Manufacture, Characterization, and Fusion Welding of Thermoplastic Composites for Space Applications

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ASME Aerospace Structures, Structural Dynamics, and Materials Conference
Renton, WA
April 29 – May 1, 2024

Thermoplastics Development for Exploration Applications (TDEA) Project

Collaborations & Partnerships

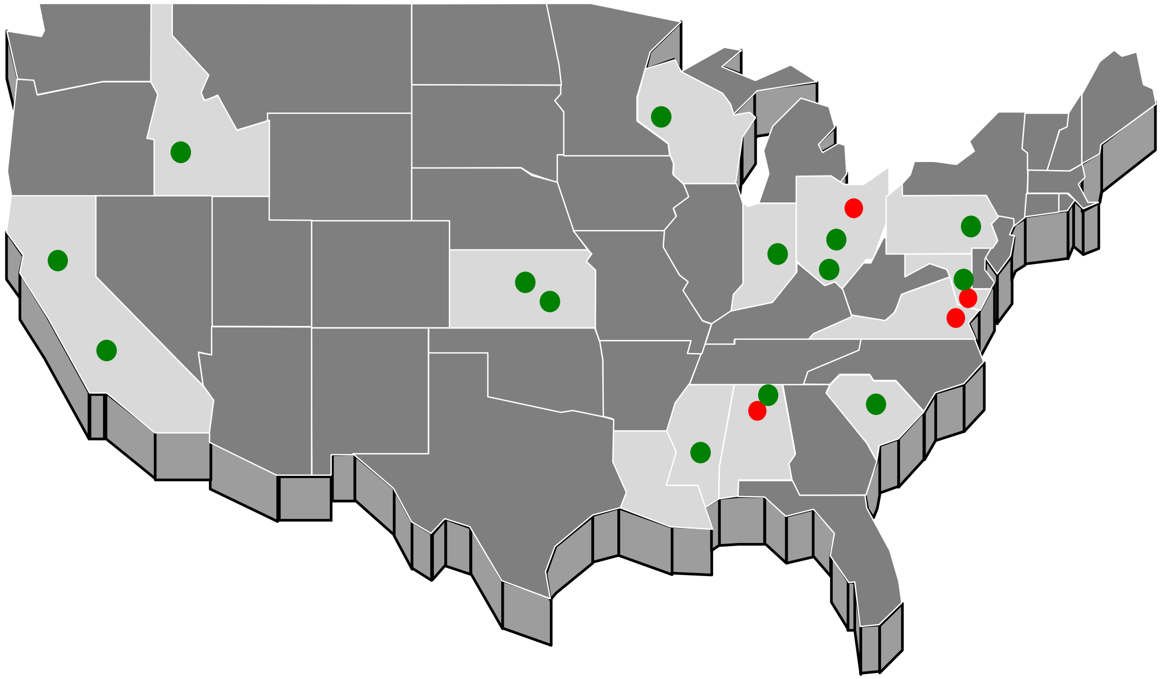
NASA Centers

- Glenn Research Center
- Goddard Space Flight Center
- Langley Research Center
- Marshall Space Flight Center

Industry/Academia

- Agile Ultrasonics
- Boise State University
- Cincinnati Test Labs
- Hexagon/MSC Digimat
- Kratos Defense (formerly Southern Research Eng.)
- Mantis Composites
- NIAR/Wichita State University
- SABIC
- Syensqo
- Spirit Aerosystems
- Toray
- University of Southern Mississippi
- Victrex

➢ **Target Potential Applications**
- Human Lander System - Thermal isolators, landing leg, cryogenic tanks, habitat structures.
- Tall Lunar Tower, Roman Space Telescope
- Advanced manufacturing and On-orbit Servicing, Assembly and Manufacturing.
- Science missions.



Why Pursue Thermoplastic Composite Technology for Space Applications?

Qualitative comparison of thermoplastic composites (TPC) and thermoset composites (TSC)

Advantages:	*Disadvantages*:
• Reduced cycle time	• **Higher processing temperature and pressure required**
• **Processing by remelting**	• **Higher residual stresses (more difficult dimensional control)**
• **Processing that enables unitization**	• Structural and chemical properties sensitive to crystallinity
• Ambient material storage (no out-time)	• Higher melt viscosity
• Automated assembly (robotic welding)	• Crystallinity may change over lifecycle
• Higher fracture toughness	
• **Welded joints with no material interface**	
• **Minimal outgassing** & low moisture uptake	

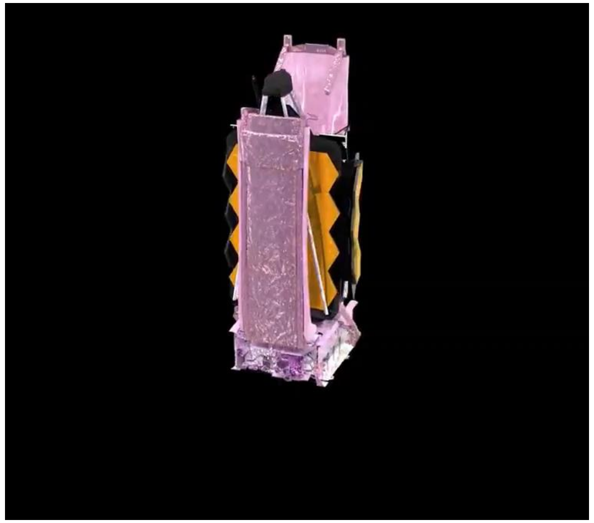
Bolded characteristics especially relevant for space applications

- Less complex mfg.
- Larger structures
- Fewer joints

Result: reduced cost

Welding is relatively simple and insensitive to processing conditions (vs. TS adhesive bonding)

Can new process modeling capability help mitigate associated design/ development costs via simulation?



- TPC can enable on-orbit assembly and manufacturing
  - NASA had recognized in-space TP/TPC manufacturing with the OSAM missions
  - Joining TPCs in-space is a key enabler that needs further development

Benefits of TPCs for in-space manufactured/assembled structures recognized since 1980s
Now underlying TPC technology has matured sufficiently to pursue application focused developments

TDEA Technology Development Roadmap

Project Goal: To advance NASA's thermoplastic composites capabilities by developing structurally efficient joining solutions for large-scale space structures and applications to support NASA's future exploration missions.

