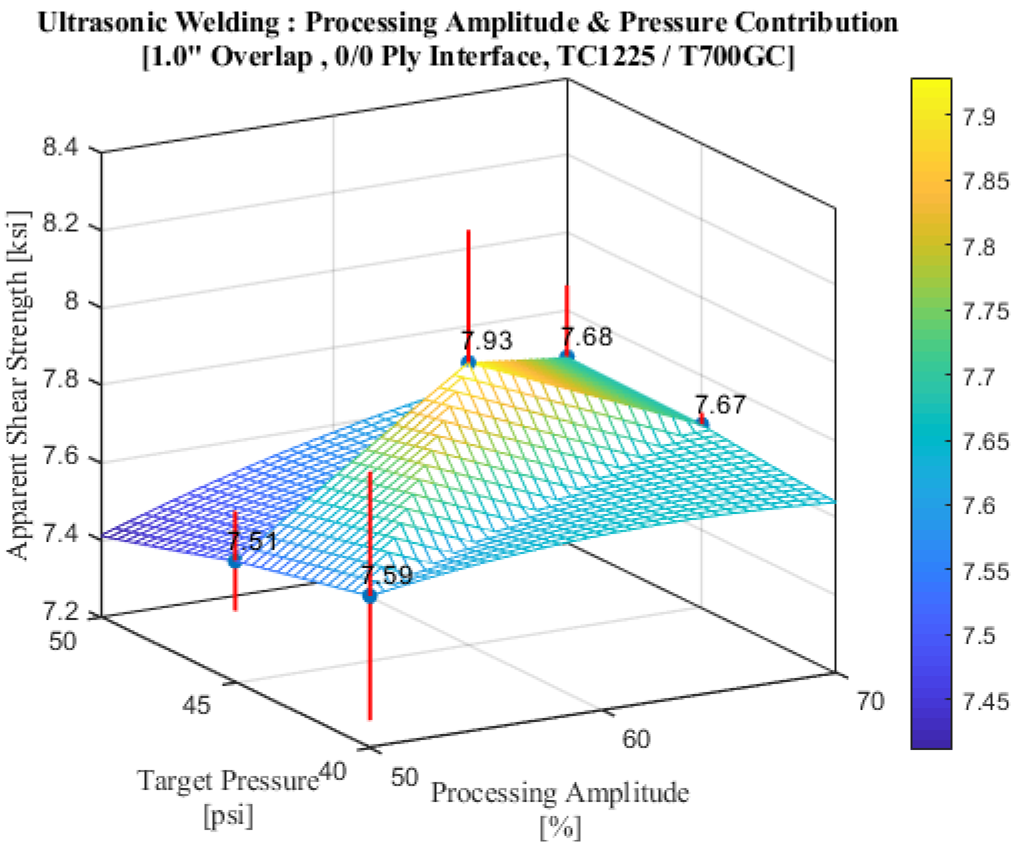
Process Parameter Trend (Pressure & Temperature) – APC / AS4D Induction Welding (1.0” OL)

Evaluated on QI o/o interface
OVERLAP LENGTH = 1.0”



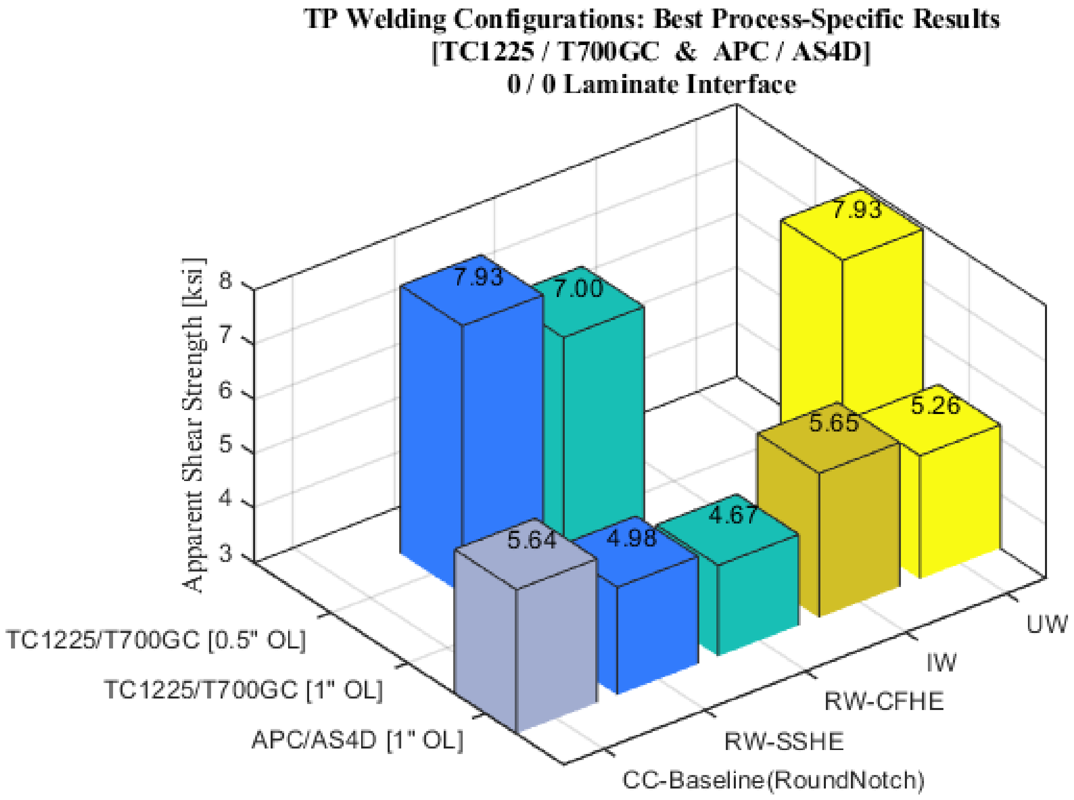
Process Parameter Trend (Pressure & Amplitude) – TC1225 / T700GC
Ultrasonic Welding (1.0” OL)

Evaluated on QI o/o interface
OVERLAP LENGTH = 1.0”

