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

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## The Composites Consortium

Thermoplastics Development for Exploration Applications (TDEA) Project

Thermoplastics Development for Exploration Applications (TDEA)

# Collaborations & Partnerships

## NASA Centers

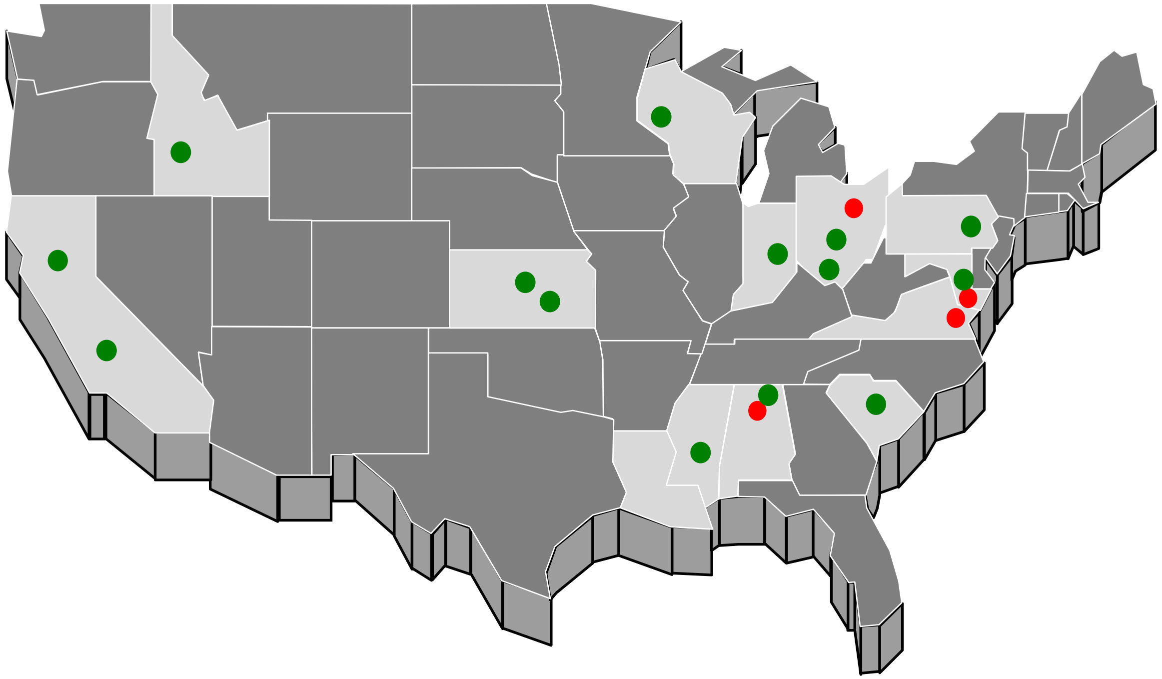
- Glenn Research Center
- Goddard Space Flight Center
- Langley Research Center
- Marshall Space Flight Center

## 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 | |

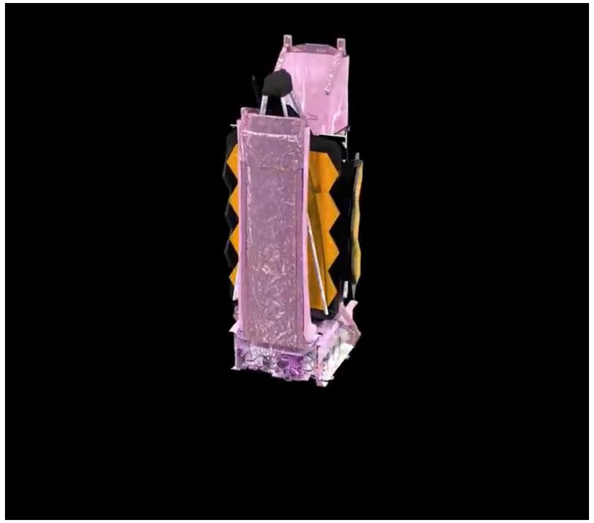
- Less complex mfg.
- Larger structures
- Fewer joints

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?

**Bolded** characteristics especially relevant for space applications



- 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

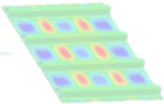
***Benefits of TPCs for in-space manufactured/assembled structures recognized since 1980s***

***Now underlying TPC technology has matured sufficiently to pursue application focused developments***

1 State-of-the-art survey

2 Launch vehicle structure mass savings

*How much mass savings with a postbuckled skin design?*

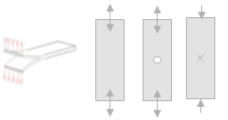


Promising concepts for TPC launch vehicle structures can be carried forward in future work

3 TPC material characterization

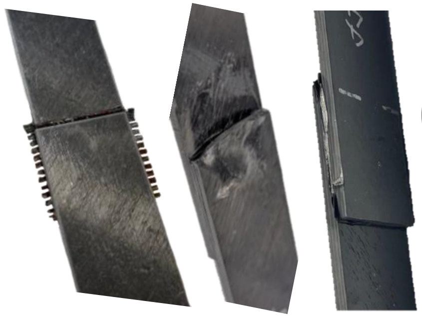
*Material properties for material selection and model inputs*

Thermal, mechanical, and physical tests

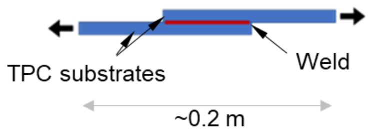


DSC
DMA
TGA
TC

- Emphasis on data required for process, material, and structural model inputs



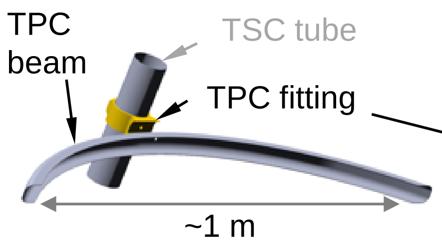
## 4 **Welded joint pathfinder:** *Foundational developments*

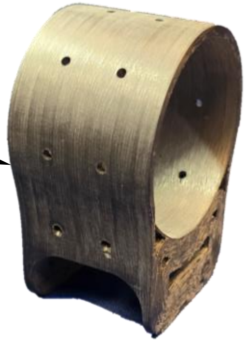



- Experiments to characterize weld performance, efficiency, and robustness across several materials and weld methods

## 5 **Thermoplastic Terrestrial Point Design (TTPD): TDEA terrestrial based welding design concept :** *Confidence building application*

Roman space telescope (RST)



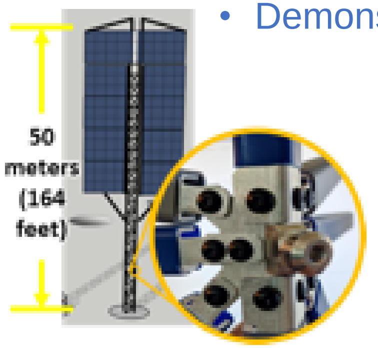



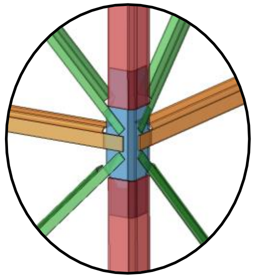
- Demonstrate terrestrially welded application