1. State-of-the-art survey


TDEA-RPT-001
REVISION STATUS: BASELINE
EFFECTIVE DATE: 12/02/2022

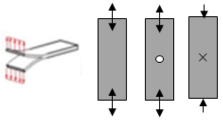
Thermoplastic Composites as an Enabling Technology for NASA Space Applications

State of the Art Review

2. TPC material characterization

Material properties for material selection and model inputs

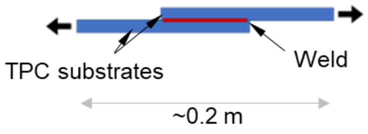
Thermal, mechanical, and physical tests



DSC
DMA
TGA
TC

- Experiments to fill in gaps in publicly available TPC material properties
- Emphasis on data required for process, material, and structural model inputs

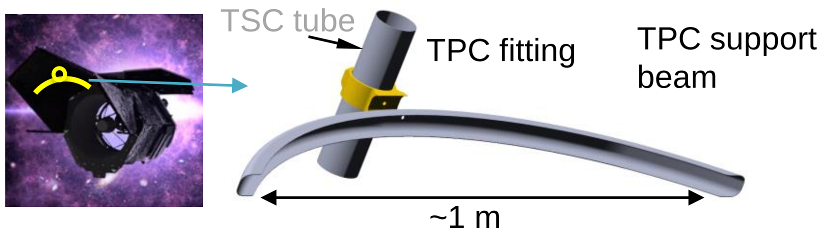
3. Welded joint pathfinder: *Foundational developments*



- Experiments to characterize weld performance, efficiency, and robustness
- 5 material systems and 3 weld methods
- Model development and evaluation to improve weld design and sizing capabilities
- Disassembly, re-assembly feasibility

4. <u>Thermoplastic Terrestrial Point Design (TTPD)</u>: Roman Space Telescope (RST) support beam

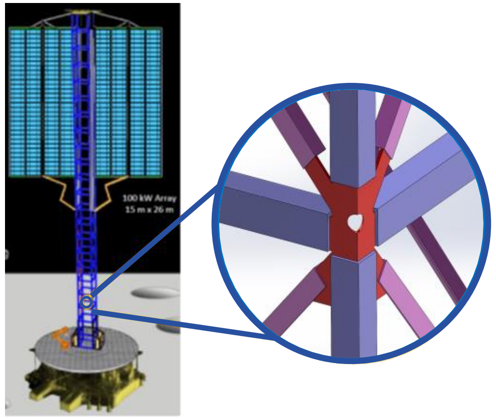
Confidence building application



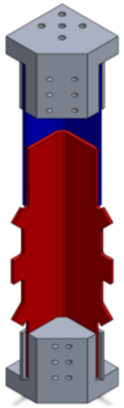
5. <u>Thermoplastic In-Space Point Design (TSPD)</u>:

Game changing application

Tall lunar tower (TLT)



- Update existing TLT design to use all-TPC design with welded joints
- Developments for in-space welding application
- Lunar dust knockdown for welds
- Modeling to predict performance in a relevant environment