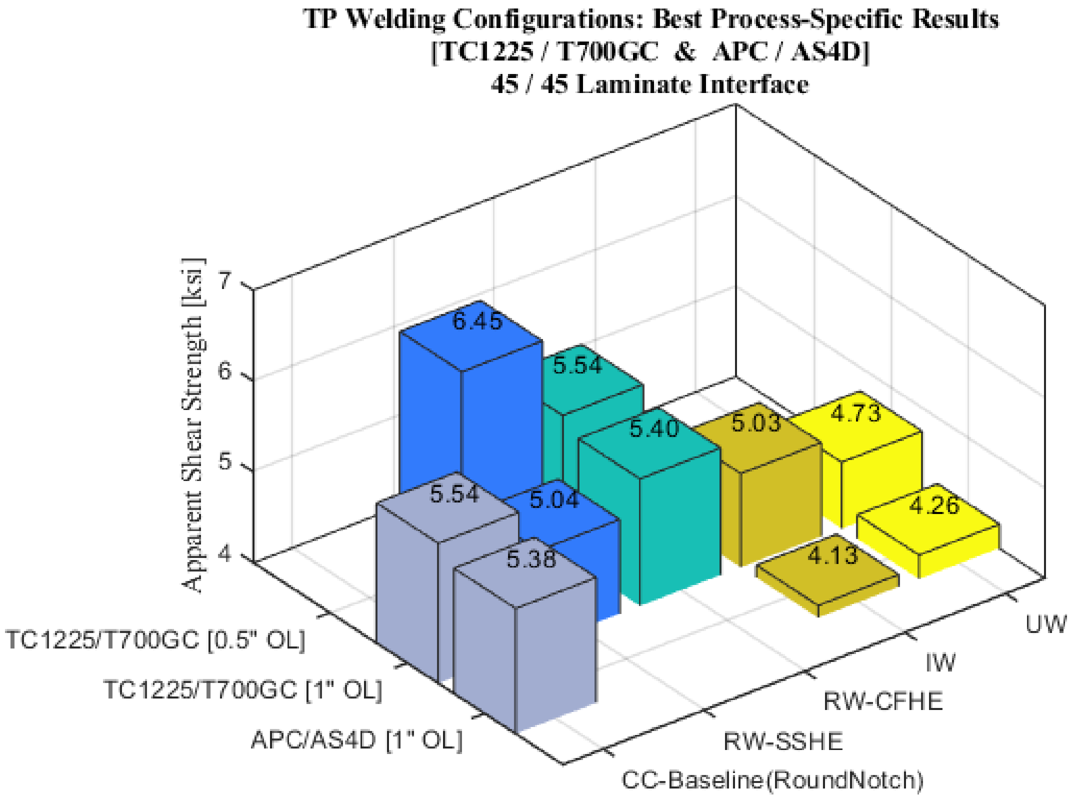


Best Case Grouping from Pressure/Temp/Amplitude Study & Initial Static Dataset

All 0/0 Interface
BEST Process Parameter Combination (Pressure/Temp./Amplitude)



All 45/45 Interface
BEST Process Parameter Combination (Pressure/Temp./Amplitude)



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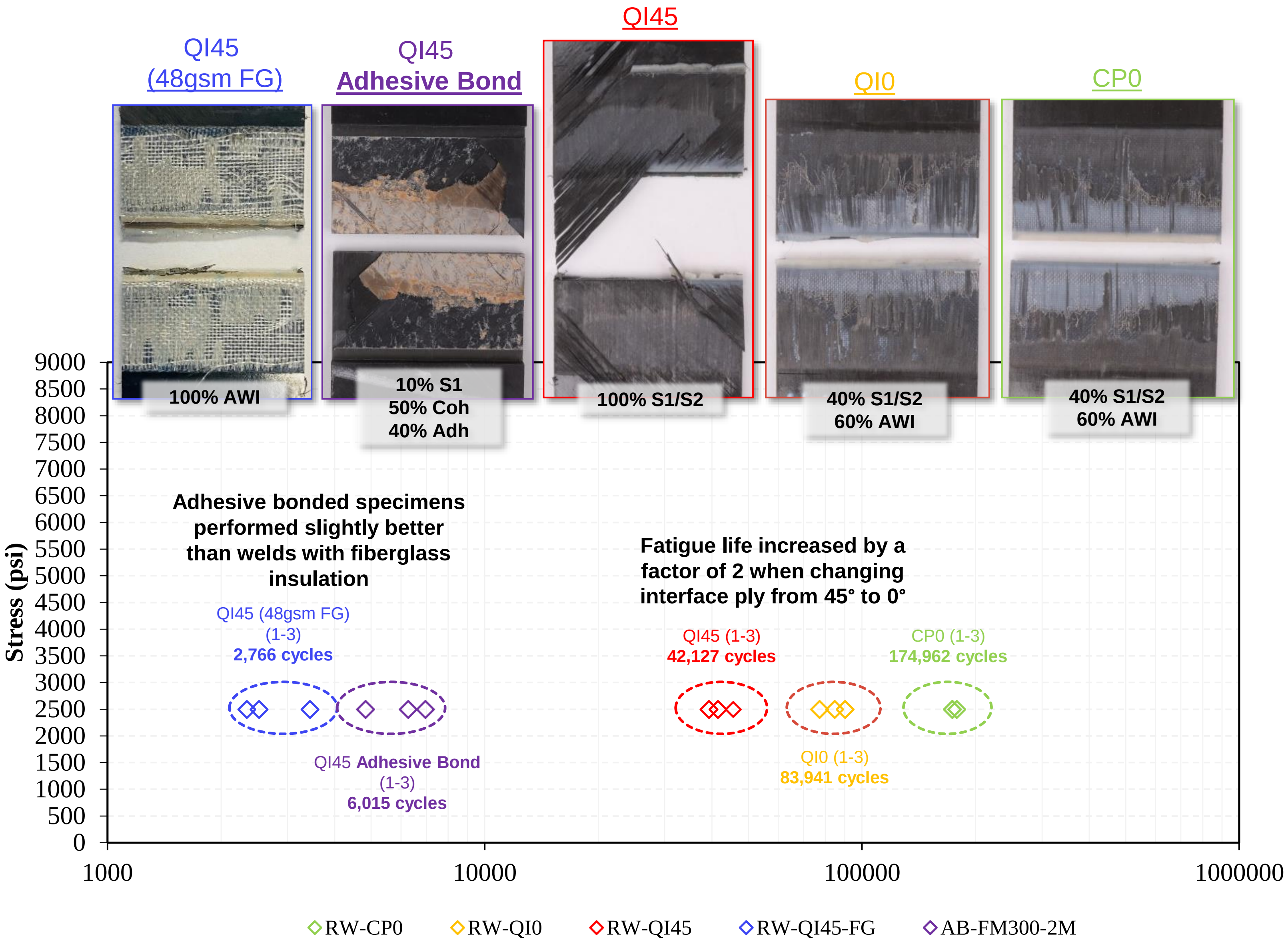
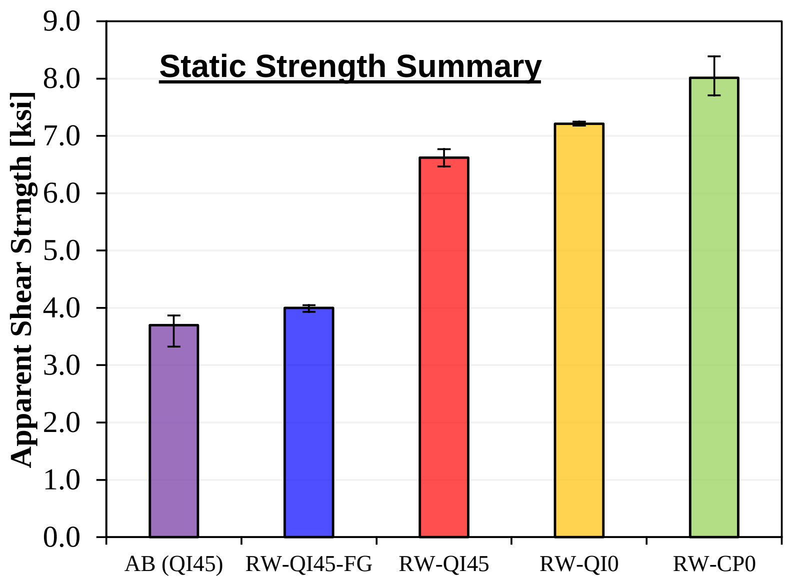
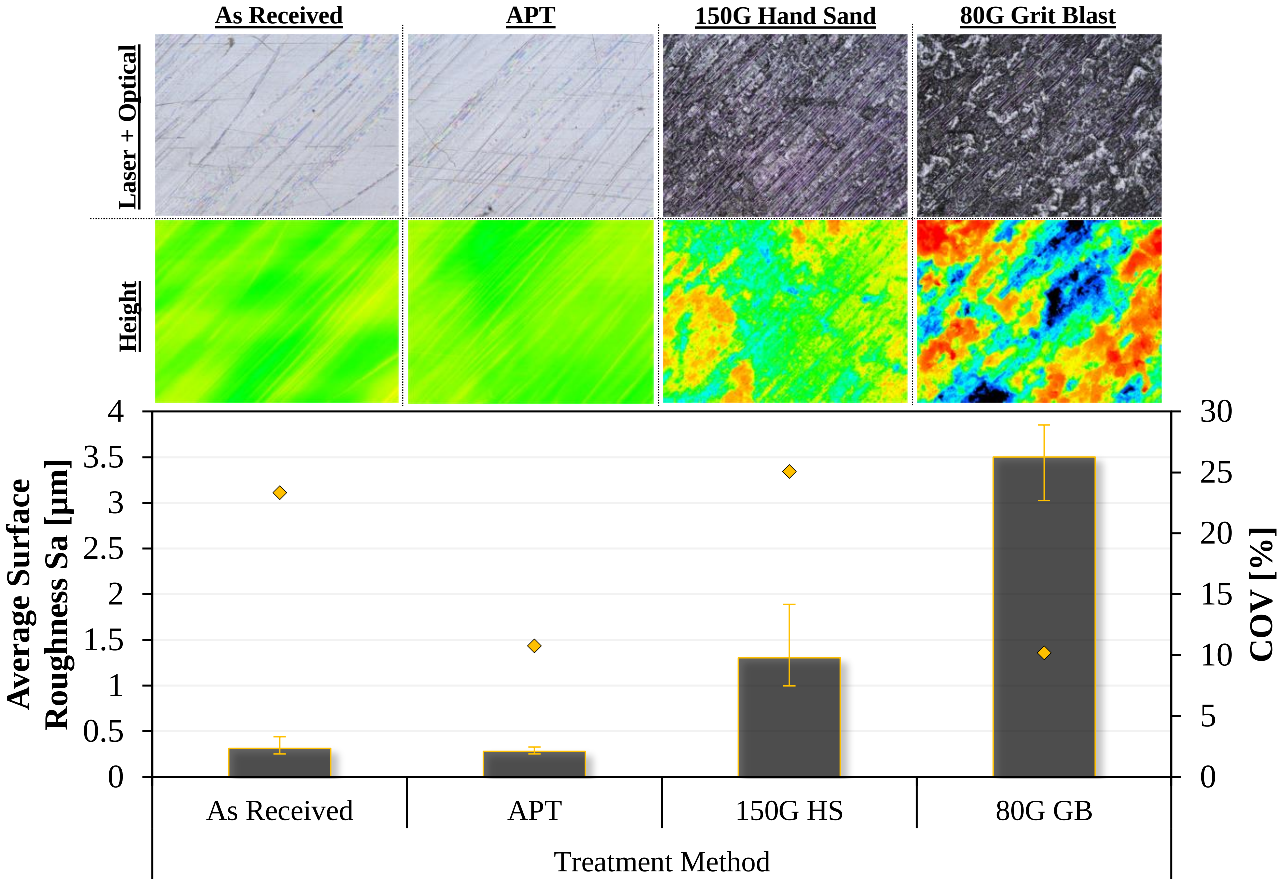
Single Lap-Shear Fatigue Testing

