Thermoplastic Composites Conference

Advancements in Thermoplastic Bonding and Joining

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American Composites Manufacturers Association

Thermoplastics in Aerospace

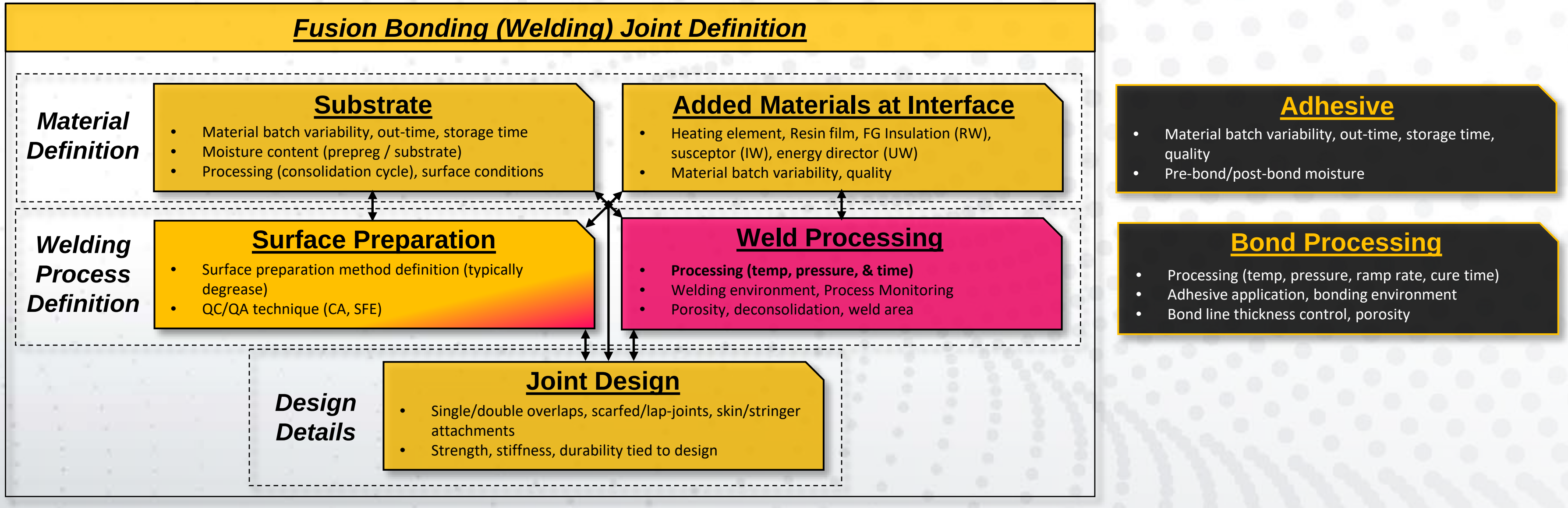
- Benefits for aerospace applications
  - Resistance to aggressive environments such as high humidity, high temperature, and saltwater exposure
  - Better flame resistance compared to most thermosets
  - Less stringent cleanroom requirements and no shelf life
  - Impact (high fracture toughness), chemical, and flame resistance
  - Lengthy and costly autoclave cycles can be eliminated
- The capability to sustain multiple cure cycles ➔ Recycling!
  - 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 (surface preparation)

Thermoplastic Bonding

- Regulations - thermosets vs. thermoplastics *(ensure reliable load path between two separate structural elements)*
  - Material and process control
  - A structural adhesive bond must be accomplished in a way that it predictably and reliably transfers load for the lifetime of the bonded structure
- Thermoplastic materials are generally more challenging to bond than thermoset materials because the surface can be more difficult to chemically activate for bonding
  - Cleaning → Chemically activating → Stabilizing (resisting hydration)
- Certification of Bonded joints
  - Bond QA → no NDI method or techniques can reliability detect bad/weak bonds or quantify long-term durability; in-service damage evaluation
  - Proof-load testing → costly and time-consuming
  - Prevention by design features → chicken rivets! (inefficient load path, stress concentration, increased laminate thickness, weight)