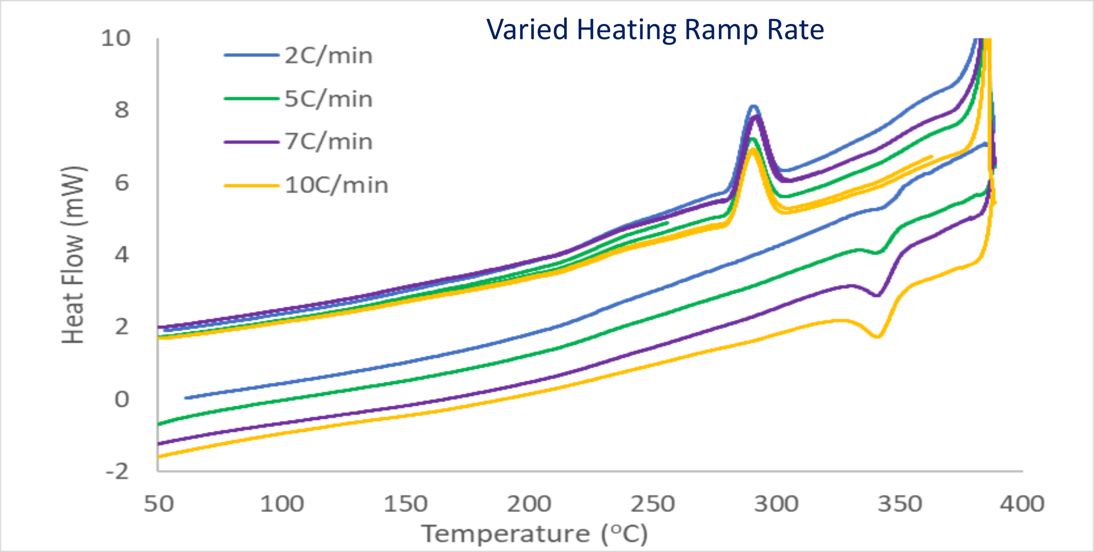


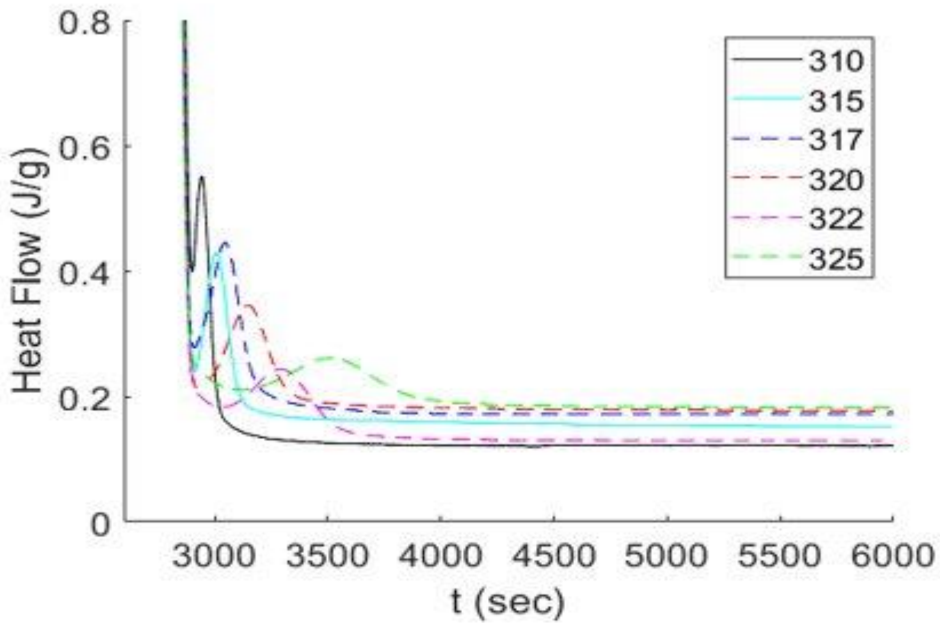
Materials Characterization

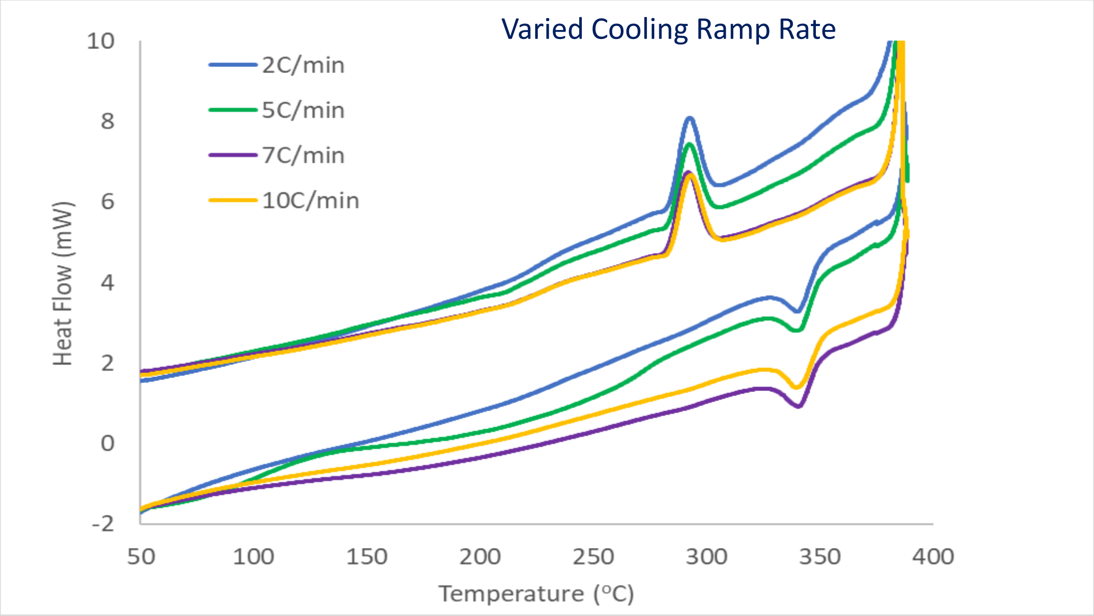
Test	Organization	Temperature Range	Purpose
Differential Scanning Calorimetry (DSC)	NASA	RT – 400°C	Crystallization Kinetics
Dynamic Mechanical Analysis (DMA)	NASA	-120°C to 400°C	Cold temperature transitions
Thermal Conductivity (TC)	NIAR/Kratos	RT – 200°C	Structural Analysis
Electrical Conductivity (EC)	NASA	RT – 170°C	
Out-Gassing	NASA	125°C	In-space application
Coefficient of Thermal Expansion (CTE)	NASA	-170°C – 50°C	Dimensional stability
Thermogravimetric Analysis	NASA	RT – 800°C	Thermal stability

Material Characterization

- Evaluate the crystallization kinetics of candidate materials as relevant to crystallization on welding.
- The DSC data (both dynamic and isothermal with post-processing) provides the melting and crystallization temperature, latent heat of melting and crystallization, and crystallization rate (Nakamura) used in the welding process model.
- Data shown for PEEK resin.

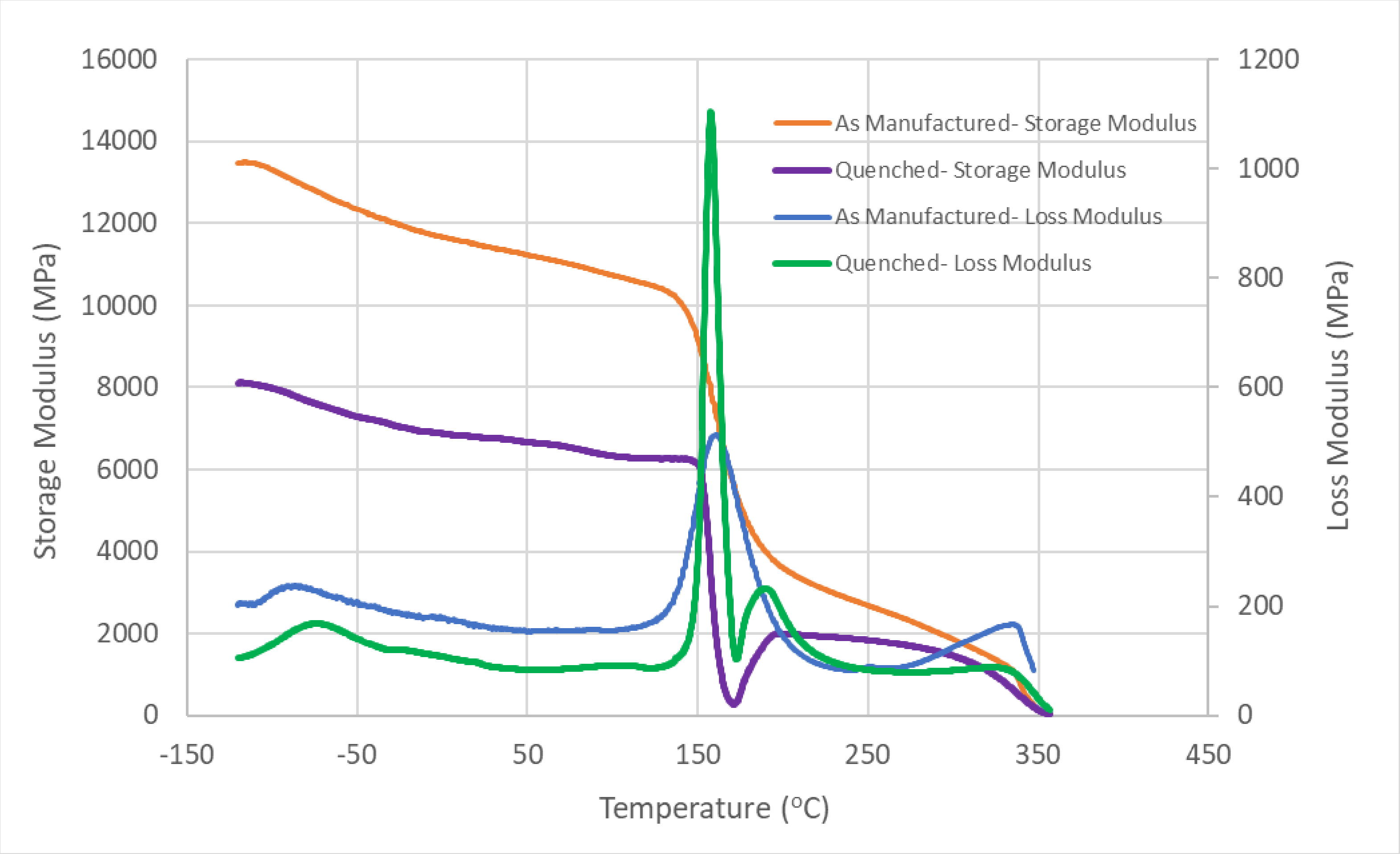






Material Characterization

DMA was used to evaluate material transitions across a wide temperature range and as a function of the degree of crystallinity



Storage Modulus:

- Reduced with decreased crystallinity.
- Increase in storage modulus above Tg related to cold crystallization.