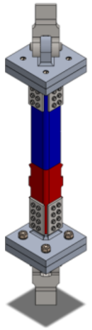
## 6 **Thermoplastic in-Space Point Design (TSPD):** *Game Changing application*

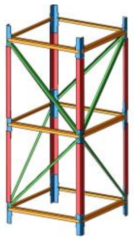
- Developments for in-space welding application
- Demonstrate scale-up and dust tolerance

Tall lunar tower (TLT)



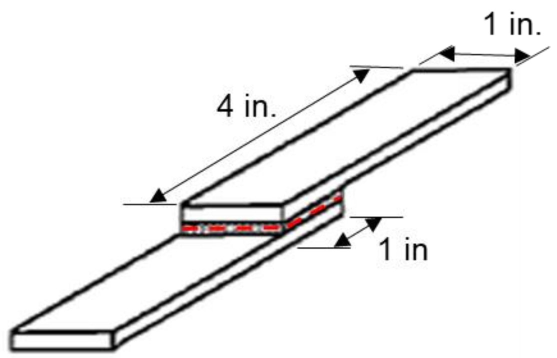




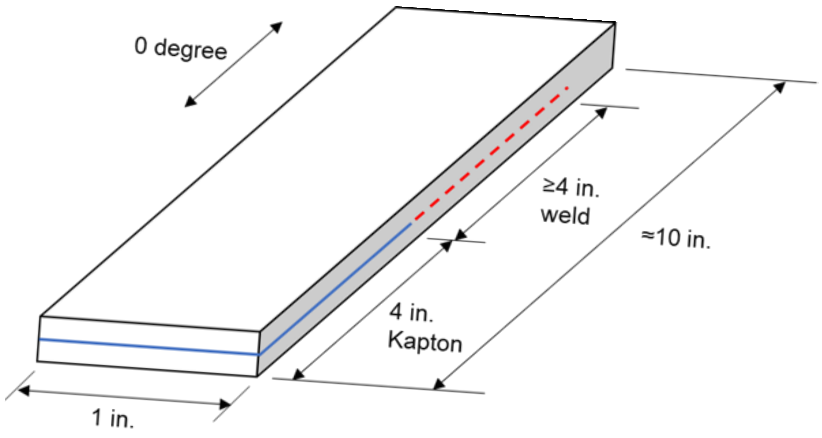
# Weldability Study: Characterized Processibility

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, n=9
- Bond quality as assessed by NDE
- Limited temperature history when possible




Single Lap Shear Coupon Dimensions

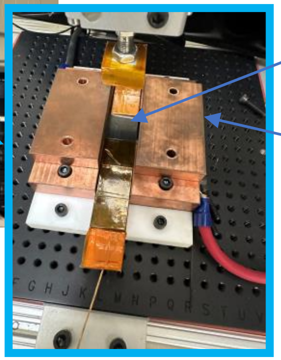


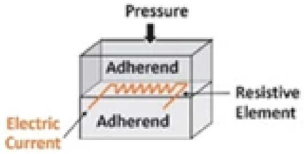

Double Cantilever Beam Coupon Dimensions

# Weldability Study: Characterized Processibility

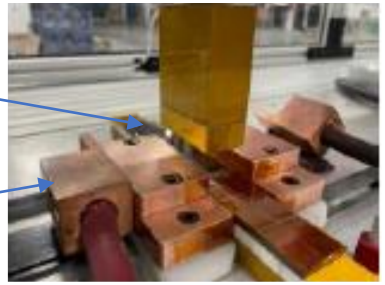
| Materials | Resistance (RW) | Induction (IW) | Ultrasound (UW) |
|---|---|---|---|
| AS4/PEEK, TC1200 | MSFC FY24 | Spirit FY24 | Agile FY24 |
| AS4/PEI, Solvay APC, *Toray | NIAR FY24* | Spirit FY24 | Agile FY24 |
| T700/LM-PAEK, TC1225 | NIAR FY24 (+3 heating elements) | Spirit FY24 | Agile FY24 (pursued scale-up) |
| AS4/PPS, TC1100 | NIAR FY24 | Spirit FY24 | Agile FY24 |
| M30S/PEKK (Thin ply) | NIAR FY24 | - | Agile FY24 |