Thermoplastic Welding

- **Regulations** - bonding vs. welding (co-cured or co-bond or secondary bond???)
- **Certification of Welded Joints**
  - AC 20-107B: Composite Aircraft Structure describes means of compliance unique to bonded structure
- Scaling issues
- Lack of established best practices and analysis methods



TCC Thermoplastic Composites Conference

The Effects of Process Parameters and Material Type on an Inductively Welded Thermoplastic Unidirectional Tape Composite Joint

John C Monsees

Chief Technologist, Thermoplastic Laboratory COE

Qarbon Aerospace

Red Oak, Texas

Qarbon Aerospace - Overview

- Qarbon is an accredited premier Tier 1 level supplier
- Currently three facilities around the world at 1.7 million square feet

Red Oak, TX

- 123 acre site
- 38 miles SE of DFW Int'l Airport
- 772,000 ft² of manufacturing space
- 415 employees
- Large Complex Structural Assembly
- AS9100D and NADCAP Certified

Milledgeville, GA

- 165 acre site
- 93 miles SE of Atlanta, GA
- 650,000 ft² of manufacturing space
- 332 employees
- Premier Composite Manufacturing
- AS9100D and NADCAP Certified

Rayong, Thailand

- 44 acre site
- 62 miles from Suvarnabhumi Int'l Airport
- 150,000 ft² of manufacturing space
- 175 employees
- Low cost Complex Composite Components
- AS9100D and NADCAP Certified

Qarbon Aerospace – Overview Cont.

- Qarbon is very active in supplying major composite structures in many aerospace programs

Red Oak, TX

Military Programs

- V-22 Integrated Empennage
  - Spare & Fleet Repair Components
- HALE Integrated Wing
  - Spare Components
- F135 Engine Compressor Duct
  - Spare Ducts
- T-7A Wing & Empennage
- C-17 Spare Components
- Lockheed F-35 Supplier Certification

Commercial Programs

- 767 Pressure Dome
  - Spare Domes
- Bell 525 Fuselage Panels
- G600 Horizontal Tail
- LIFT Aircraft HEXA eVTOL
- G550 Spare Components

Milledgeville, GA

- 787 Frames, Longerons and Stringers
- 777 Flaps, Spoilers and Ailerons
- 767 Wing Center Section Keel Beam & Seal Depressor panels
- KC-46A Tanker Engine Cowls
- G650 Spoilers, FTE, Winglets & Cove panels
- HALE Wing Structure
- V-22 Wiper Fairings and Ramp & Door assemblies
- Embraer E-2 Rudder & Elevator

Rayong, Thailand

- Trent 700 (A320)
  - Front & Rear Acoustic Panels
  - Fan Track Liners & Carbon Seals
- Trent 800 (777)
  - Rear Acoustic Panels
- BR725 (G650)
  - Rear Acoustic Panels
  - Fan Track Liners
- Pearl 700
  - Front & Rear Acoustic Panels
  - Fan Track Liners
- A350
  - Rudder Leading Edge Fairings
  - NSBB EPDC & Umbrellas
  - Sewing Angles & Rudder Details
- Parts on A320, A330, 787 & LIFT Hexa eVTOL

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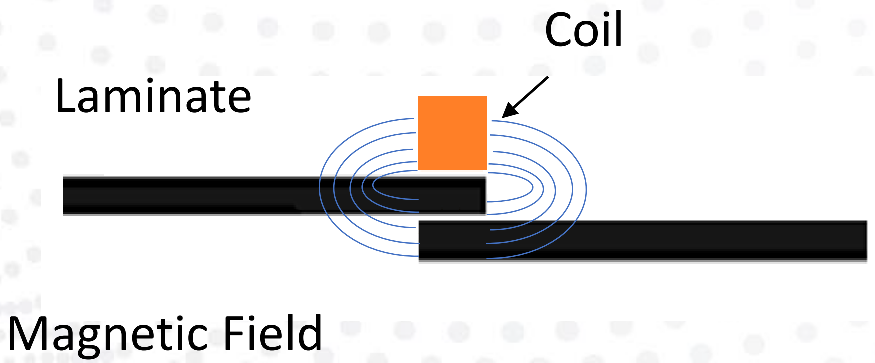
Basic Induction Technology Overview