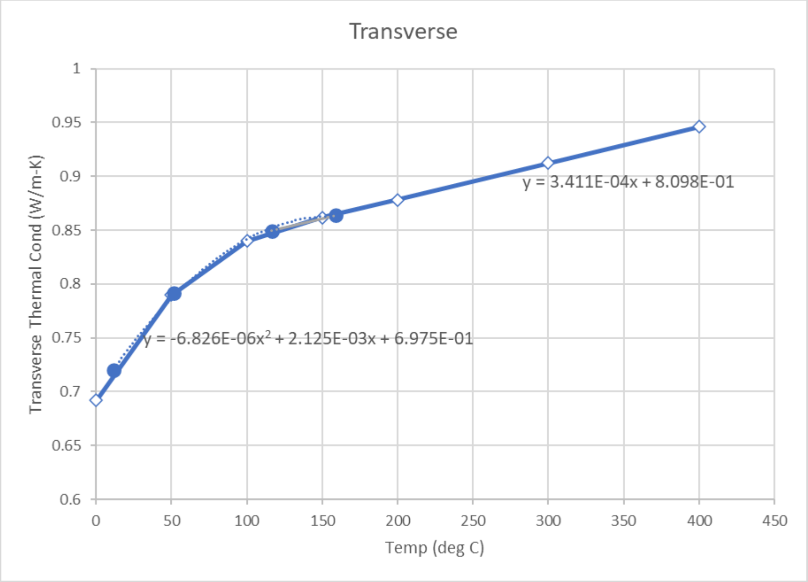
Loss Modulus:

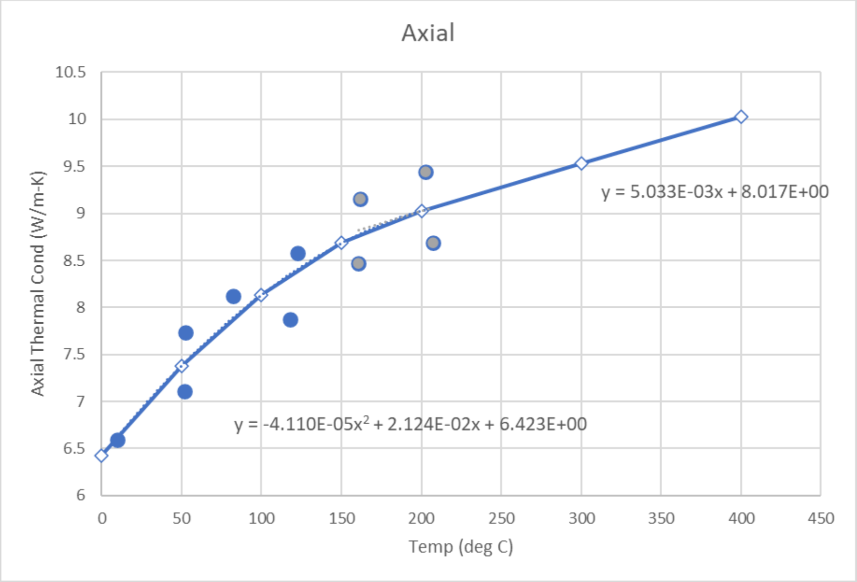
- Transition observed above Tg related to crystallization
- Transition at -75°C observed in both coupons.

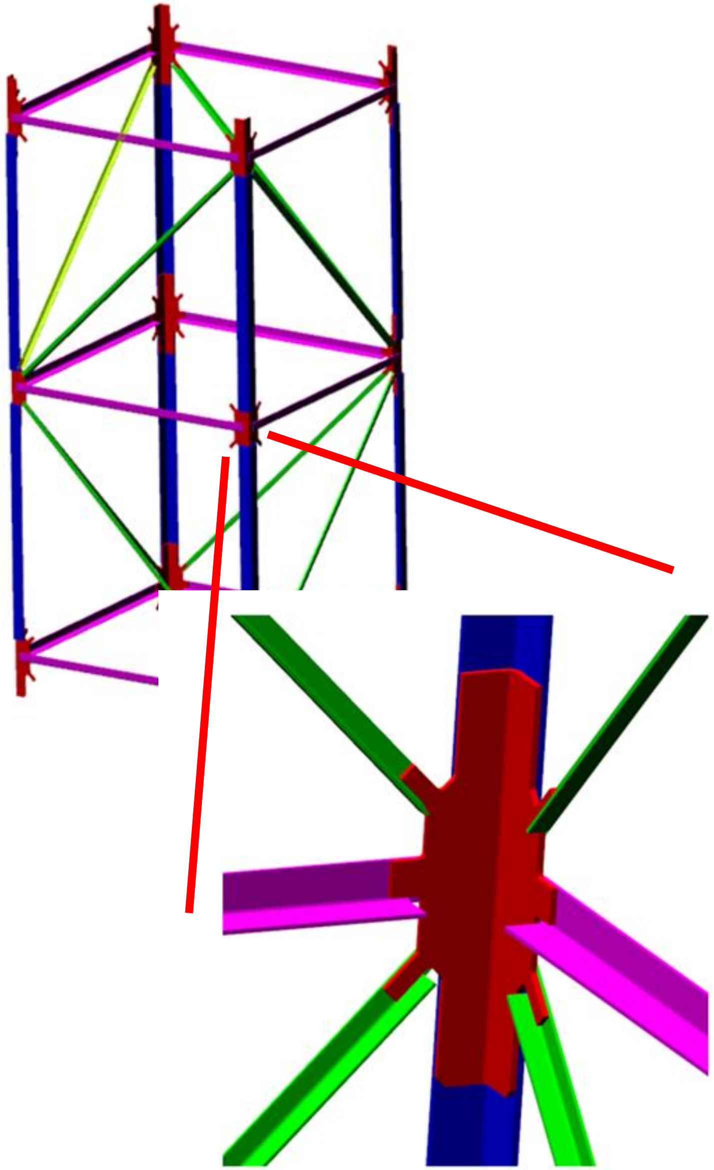
AS4/PEEK: $[90]_{16}$
As Manufactured DOC: 25%
Quenched DOC: 10%-15%

Material Characterization

Thermal conductivity data was collected from room temperature to 200ºC and utilized to calculate the ply level through thickness thermal conductivity as required for structural analysis of the tall lunar tower.