MSFC RW setup

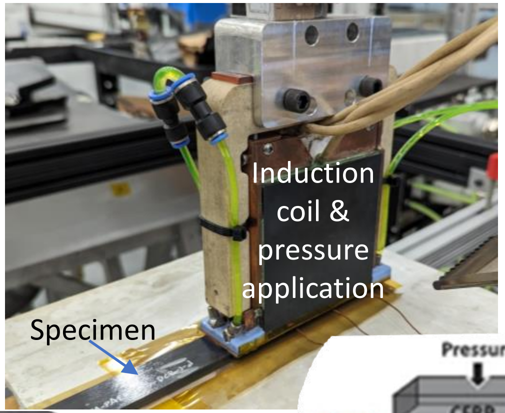


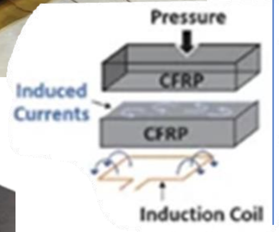



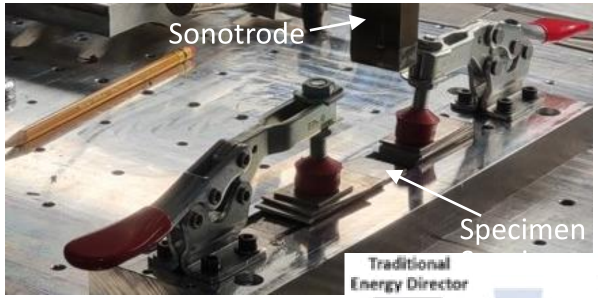

NIAR RW setup



Using carbon-fiber plain weave heating element



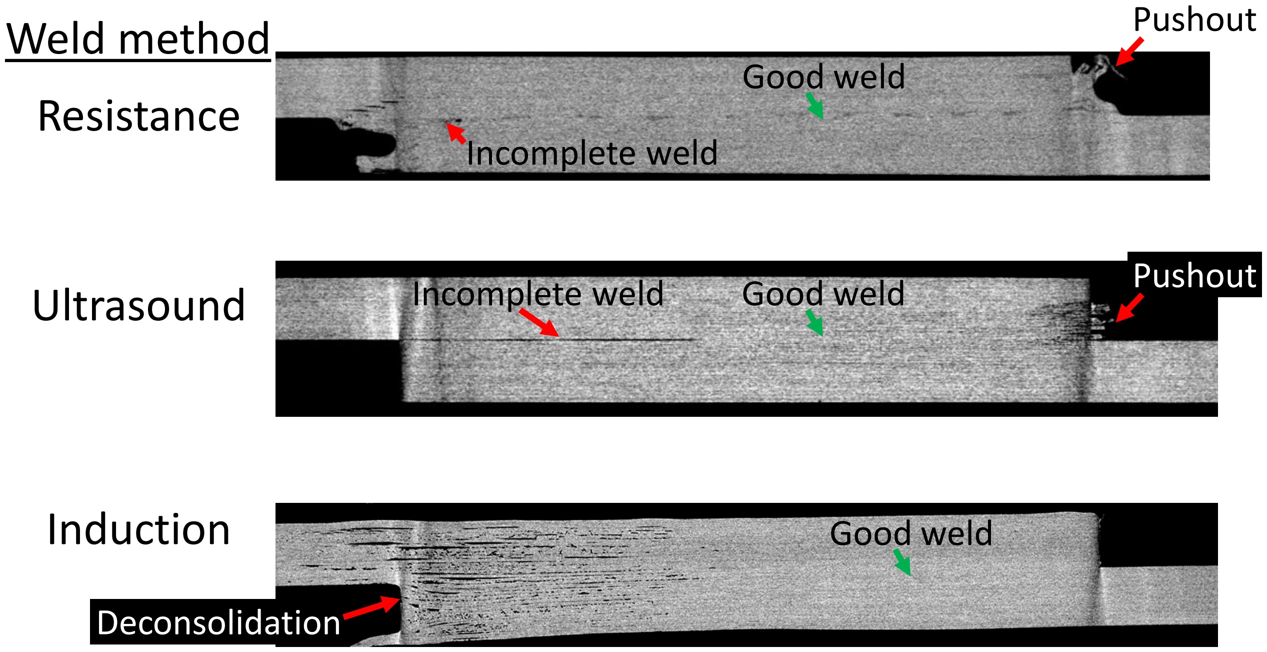


*Completed over 600 coupon (~1 $in^2$) lap welds; gained new insights into advantages, challenges, and trade-offs in thermoplastic composite welding at small scale*

# Weldability Study: Characterized Welds 4

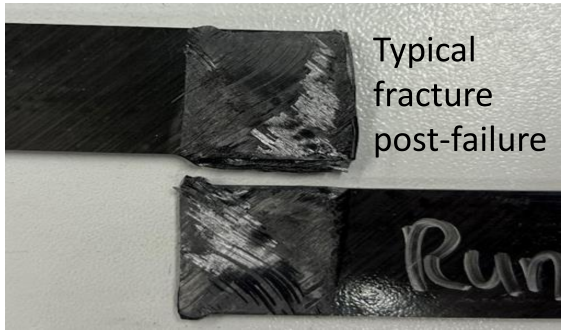
Welded joint performance assessed through nondestructive and destructive tests (KPP-2 for strength repeatability)

## Non Destructive Evaluation (NDE): defects can occur in each welding method




*X-Ray CT and ultrasonic NDE identify relevant defects; comparing results to microscopy*

## Mechanical test to characterize joint strength and repeatability (TC1225, UW)





| Iteration | Mean strength (psi) | CoV (n=6) |
|---|---|---|
| 1: Baseline | 1420 | 23% |
| 2: Updated tool, pre-heating | 2250 | 9.8% |

KPP-2 Coefficient of variation (CoV) threshold: 10%

*Mechanical tests for each material/weld method:*

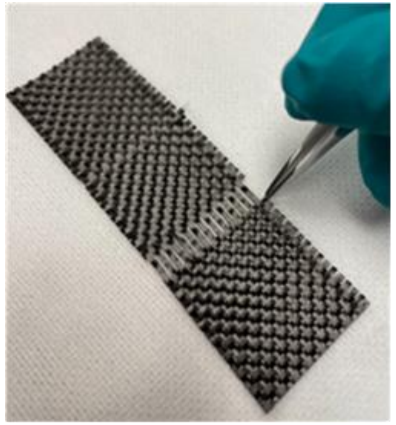
- *Correlate process to NDE to strength*
- *Inform process updates to improve performance*

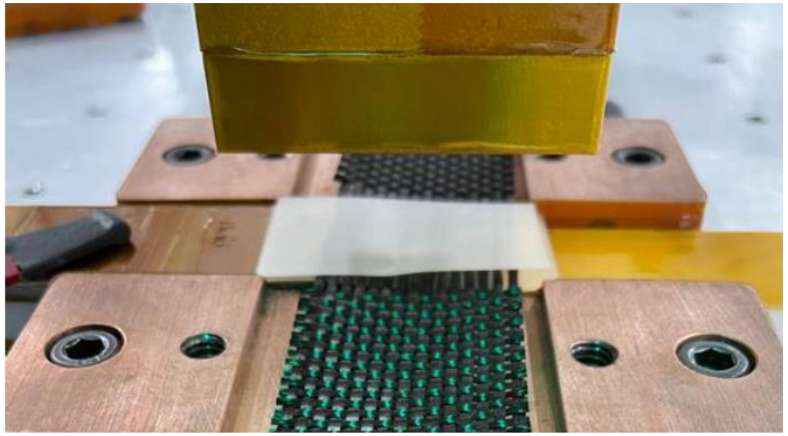
# Resistance Welding- Process Development

Welds performed on individual coupons to assess edge effects and reproducibility.