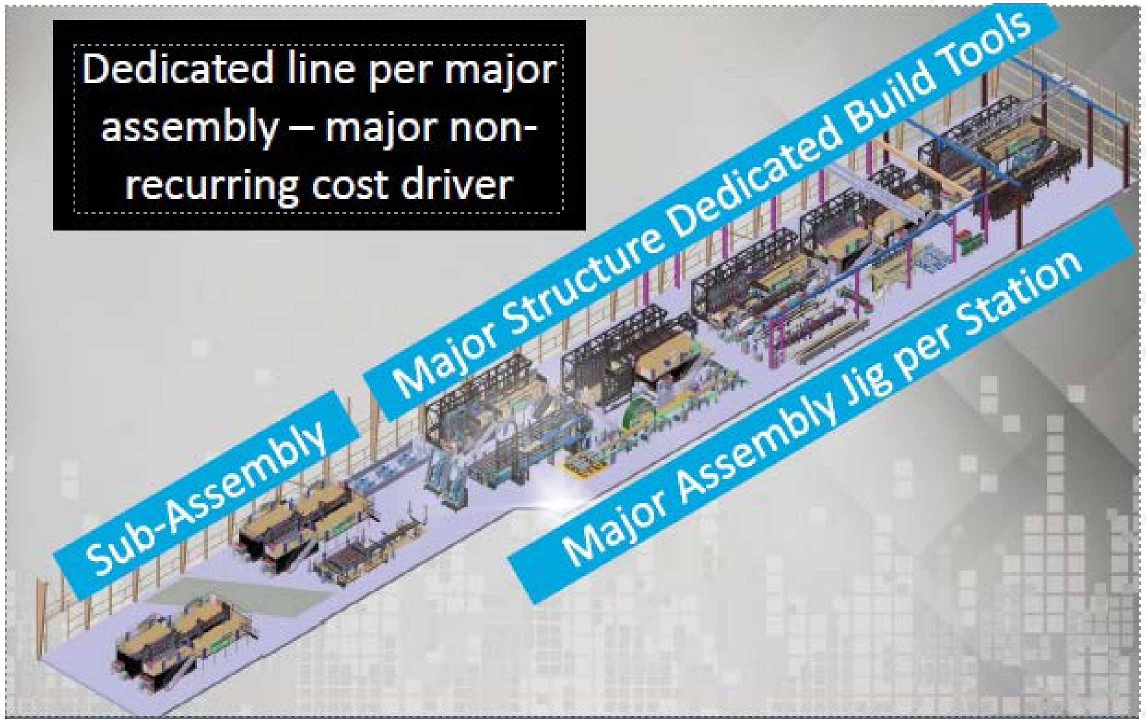
- Qarbon Aerospace - along with other notable Tier 1 suppliers are investing millions into this revolutionary joining process
- The processes are similar and yet different in their approaches – but the goal is the same . . . .

Thermoplastic Fabric or Unitape Induction welding is an attractive alternative to adhesive bonding or fastening due to its potential for out-of-autoclave processing, weight savings, and labor reduction.



Alternating current passes through a coil → Coil generates Alternating Magnetic Field → Eddy currents are generated in carbon fibers → Joule heating melts the resin → Laminates are reconsolidated under pressure

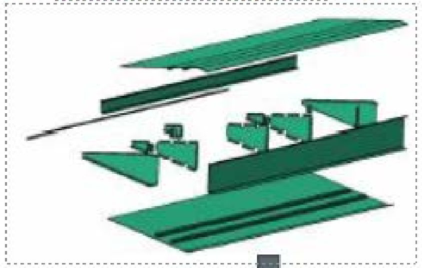
Manufacturing Assembly Process – The Driver!