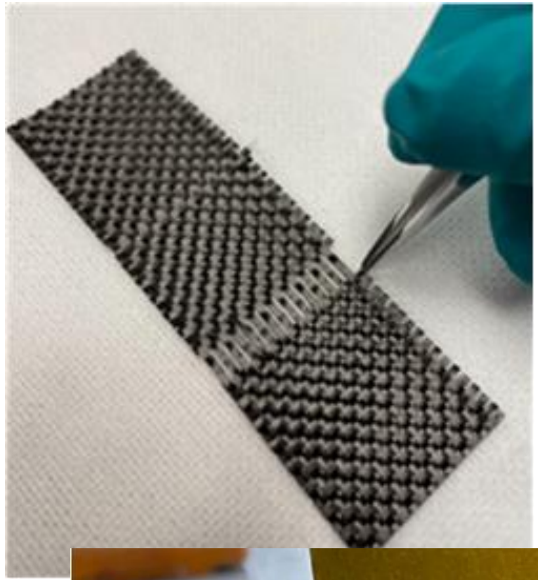


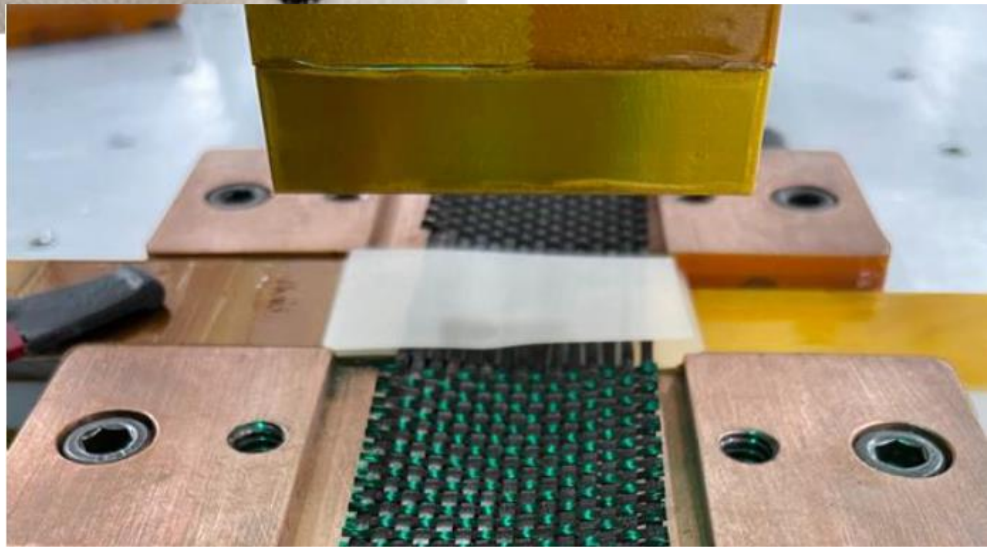
Material: T700/TC1225 (LMPAEK)

Weldability Study- Resistance Welding

The weldability study is an ongoing effort within TDEA to explore the response of 5 thermoplastic materials to 3 welding processes. Completion of the weldability study will include manufacture, test, and characterization; the outcome is anticipated to include:

- Bond strength- single lap shear test data
- Fracture toughness- double cantilever beam test data
- Reproducibility through the measured coefficient of variation
- Bond quality as assessed by NDE
- Temperature history when possible





Single lap shear- resistance welded coupons (NIAR)

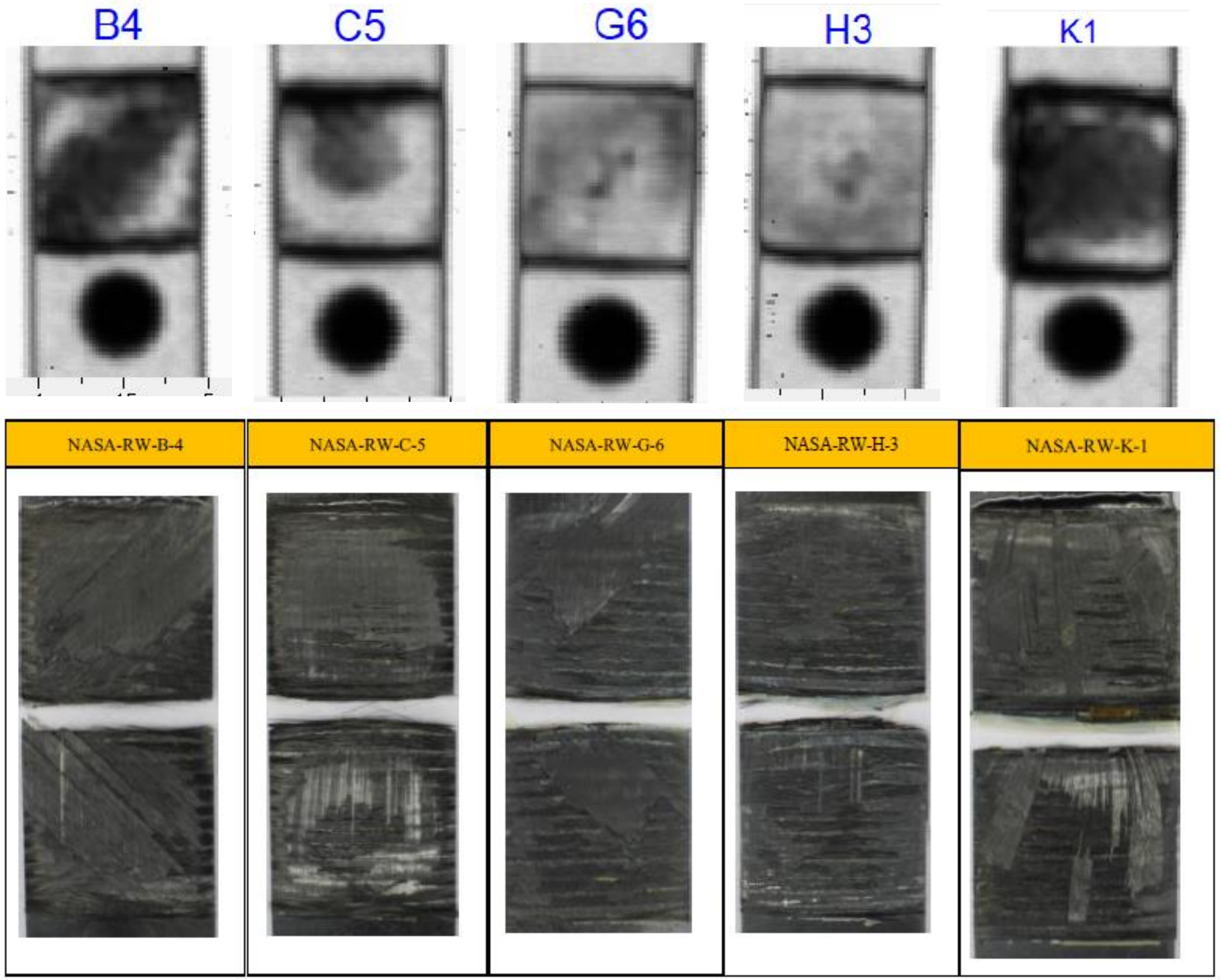
Category	Average Apparent Shear Strength [MPa]	COV [%]
NASA-RW-PEI (45°)	18.36	11.78
NASA-RW-PEI (0°)	20.54	6.72
NASA-RW-PEEK (45°)	27.56	9.39
NASA-RW-PEEK (0°)	30.04	5.24

Welds performed on individual coupons to assess edge effects and reproducibility.
Materials include T700/LMPAEK, AS4/PEEK, AS4/PEI, AS4/PPS, and M30S/PEKK

Weldability Study- Resistance Welding

Through transmission C-scan of the welded area provided assessment of bond uniformity.