## 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 |
| | | |





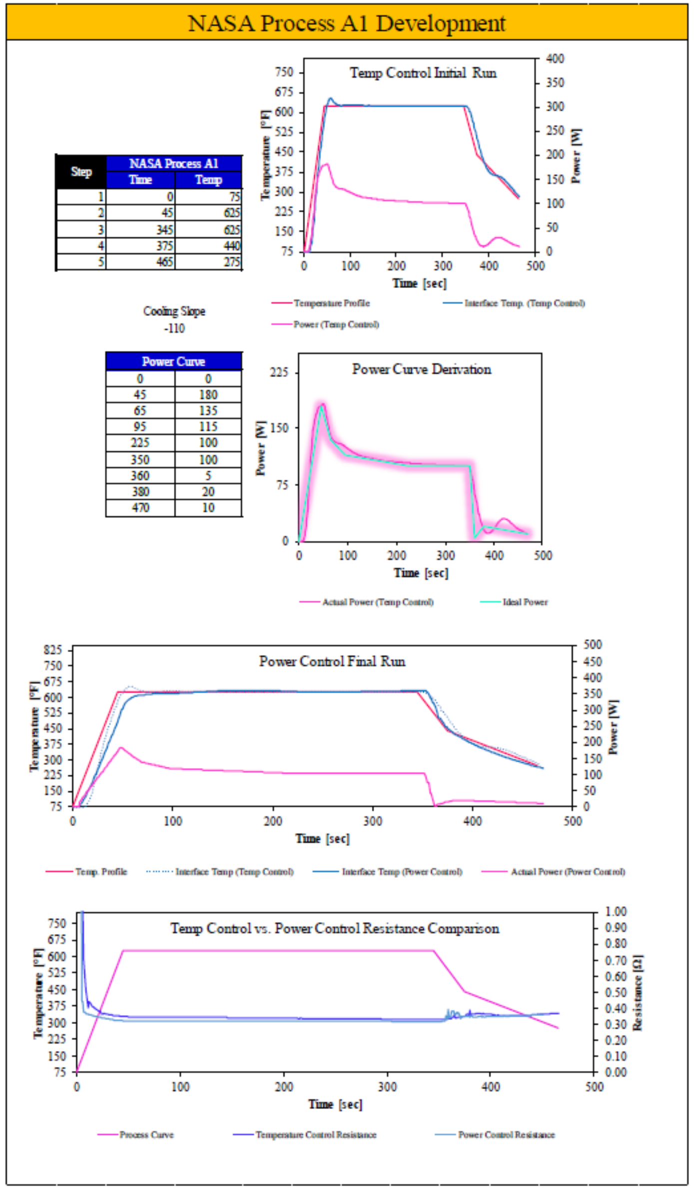



*Figure 15 – Process A1 Development*

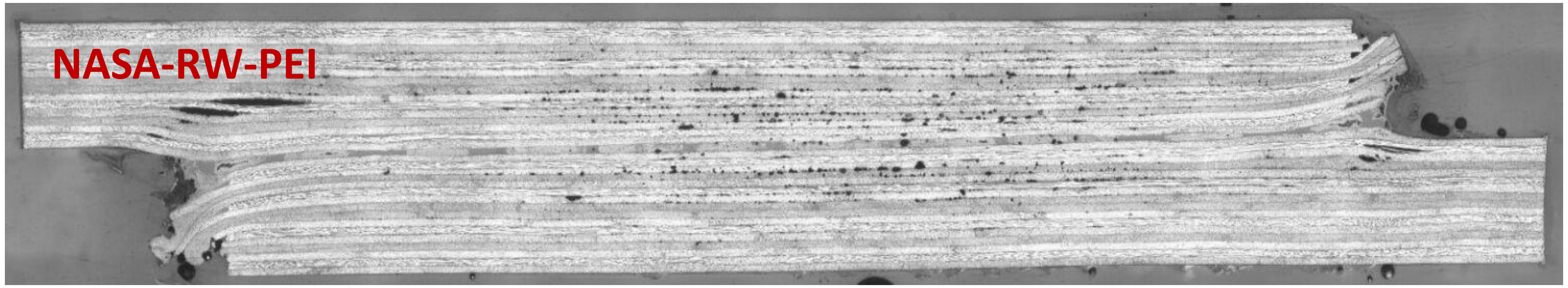
# Weldability Study- Resistance Welding

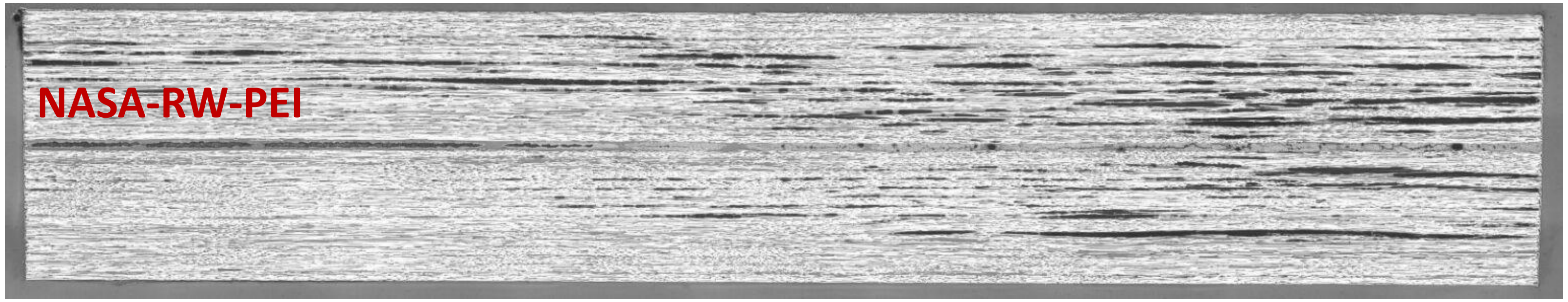
Process parameters include pressure, resistance, voltage, current, and weld time.

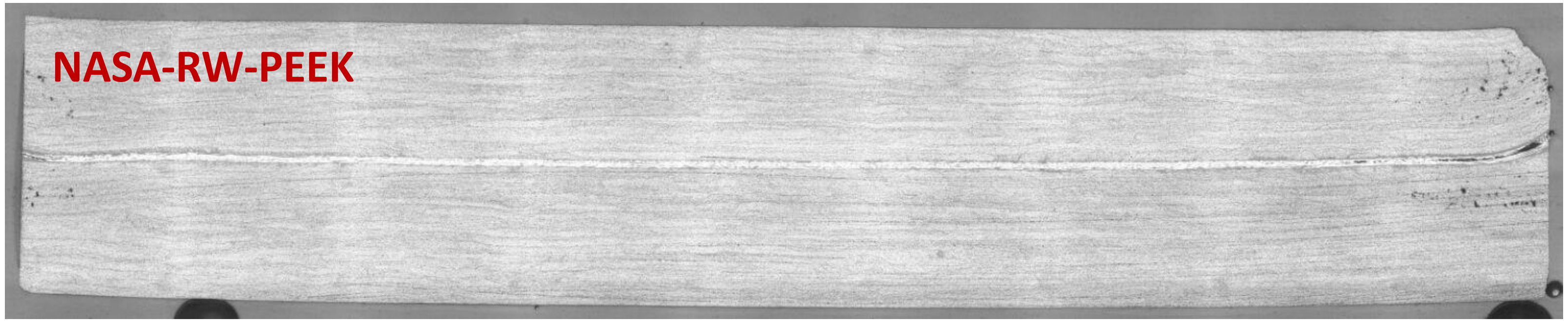
Defects observed within the adherend include delamination, voids, and fiber flow-out.

Fiber flow-out can occur 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.