LEGACY ASSEMBLY METHOD

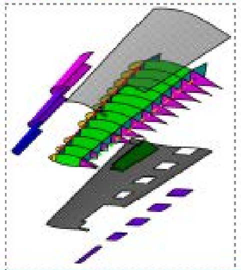
-Tooling intensive
-Significant effort to change configuration or alter detail part designs
-Large footprint with fixed costs

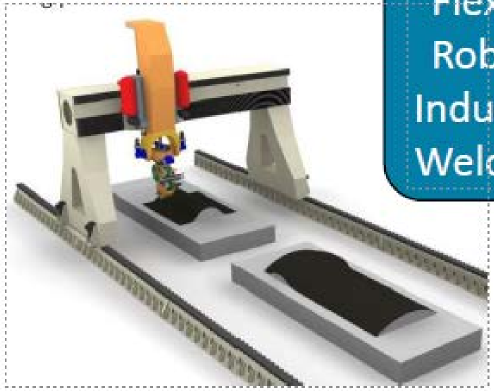
Structure Type 1



Modular Locating Assembly Jigs Drive add flexibility & lower costs

Structure Type 2



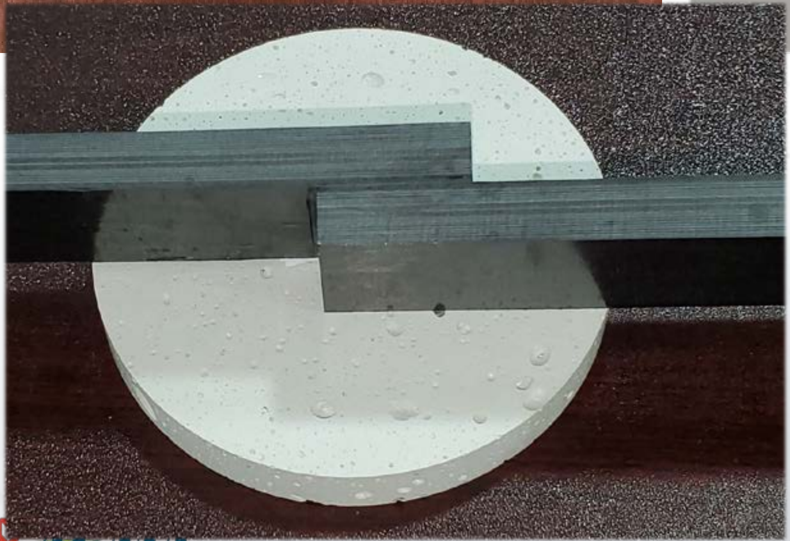


Flexible Robotic Induction Weld Cell

QARBON POTENTIAL

-Lower costs without major assembly jig per assembly
-Flexible robotic work cell has capacity to support multiple programs
-Modular factory adaptable to multiple vehicles & volumes