Fracture surfaces were examined and provided a visual assessment of regions of greater contact.



Material	PEI	PEI	PEEK	PEEK	PEI/PEEK
Bond Strength	19.2	21.7	30.9	29.2	16.6

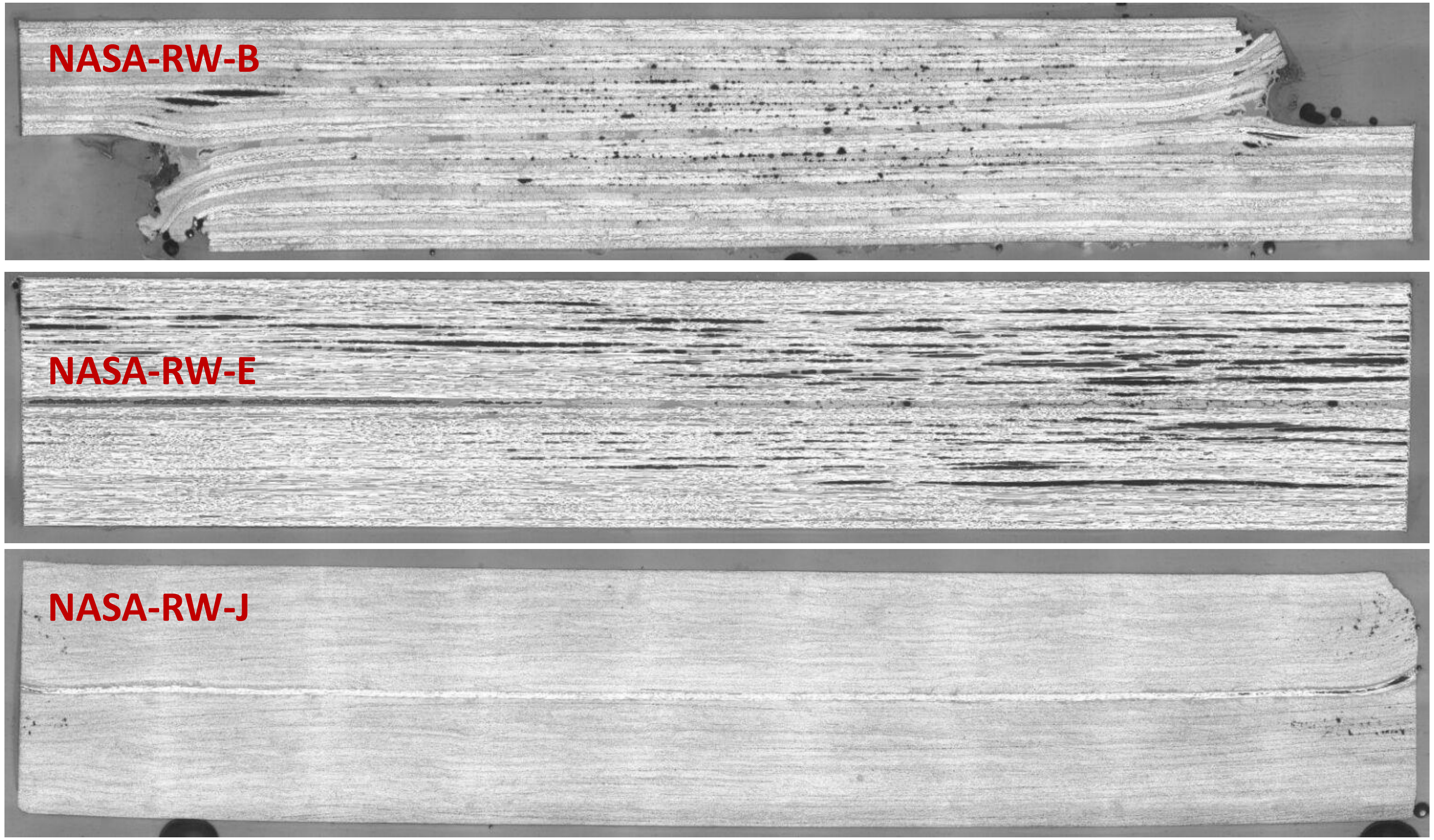
Weldability Study- Resistance Welding

Process parameters include pressure, resistance, voltage, current, and weld time.

Defects observed within the adherend include delamination, voids, and fiber flow-out.

Fiber flow-out can occur with due to heat at the bond-line and applied pressure. Changes in bond area thickness can lead to changes in applied pressure and ultimately voids.

Fiber flow-out mitigated through shimming.