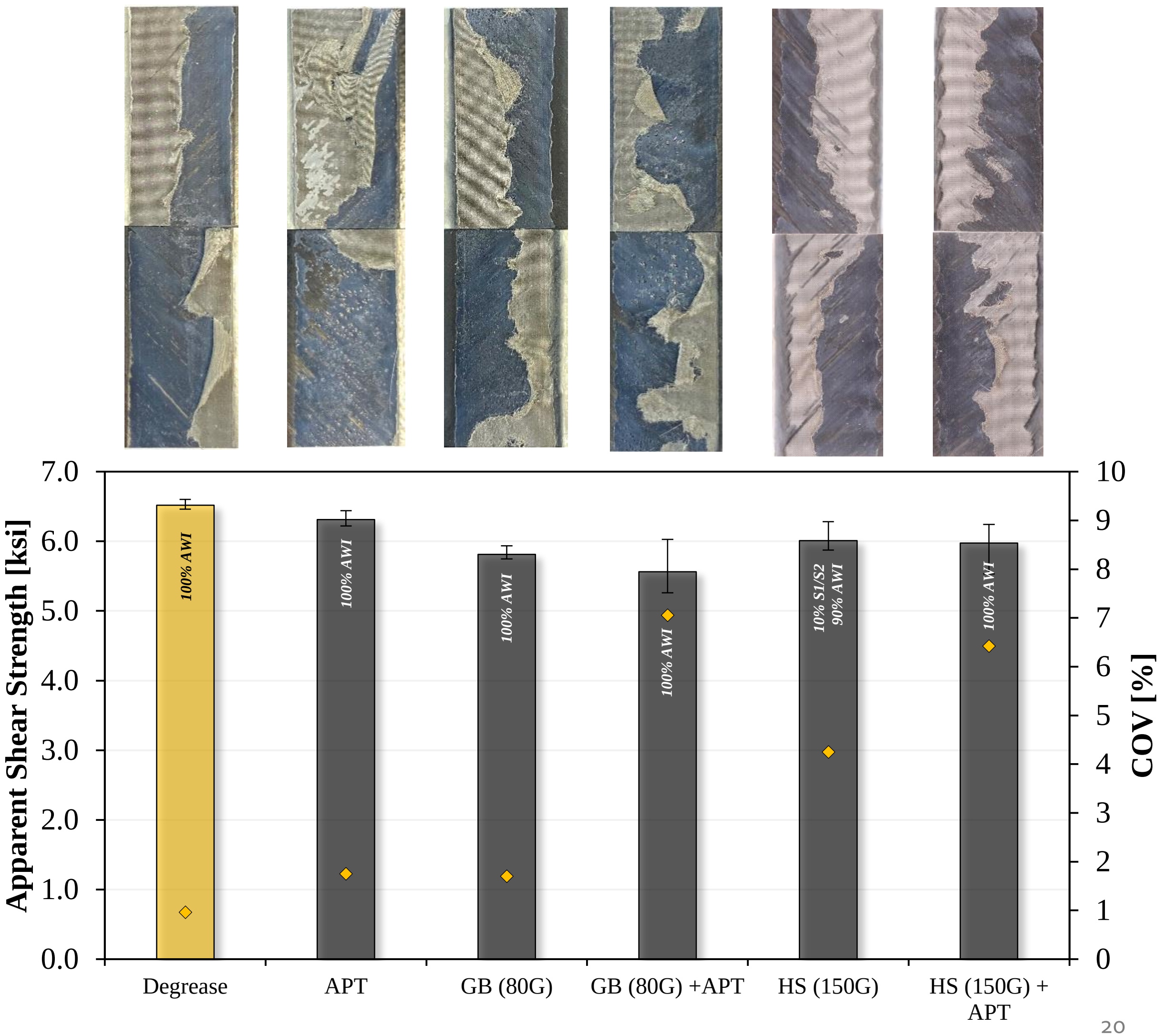


- Substrate Material (TC1225):
  - **QI45:** $[45/0/-45/90]_{2S}$
  - **QI0:** $[0/-45/90/45]_{2S}$
  - **CP0:** $[0/90]_{4S}$
- Adhesive Bond:
  - Adhesive: FM300-2M (0.06 psf)
  - Surface Preparation: Atmospheric Plasma Treatment
  - 250°F at 40-psi