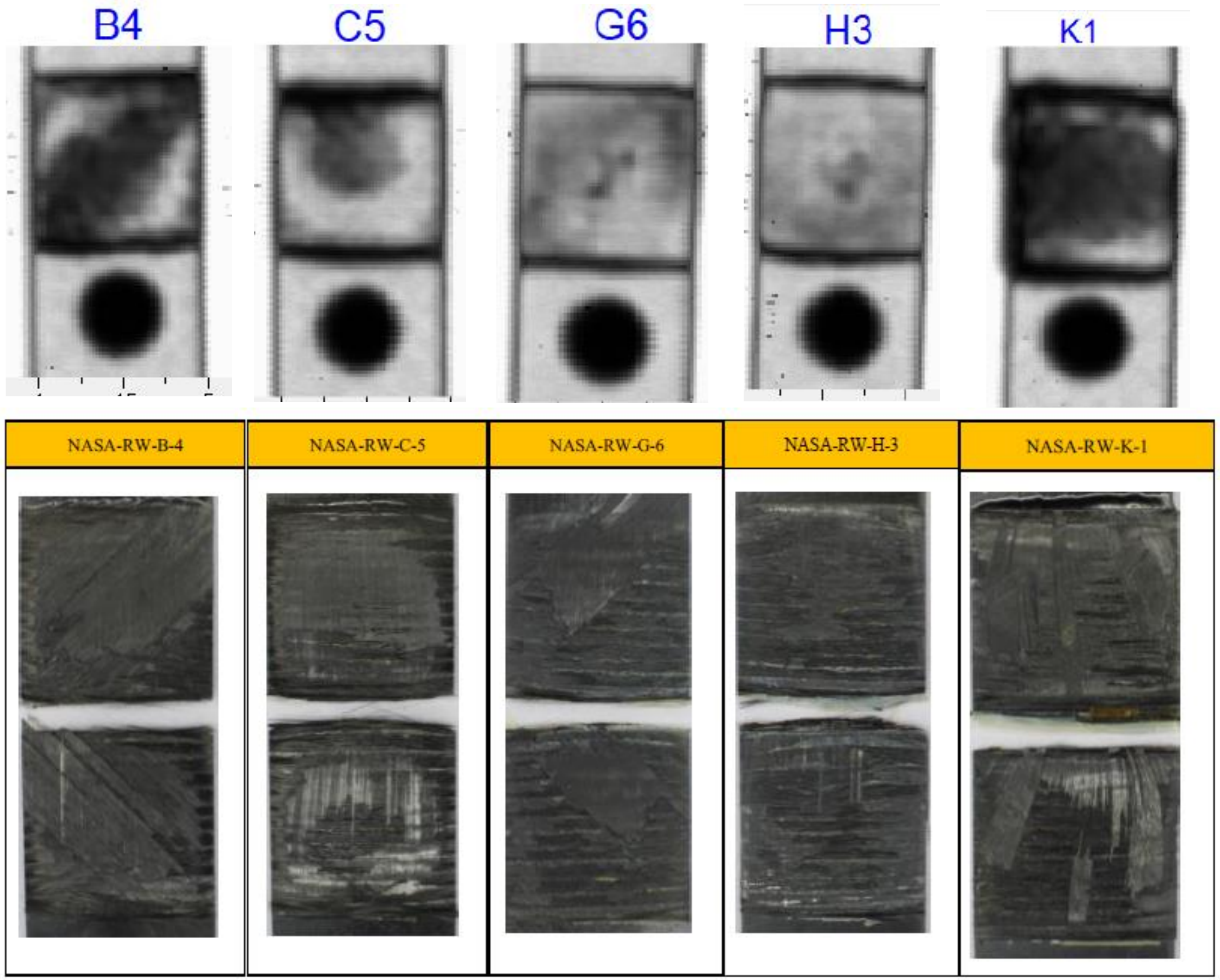



# Weldability Study- Resistance Welding

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.



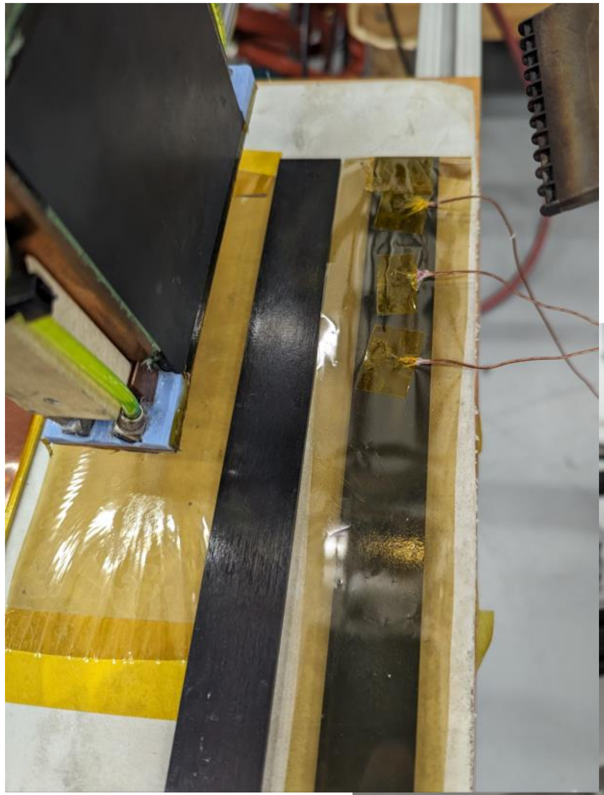

| | | | | | |
|---|---|---|---|---|---|
| Material | PEI | PEI | PEEK | PEEK | PEI/PEEK |
| Bond Strength (MPa) | 19.2 | 21.7 | 30.9 | 29.2 | 16.6 |

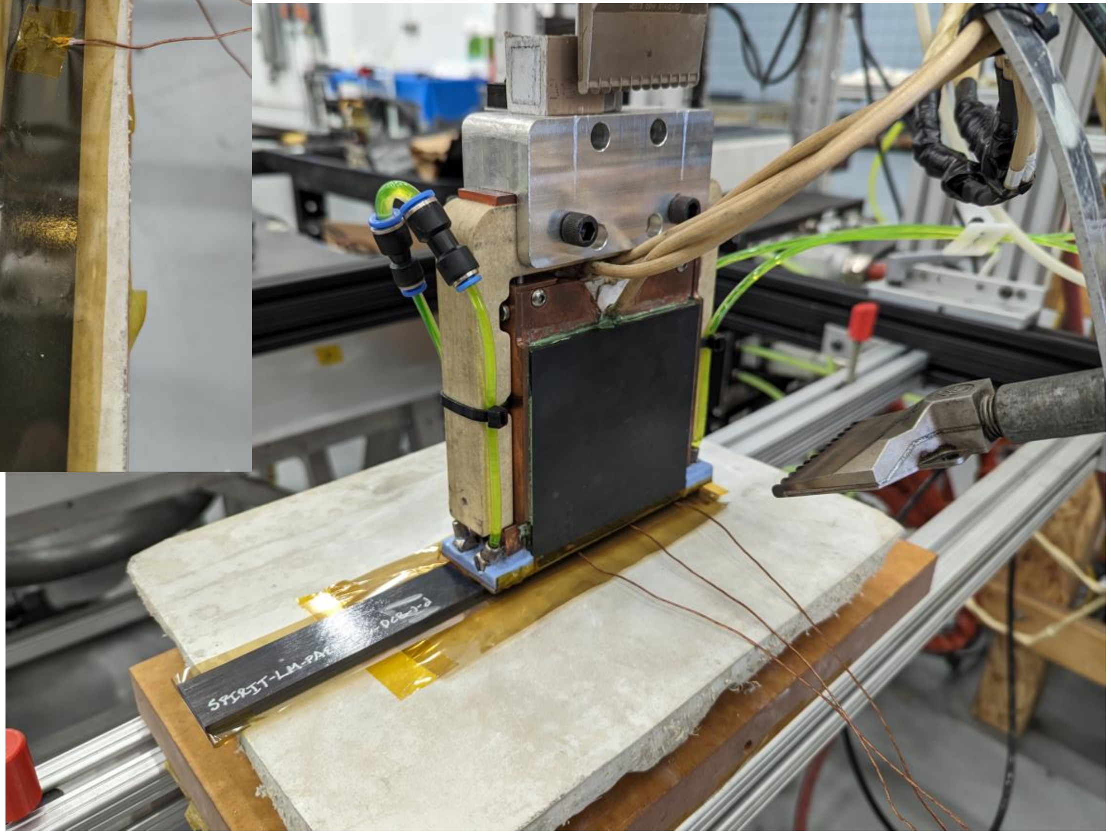
# Weldability Study- Induction Welding

Process development for induction welding DCB coupons.

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

Output current and applied pressure are monitored throughout the joining process.