Start with analysis – Joint Design & ANSYS



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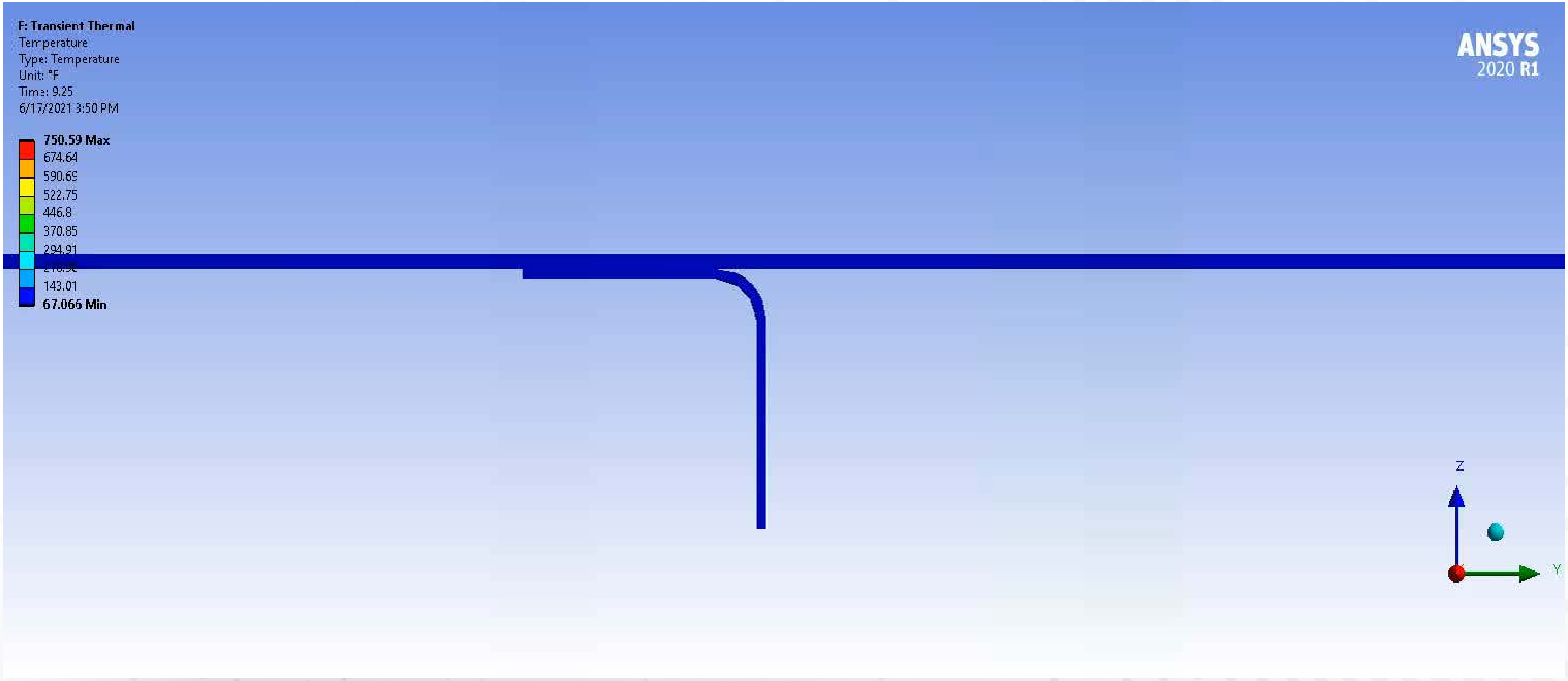
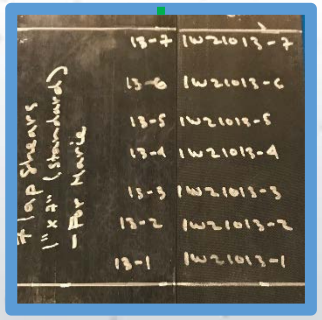
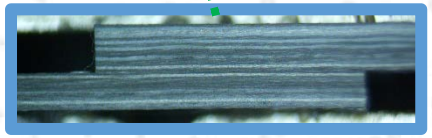
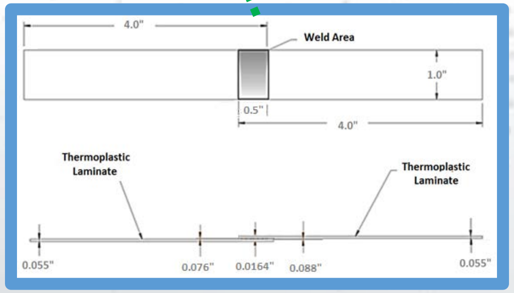


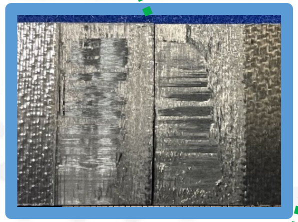
General Weld Development Procedure

Dynamic W elding → Inspection → Machining → Macros → Lap Shear Testing ASTM D1002 → Weld Size → DSC ASTM D3418