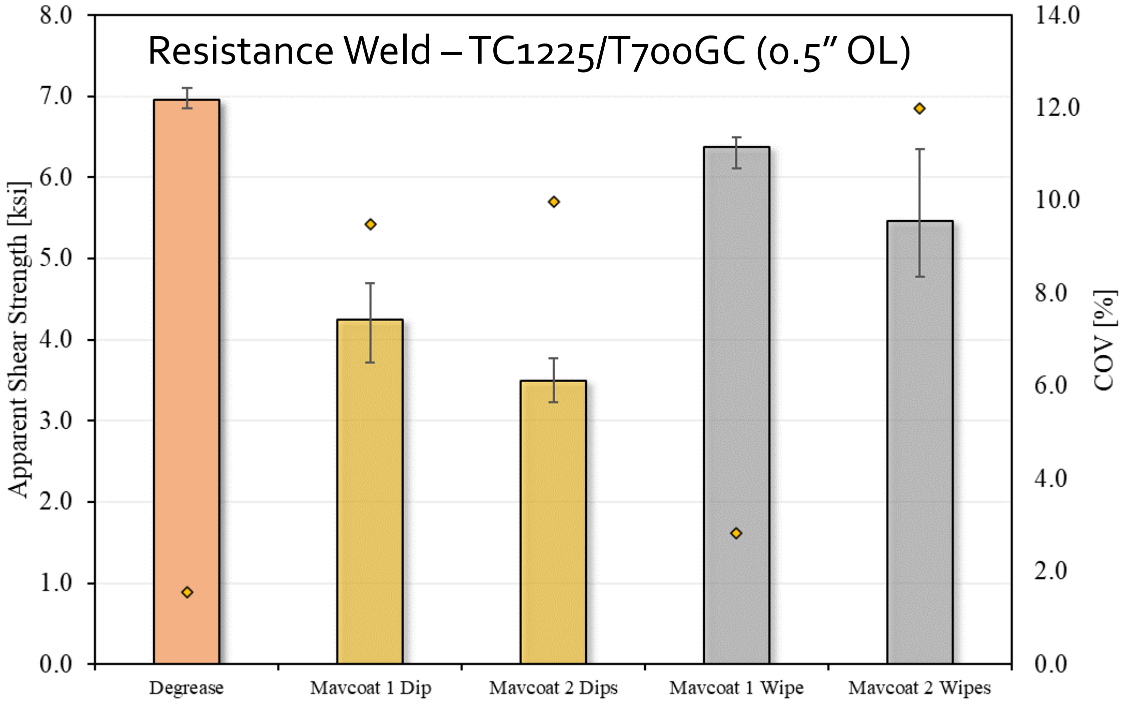


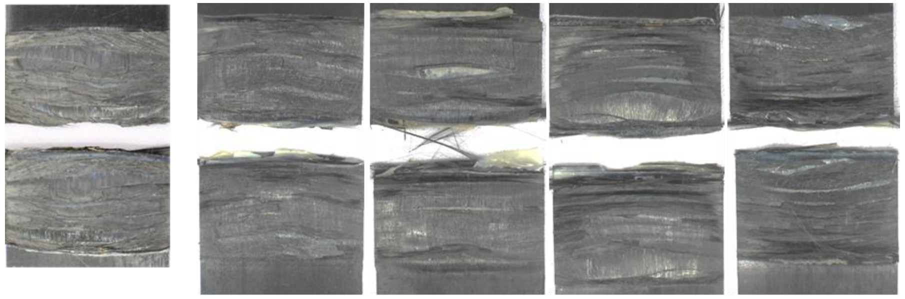
RW Substrate & HE Surface Preparation Considerations