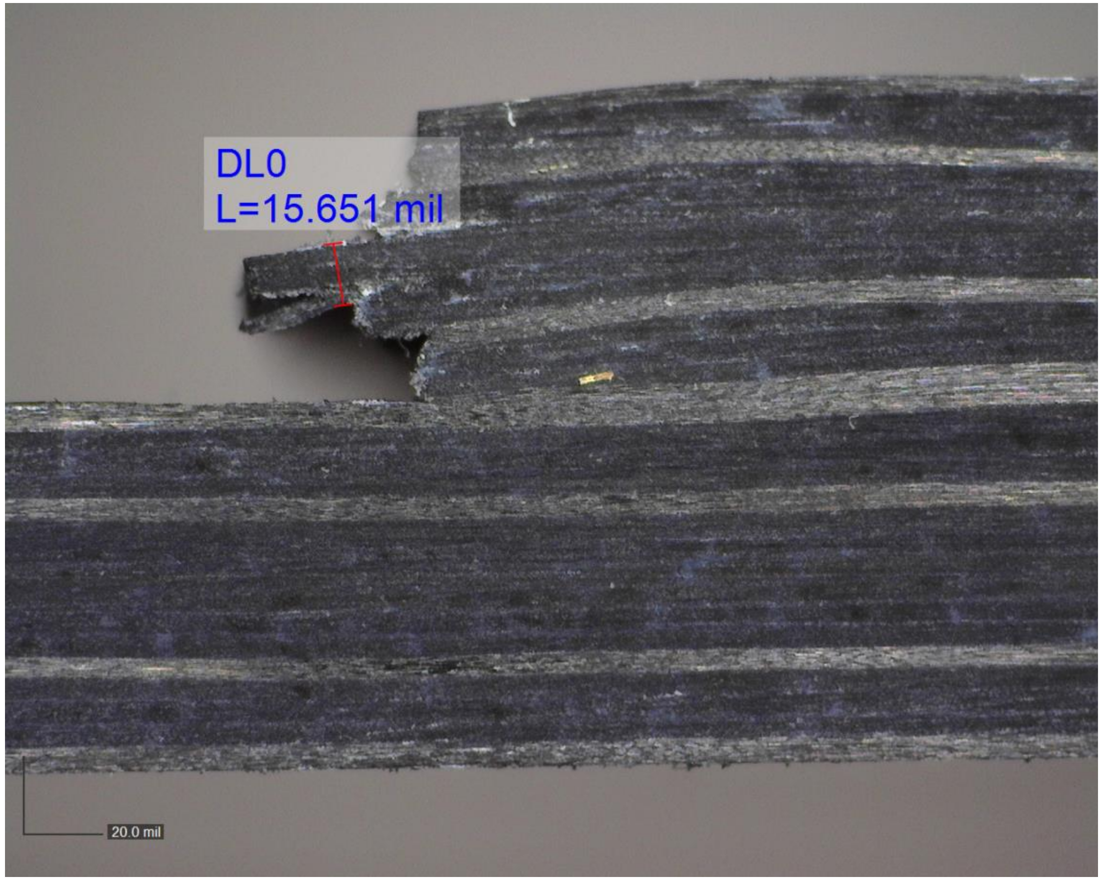


# Weldability Study- Induction Welding

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.

AS4/PEI max strength: 22.9 MPa
T700S/LM-PAEK max strength: 18.4 MPa
AS4/PEEK max strength: 18.3 MPa
AS4/PPS max strength: 13.3 MPa


Examples of ultrasonic welds using different process parameters

# Process Development for Ultrasonic Welding

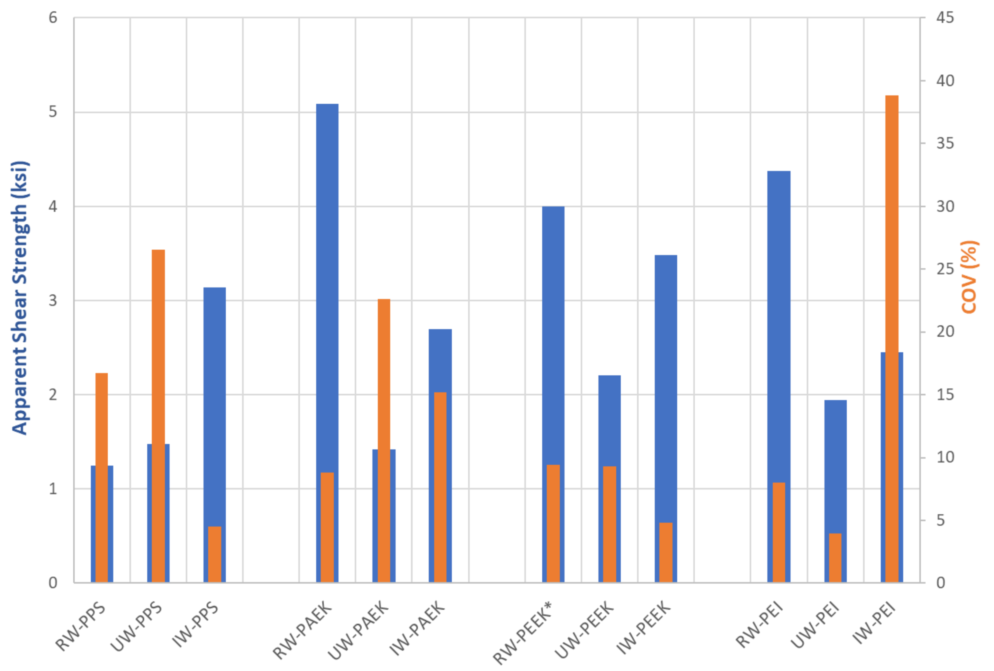
DOE Results- Ultrasonic Welding/ PEI

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




# K15 Weldability Evaluation: Commercially Available Materials

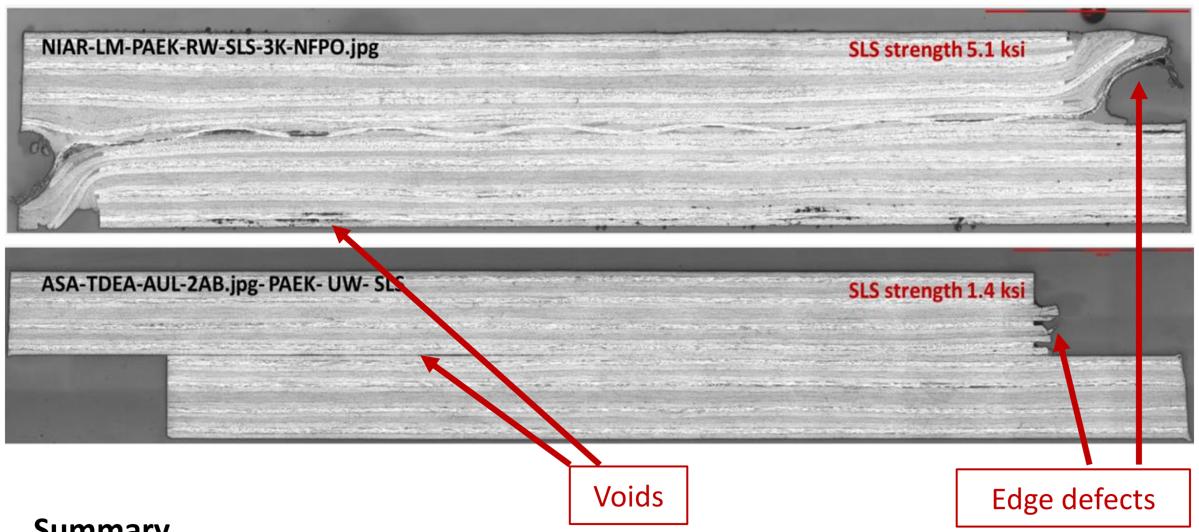
The purpose of this milestone was to generate single lap shear data for thermoplastic composite adherends welded by resistance welding (RW), ultrasonic welding (UW), and induction welding (IW). Materials welded for this study include 4 semi-crystalline matrix thermoplastic composites: T700/LMPAEK, AS4/PEEK, AS4/PPS, and M30S/PEKK and 1 amorphous matrix thermoplastic composite: AS4/PEI. Completion of the weldability study includes manufacture, test, and characterization data with the outcome of the study including: (1) bond strength- single lap shear (SLS) test data, (2) reproducibility through the measured coefficient of variation (CoV), (3) bond quality as assessed by NDE, and (4) edge effects by photo-microscopy.