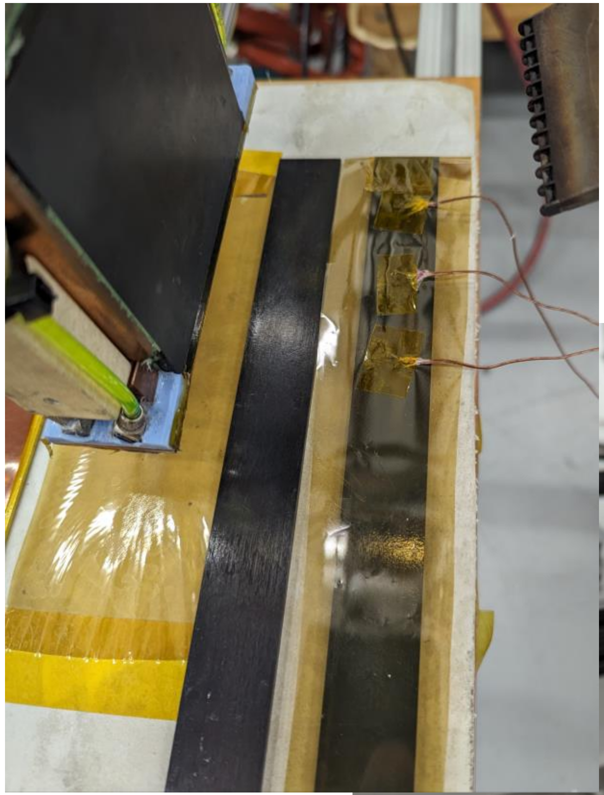


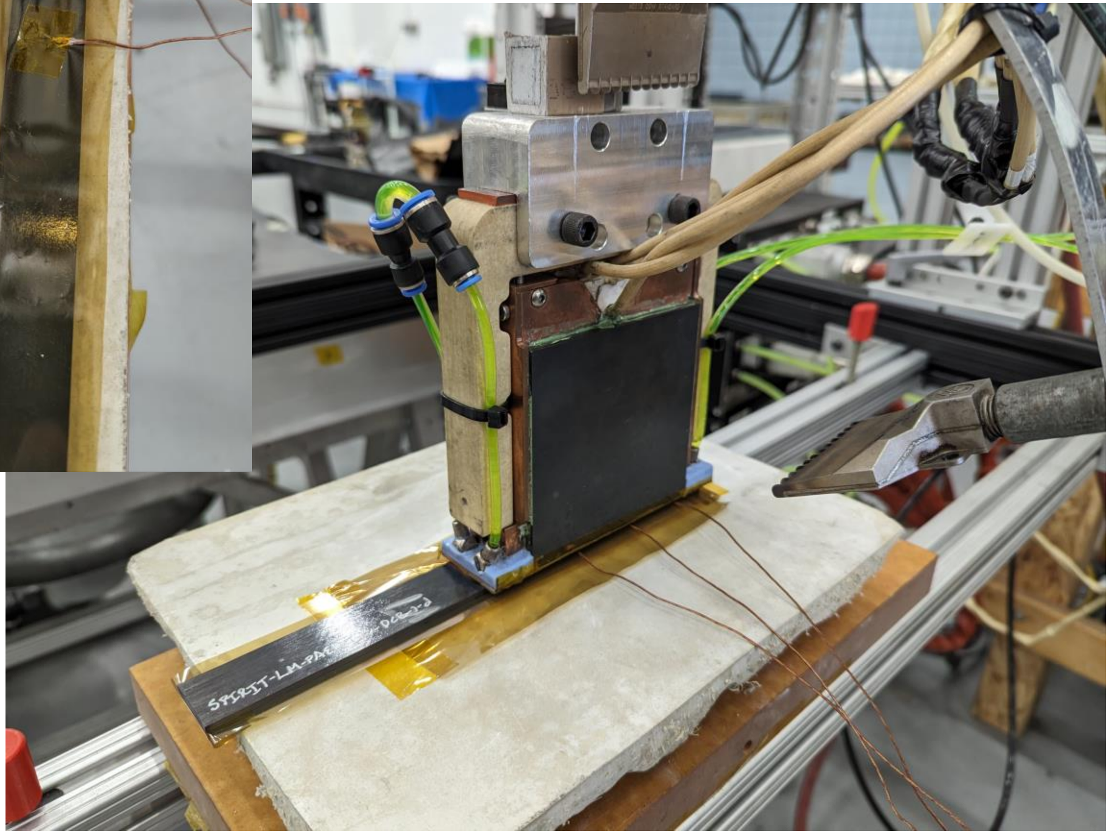
Weldability Study- Induction Welding

Process development for induction welding DCB coupons.

Thermocouples are placed at the bond-line to monitor the temperature profile during the weld process.

Are any other variables monitored during process development? Pressure?



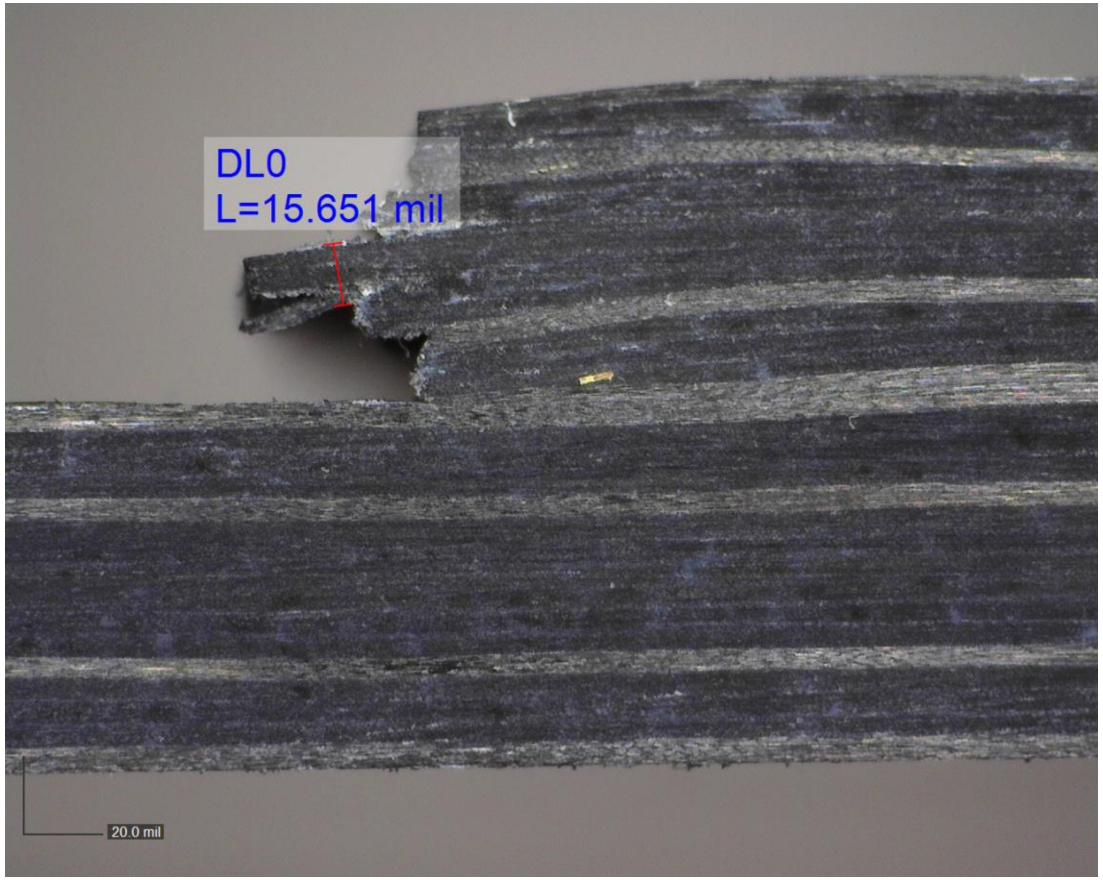


Weldability Study- Induction Welding

Example defect is squeeze-out from a lap shear weld where the adherends are not properly tooled.

Tooling concerns unique to induction welding include

- Heat dissipation - The setup at Spirit Aerosystems recirculates liquid coolant through the coil to draw heat out of the top surface and utilizes plaster tooling to pull heat from the rest of the coupon.
- Squeeze out protection - the tendency of interior plies to move in-plane results in squeeze out if all edges of the weld area are not supported.



Process Development for Ultrasonic Welding

Five materials were delivered to Agile Ultrasonics for welding single lap shear and double cantilever beam coupons.

A design of experiments was initiated by Agile to optimize process variables for each material. The DOE included 54 welds per material with each of the coupons within the DOE sent to NASA for single lap shear test. Data from those tests was provided to Agile for process selection.