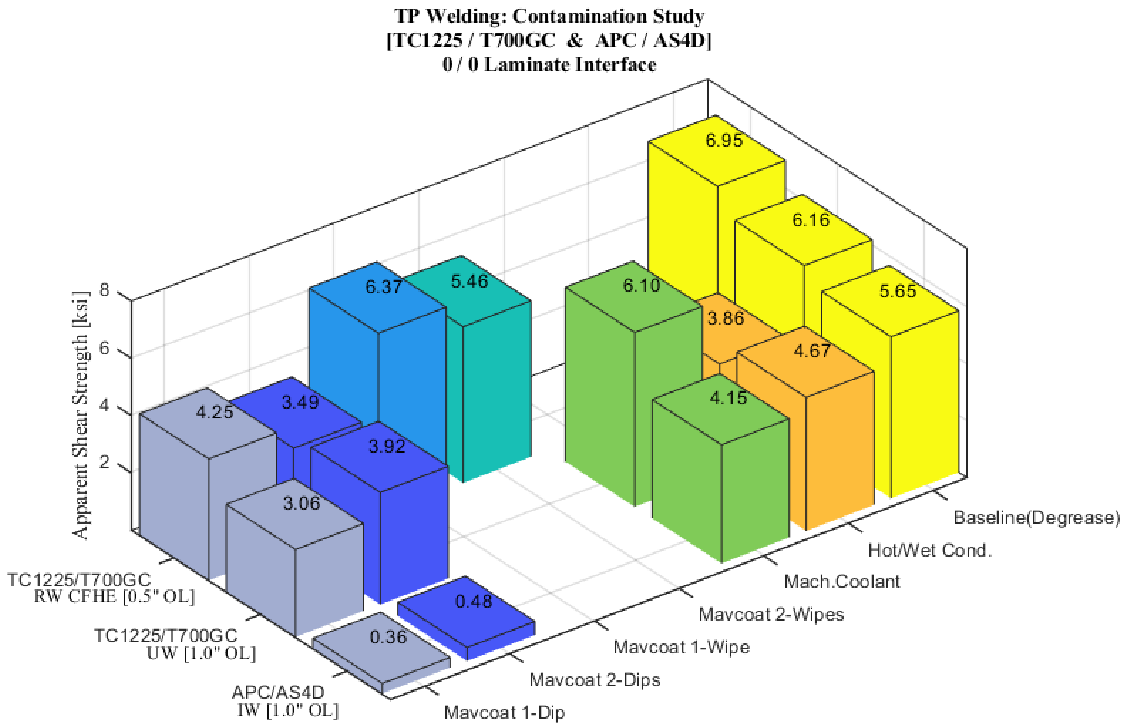




Mavcoat Contamination Study: Single Lap Shear Strength - 0/0 Interface

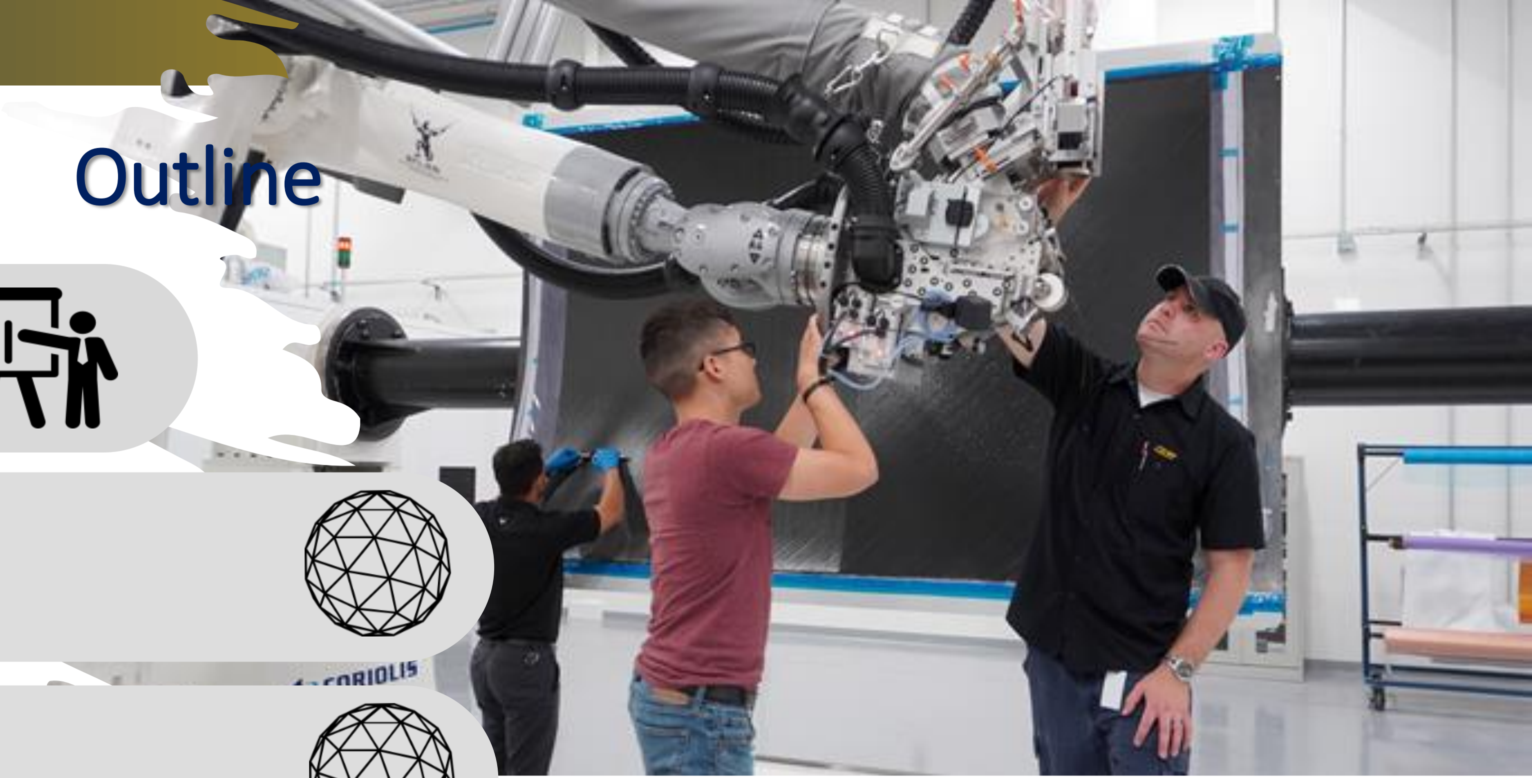






This is in progress for all three weld methods with various other contaminants

Outline



- Program Overview
- Thermoplastic Bonding
- Thermoplastic Welding
- Process Development
- **Performance Evaluation - Scaling**

Certification of Thermoplastic Joints

Material/Interface Properties

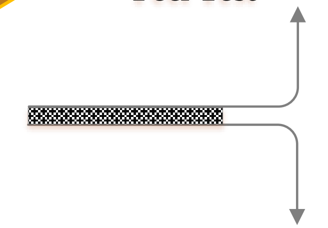
Engineering Constants

Fracture Properties
- Mode I (D5528)
- Mode II (D7905)

Configurations
- Laminate (Baseline)
- Bonded
- Welded (IW, RD, UW)

* Blind Study *

Peel Test

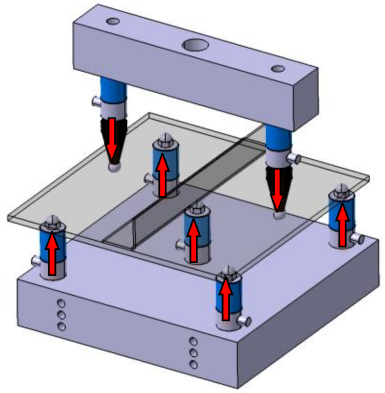


Validation

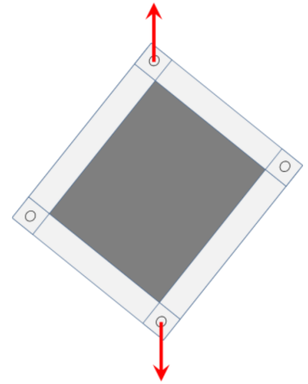
Calibration

Cohesive Parameters
f(Gc, τ_o, Kn)