Single lap shear (SLS) strength and CoV are plotted per material and weld method. The CoV goal for the TDEA project was 10% and the average COV across all materials for each welding method is:

- RW = 10.1% (7.9% removing outlier)
- UW = 15.6%
- IW = 15.8% (10.2% removing outlier)

These values represent a first attempt at each welding process. Schedule did not allow for rigorous process optimization.




**Summary**

The primary factors contributing to weld quality in this study include matrix material, weld method, and coupon dimensions.

In general, resistance welding generated the highest single lap shear strength and lowest CoV. However, the 1” x 1” coupon dimensions complicated the induction welding process through current loss at the edges. Edge effects were also an issue in ultrasonic welding. The data calls attention to the limitations of these thermoplastic welding methods and to areas needing further process optimization, such as ultrasonic scan welding.

# TDEA Thermoplastic Space Point Design

## Motivation:

- In-space thermoplastic composite (TPC) welding offers potential for simple and robust structural joints to build huge space structures
- TPC welded joint designs can eliminate metallic end fittings, adhesive bonding, and mechanical fastening, which may simplify development and reduce costs

## Objective:

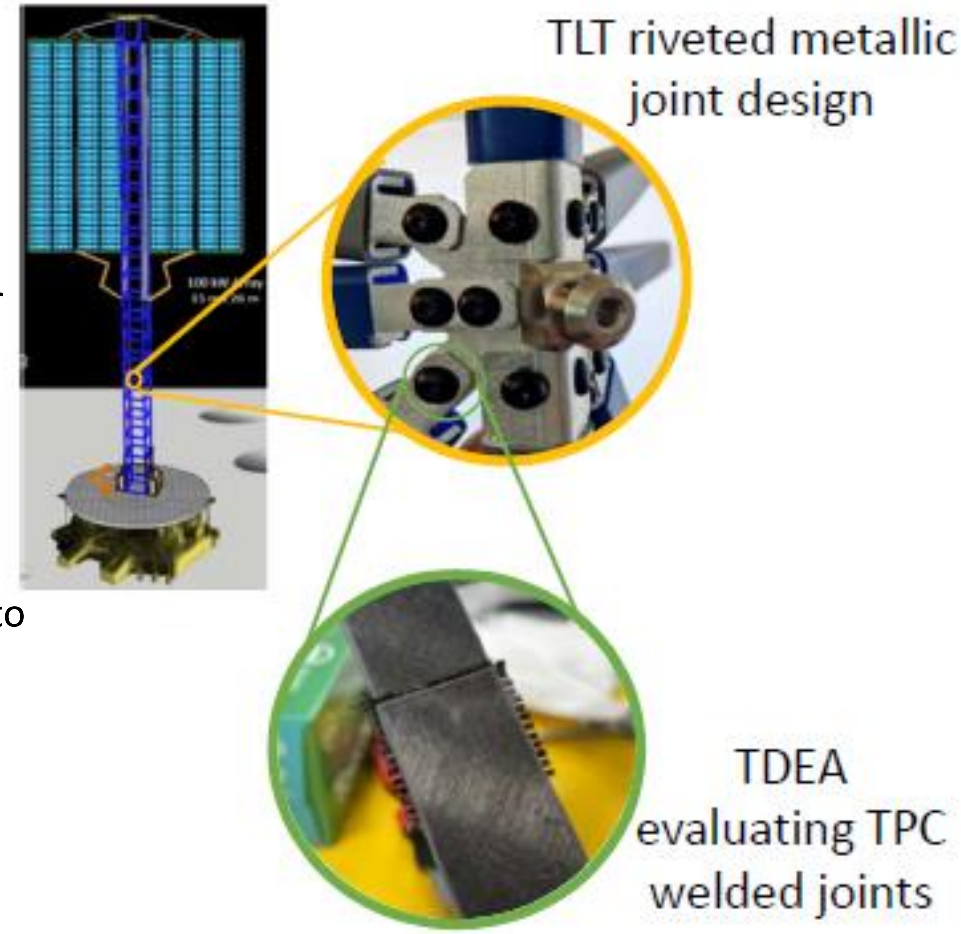
- Demonstrate through design, analysis, and ground tests, a TPC welding approach for assembly of a truss structure relevant to a 50-m tall solar array tower

## Approach:

- Leverage the requirements and designs shared by the Tall Lunar Tower (TLT) project to establish the TDEA TSPD – an all- TPC-m-tall tower
- Characterize effect of welding in simulated lunar environments at the coupon scale to establish knockdown factors (limited to effect of lunar dust simulant)
- Design, analyze, manufacture, and test at the sub-element scale to characterize structural performance and advance capability

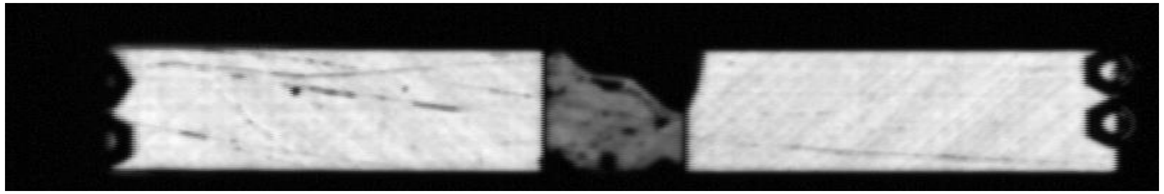
## Status:

- Completed global tower design and analysis to establish sizing and joint loads
- Developed building block test plan
- Started truss element manufacturing