PEI max strength: 22.9 MPa
LM-PAEK max strength: 18.4 MPa
PEEK max strength: 18.3 MPa
PPS max strength: 13.3 MPa

Examples of bond quality based on process variations

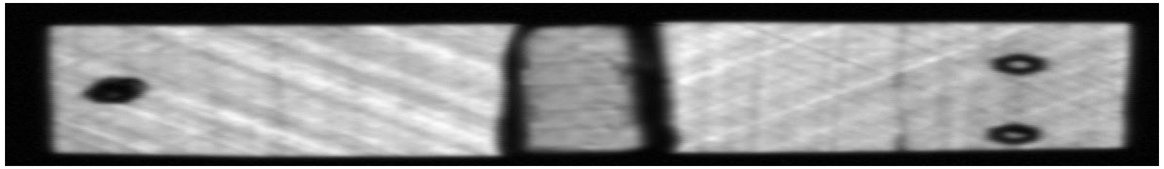
Process Development for Ultrasonic Welding

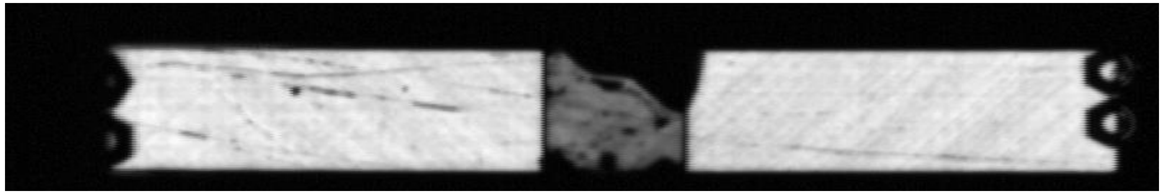
DOE Results- Ultrasonic Welding/ PEI

Run 6: 12.9 MPa
Run 45: 20.9 MPa
Run 53: 22.3 MPa

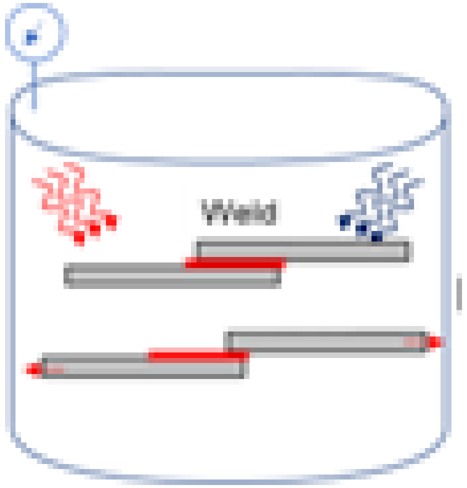
Thermoplastic Composite Welding Trials

NDE of process development coupons shows variation in weld quality. Bond strength and inspection information used to inform weld parameters.





Welding methods locally heat the substrates producing a heat affected zone (HAZ) and defects may develop anywhere within the HAZ → HAZ is inspection domain



Next steps: weld in a relevant environment

Feasibility of Joint Disassembly and Reassembly

OBJECTIVE:

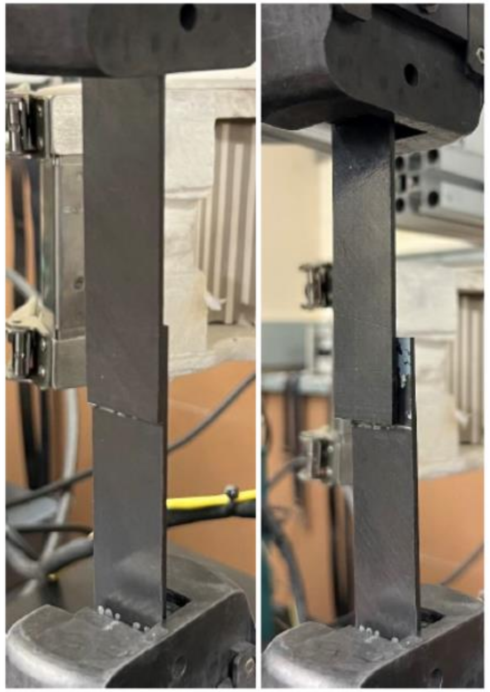
- Evaluate the feasibility of thermoplastic joint disassembly and reassembly.

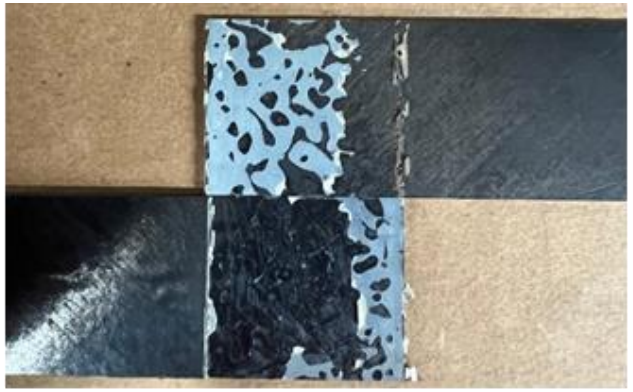
APPROACH:

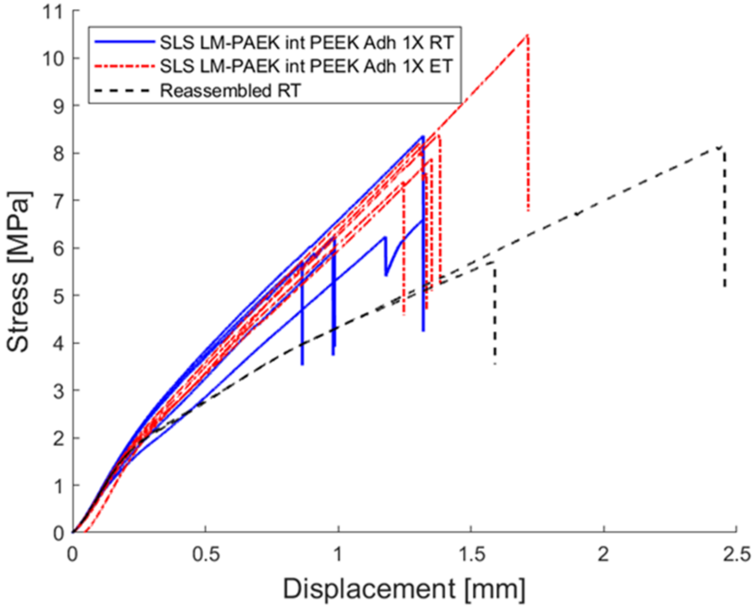
- Composite materials were selected based on their thermal transition temperatures and ease of reprocessing.
- Lap shear and 3 pt bend coupons were manufactured, along with a reassembly frame.

ACCOMPLISHMENTS:

- PEEK/carbon fiber quasi-isotropic panels were bonded with PPS and LM-PAEK films.
- The panels were cut into ten single lap shear & 3 pt bend coupons and tested at room (23°C) and elevated (121°C) temperatures.
- Strength data was recorded, and the failure mode was observed.
- The coupons were able to be re-pressed (167 psi, 625°F, 30 min for PPS) to reassemble the joint at similar strength to the original.







Next Steps

Ultrasonic Welding

- Evaluate ultrasonic welding in relevant environment
  - Under vacuum
  - Cold Temperature
  - Dust Additive

Disassembly and Reassembly

- Evaluate ultrasonic welding for disassembly and reassembly
- Evaluate bond-line materials to facilitate joining

Complete part fabrication, weld, and test of the vertical joint elements for the TSPD.