7PB Test of TP Weldments

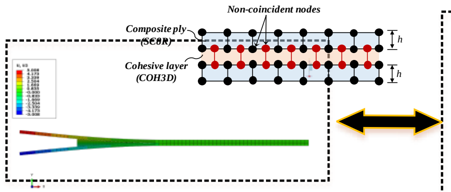


Picture Frame Shear Test

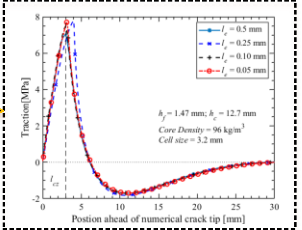


Cohesive Law Derivation

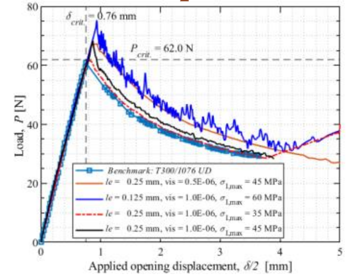
FE-Model



Traction-Separation Law



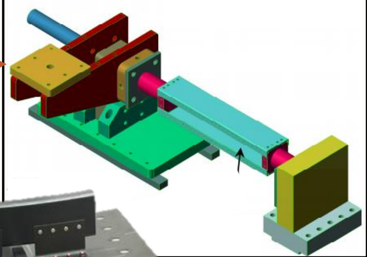
Global Load-Displacement Curve

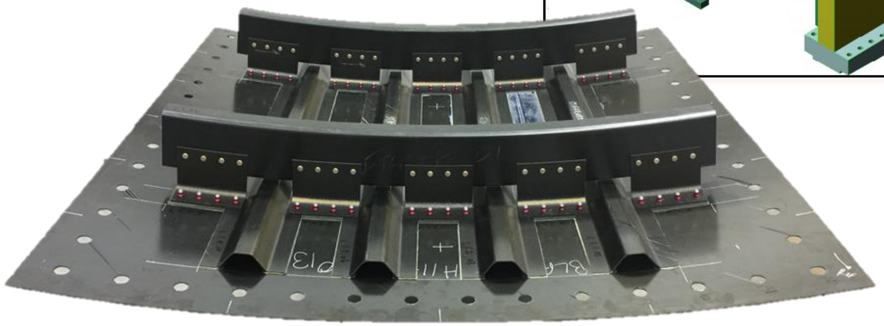


Sizing Study of 7PB Specimen

Box-Beam Torsion Test

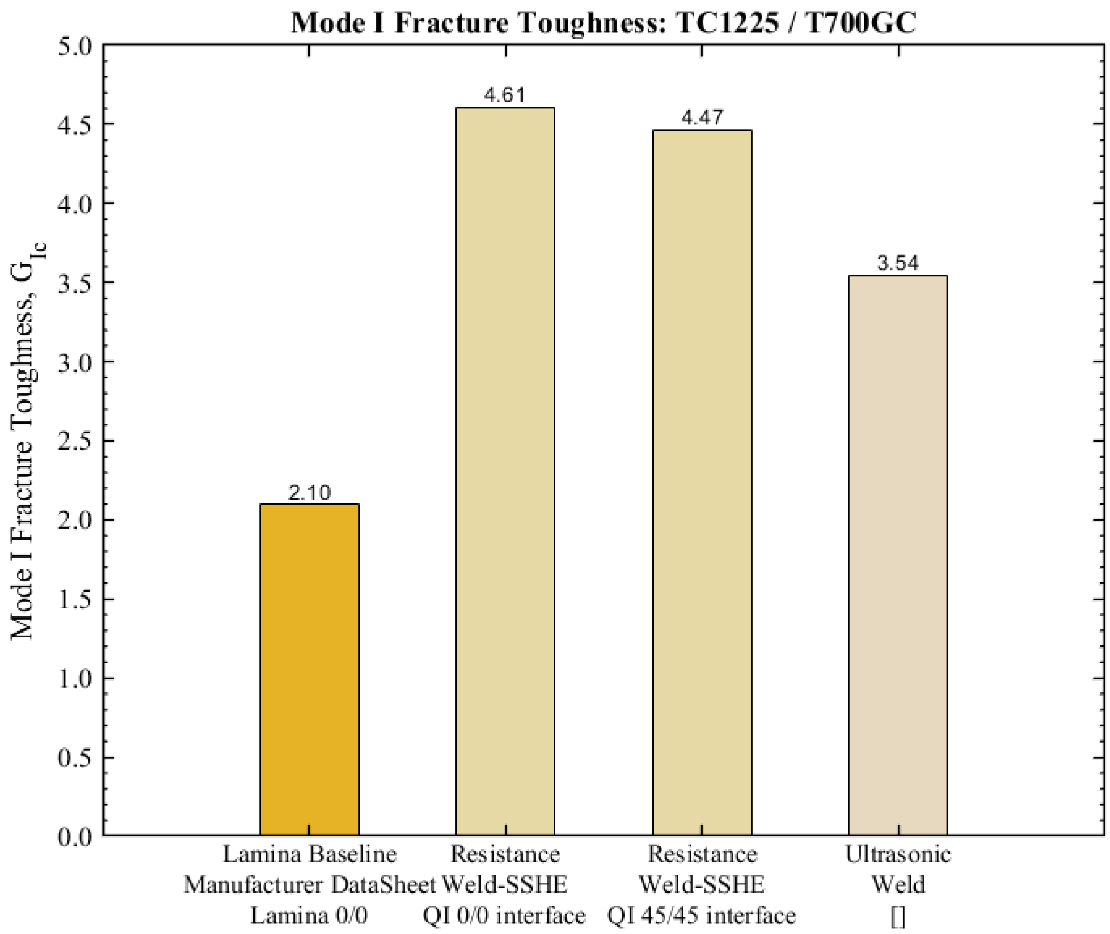
(DOT/FAA/AR-03/21)

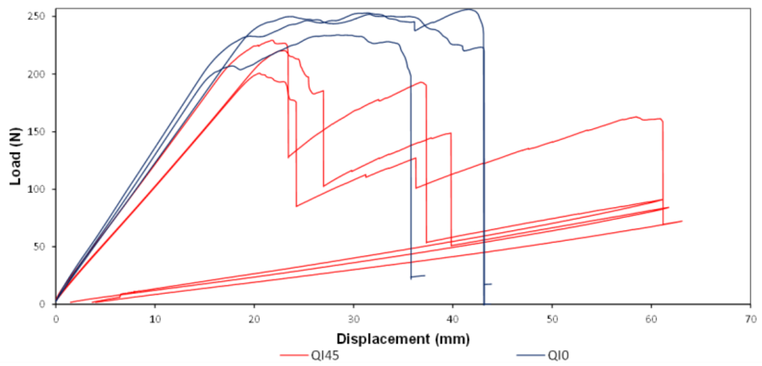




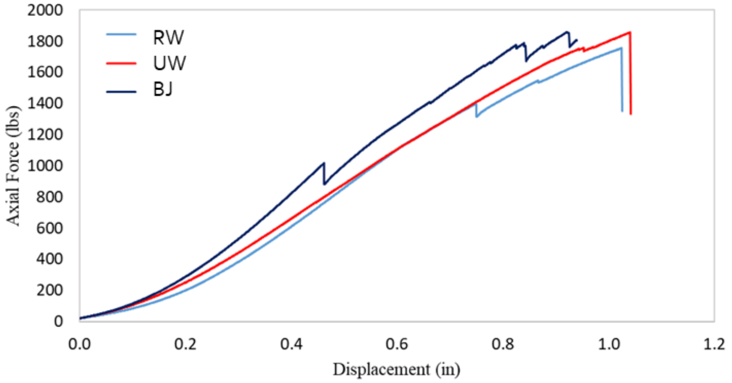
- ***TP Weldment qualification using 7PB*** test method
- Analytical benchmarking, calibration & validation exercises
- ***Sizing study*** *of 7PB test load application points & effect on* ***mode-mixity***

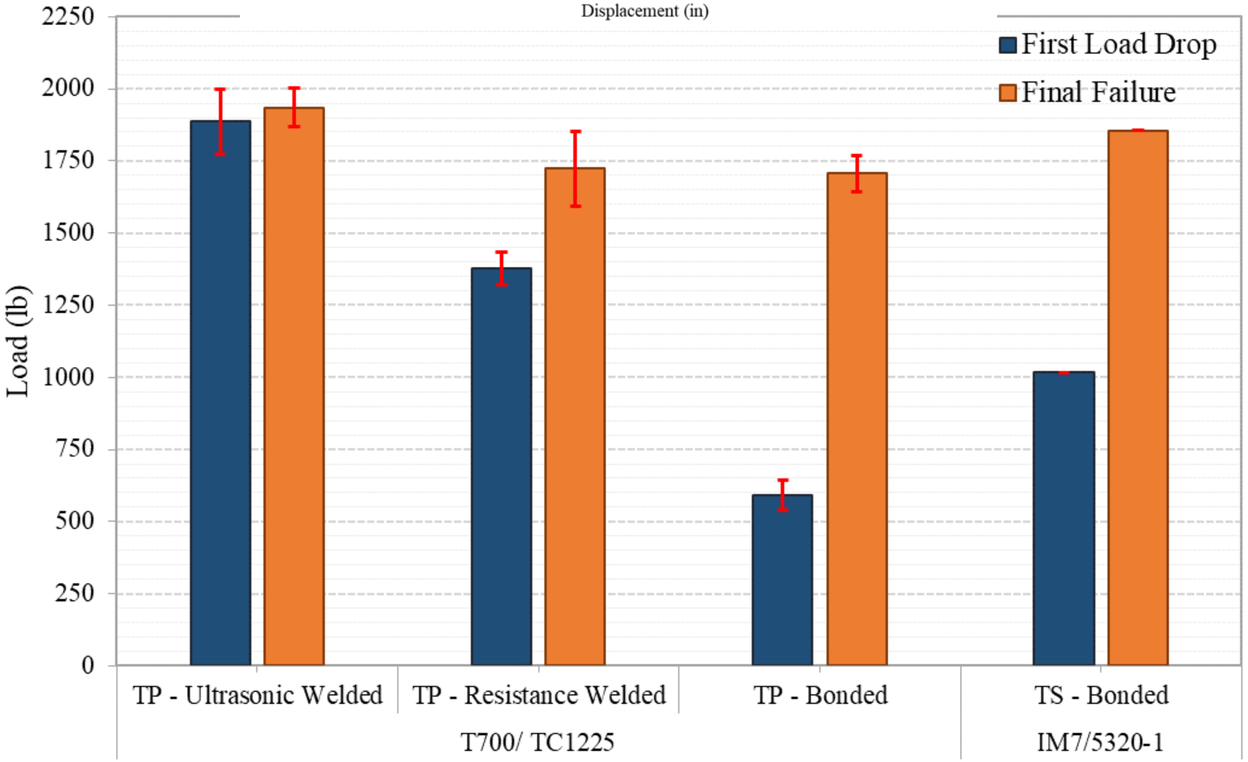
Fracture Toughness Mode I (TC1225/T700GC)
Effects due to Fiber Bridging