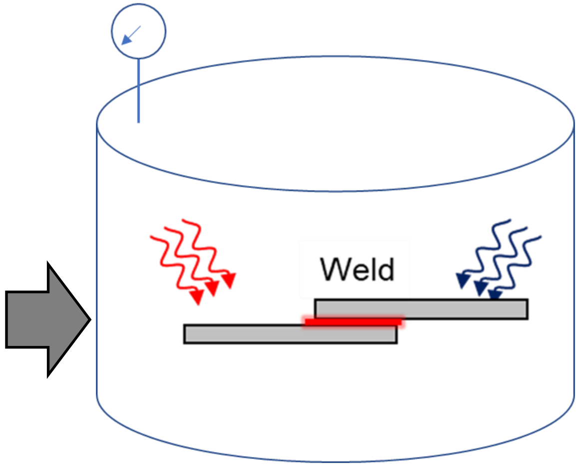


# Thermoplastic Composite Welding Trials

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



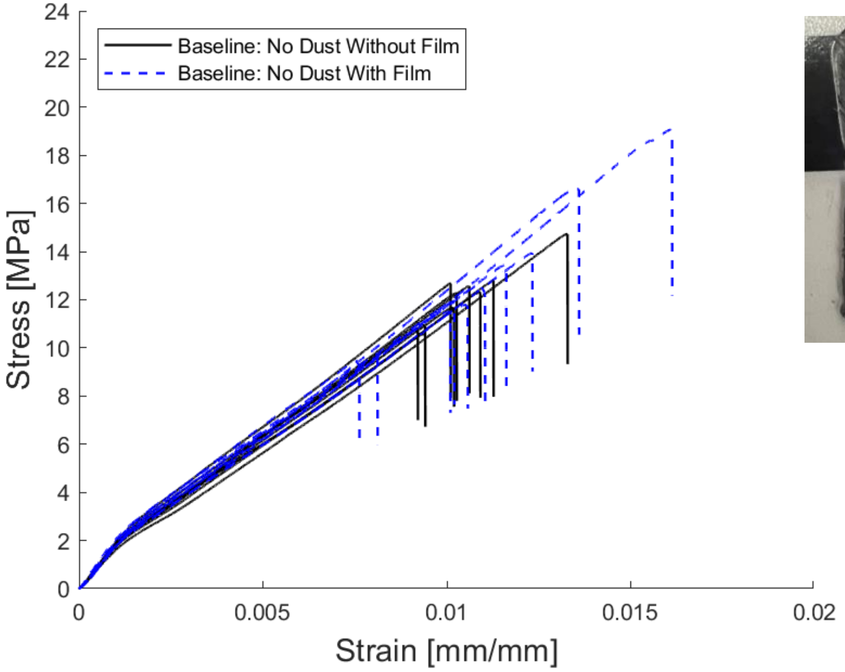
Welding methods locally heat the substrates producing a heat affected zone (HAZ) and defects may develop anywhere within the HAZ → HAZ is inspection domain


Next steps: weld in a relevant environment

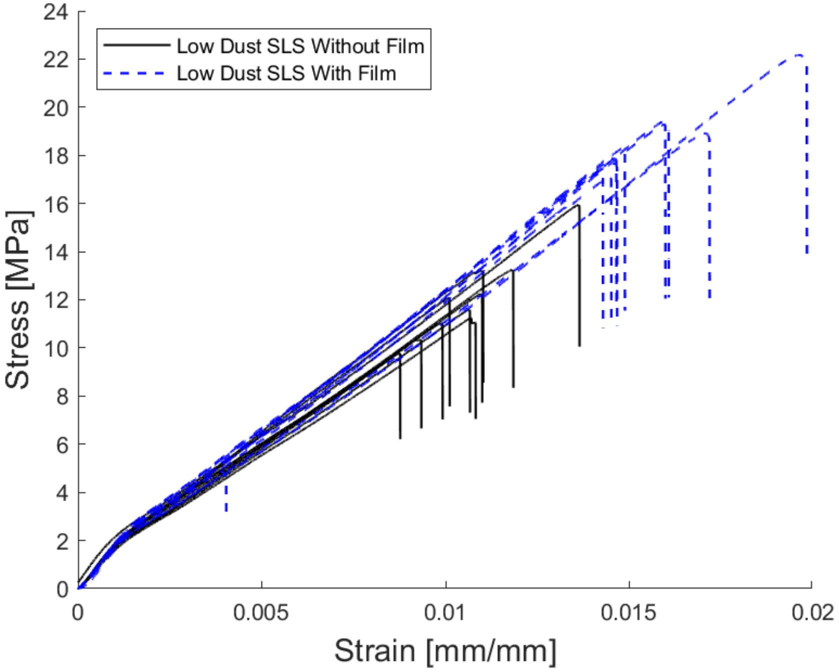
# C7: Thermoplastic Space Point Design (TSPD) In-Space Welding Knockdown Factors Based on Coupon Test Data

The purpose of this milestone was to evaluate mechanical property data of thermoplastic composites joined through ultrasonic welding. This was accomplished through testing of single lap shear (SLS) coupons with and without LM-PAEK film interlayer at conditions of no dust (baseline) and low lunar dust simulant at bond surface prior to welding. SLS tests for baseline coupons without film demonstrated an average lap shear strength (LSS) of 12.1 MPa with a 10.1% coefficient of variance (CoV), and baseline coupons with film had an average LSS of 13.0 MPa with 22.9% CoV. Adherends failed at the joining interface with minimal fiber breakage, with a slight increase in fiber breakage noticed for coupons with film. Low dust coupons without film had a LSS of 12.1 MPa and 14.6% CoV (same LSS as baseline but increased CoV), however low dust with film had an increased LSS of 18.7 MPa and 8.3% CoV (excluding one outlier). The low dust with film specimens exhibited fiber breakage occurring outside the bond region. This work provides the first data on how ultrasonically welded composite joints may perform when welded in a lunar environment.

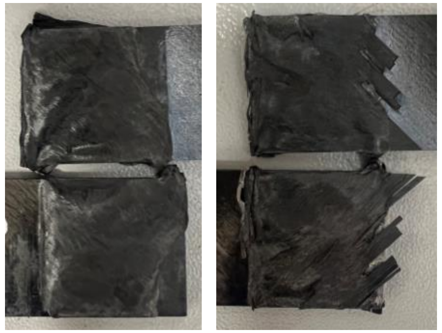



SLS data for baseline (no dust) coupons.

Representative SLS failure modes for baseline coupons without (left) and with (right) film interlayer.




SLS data for low dust coupons.



Representative SLS failure modes for low dust coupons without (left) and with (right) film interlayer.

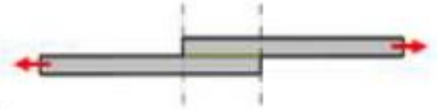
# TSPD Manufacturing and Test Plan

## Objectives

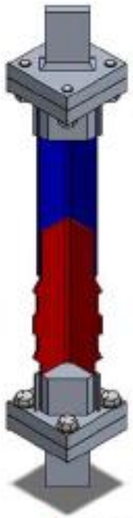
- Determine welding process parameters for specific thicknesses and lay-ups
- Obtain coefficient of variation (COV)
- Quantify sensitivity to lunar dust simulant contamination

- Build and test articles with TSPD tower vertical joint geometry and with representative vertical direction loading (tension and compression)
- Conduct structural tests to characterize the joint behavior

- Demonstrate truss manufacturing in lab environment
- Conduct welding with ultrasonic welding end-effector mounted on an industrial robot arm



Single lap shear coupons



Vertical joint sub-element

Repeating unit cell (RUC)

# Summary

- Benefits of TPCs for in-space manufactured/assembled structures recognized since the 1980s
- Now is the time to increase the TRL for infusion into NASA programs

- TDEA is working to advance the TRL of TPCs for space applications through material characterization and modeling, welding investigations, and a design-analyze-build-test effort

- TDEA will be generating new test data this summer:
    - Weldability study
    - TSPD coupons, sub-element, and RUC manufacturing demo