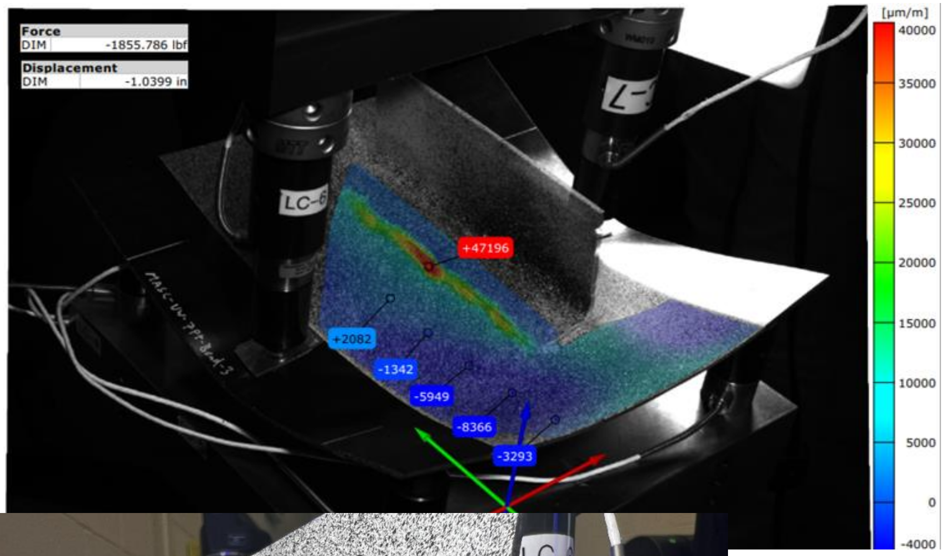


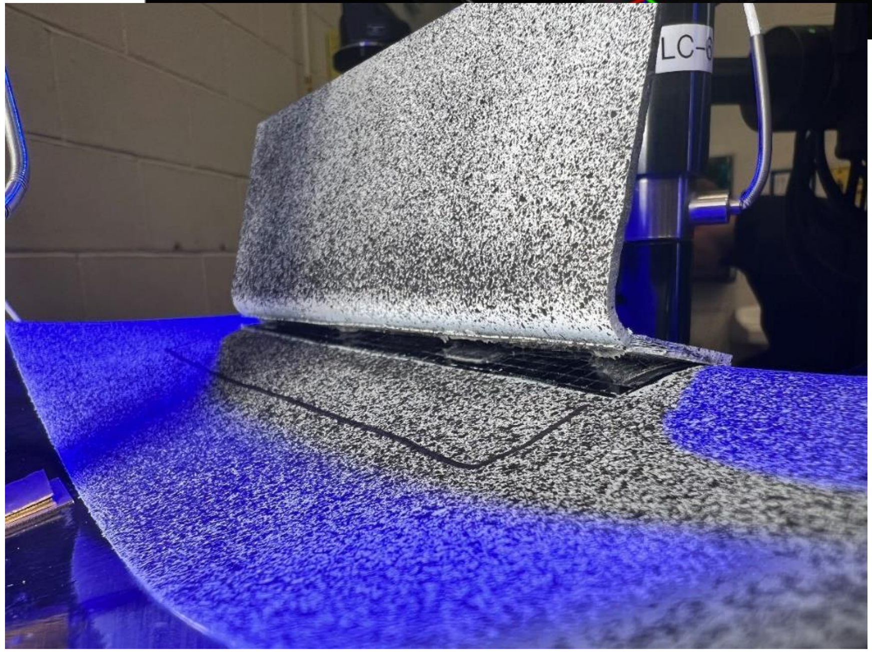


7-Point Bend Static Testing

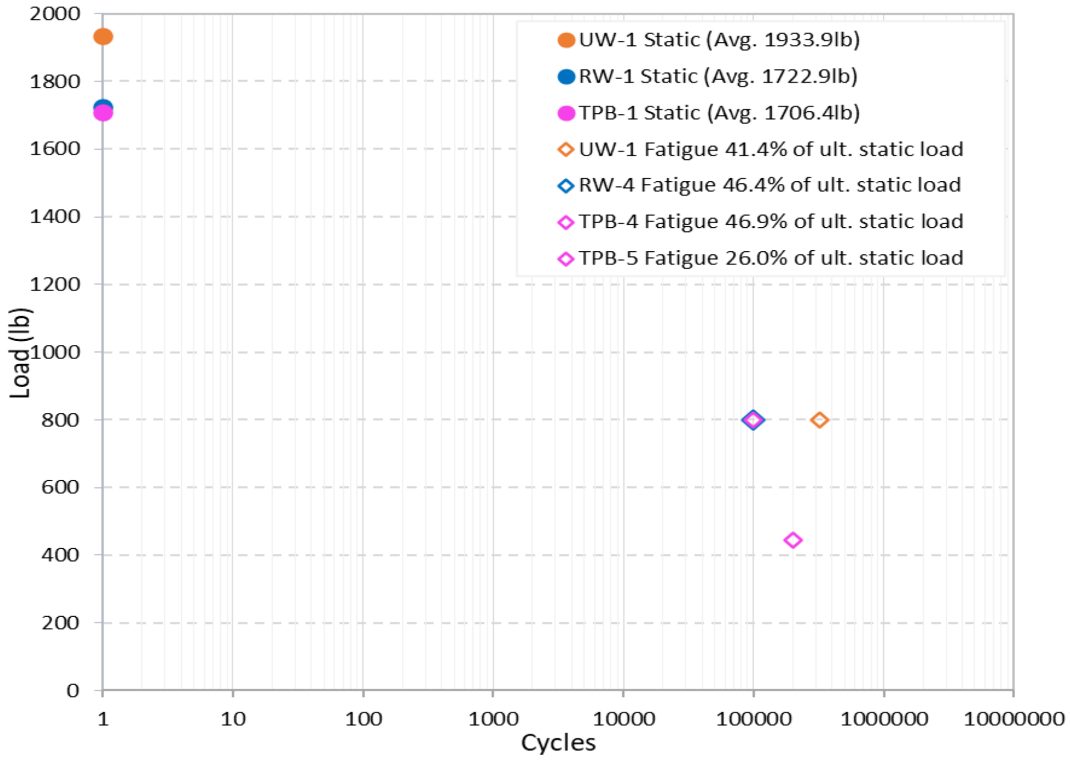


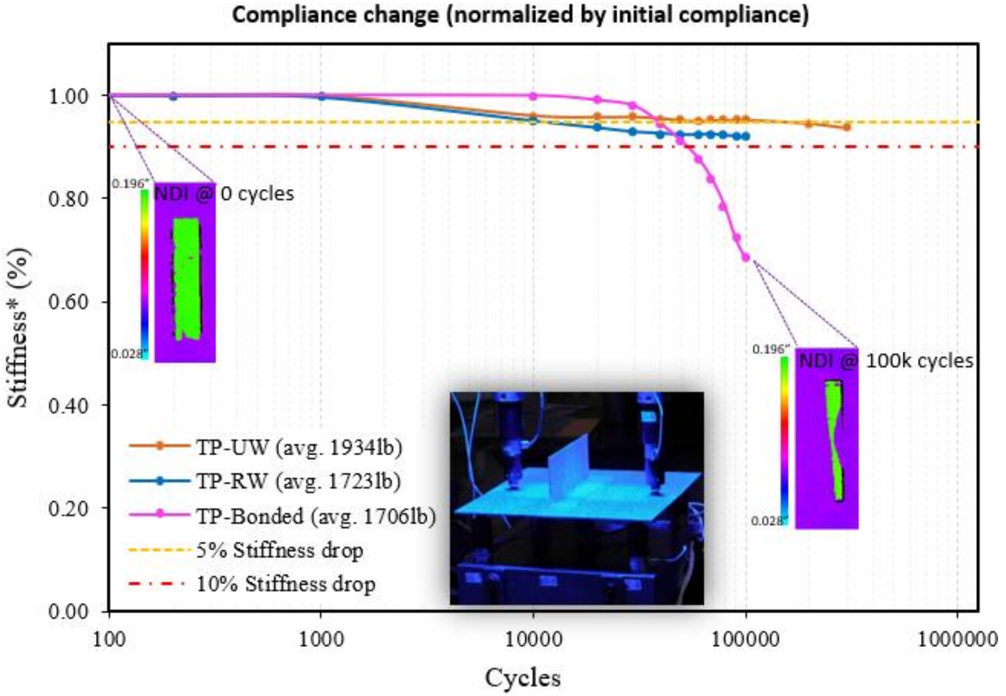






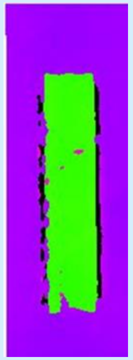
Thermoplastic Welded Element Level – 7pt Bend Test



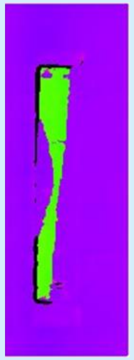


Progressive failure monitored during fatigue using video camera + intermittent NDI (UT-PE and XCT)

NDI pre- and post-fatigue on thermoplastic bonded specimen



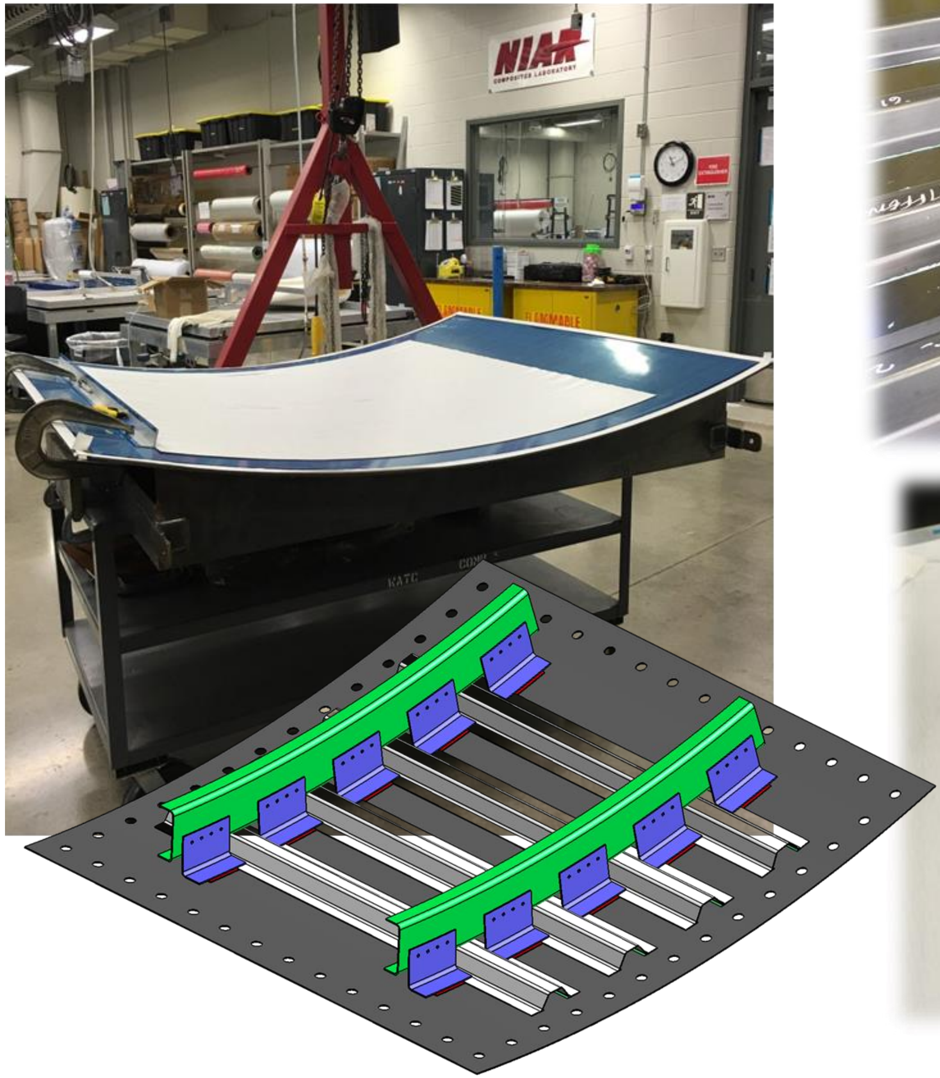
Before fatigue @ 0 cycles

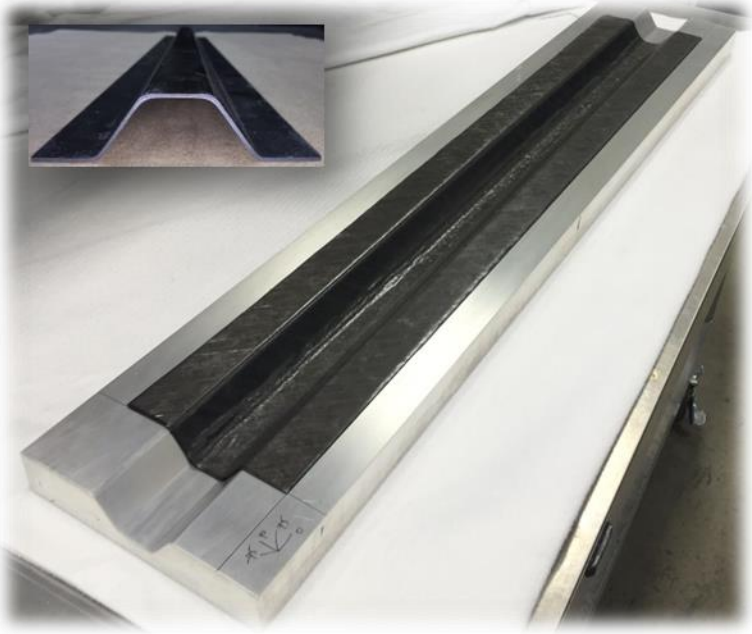


After 100k cycles @ 444lb fatigue max. load

After 100k cycles @ 800lb fatigue max. load

Tooling for Fuselage Panel Demonstrator





Summary

- Adhesive Bonding
  - Abrasion surface preparation techniques that have been historically used to prepare thermoset composites are insufficient for thermoplastic composites because the surface is not chemically activated in the abrasion process
  - Atmospheric plasma treatment can increase the surface free energy (specifically the polar surface free energy) and chemically activate the substrate to form a strong bond with the adhesive
  - Laser ablation surface preparation require further studies for process development
  - Minimal substrate failures were witnessed with thermoplastic bond failures due to the increase in interlaminar fracture properties associated with thermoplastics over thermosets
- Fusion Welding
  - Controlling and monitoring interfacial temperature, pressure, and time is essential to weld quality and performance
  - Weld certification guidance will be addressed though scaling studies
  - Fatigue data indicated a significant sensitivity to process parameters and interfacial plies
  - Welds do not require the surface of the substrate to be chemically activated, as the polymer near the weld interface is melted (no chemical bonding occurring)
  - Initial surface contaminate studies have demonstrated the robustness of welding, but require further studies to establish guidance

Looking Forward / Future Work

- Benefit to Aviation
  - Generating guidance materials for adhesive bonding and welding reinforced thermoplastic composites
  - Identification of critical processing parameters in adhesive bonding and weld processes to aid in establishing process controls
- Next Steps:
  - Development of laser ablation as a surface preparation method
  - Scaling studies for fuselage panel demonstrator
  - Development of ultrasonic welding gantry for fuselage panel demonstrator
  - Development of guidance materials for joining of thermoplastics