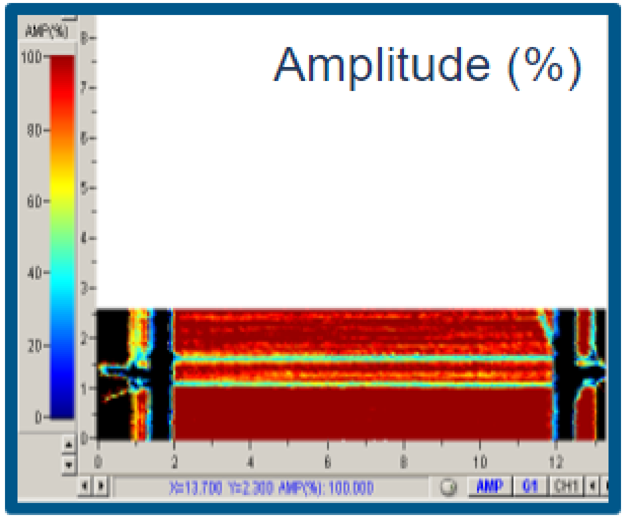


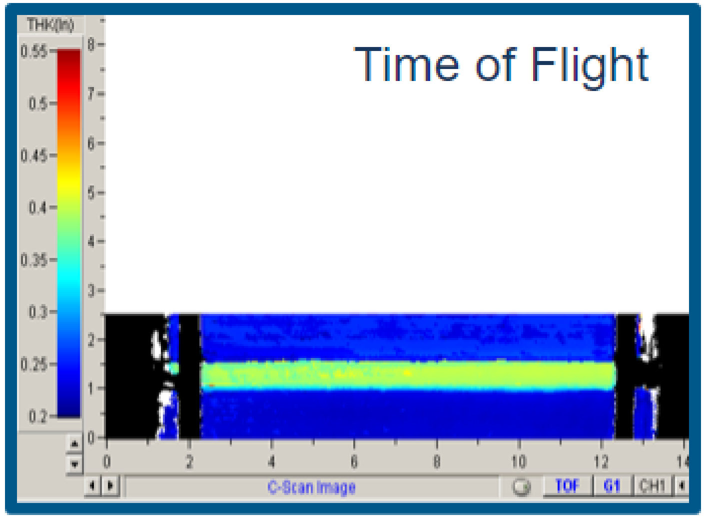




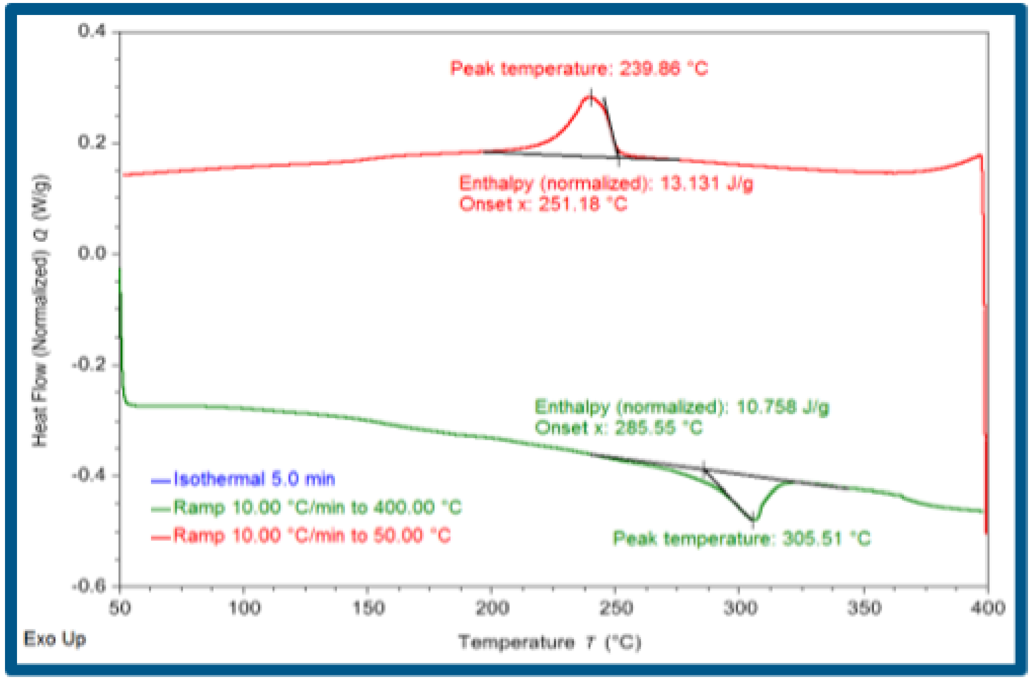
Baseline – Autoclave Results

Parameter	Fabrication	Weld Preparation	LSS (MPa)	% Crystallinity
Baseline	Autoclave Cycle	Ambient, Solvent Wipe	45.5 ± 4.8	23.0 ± 2





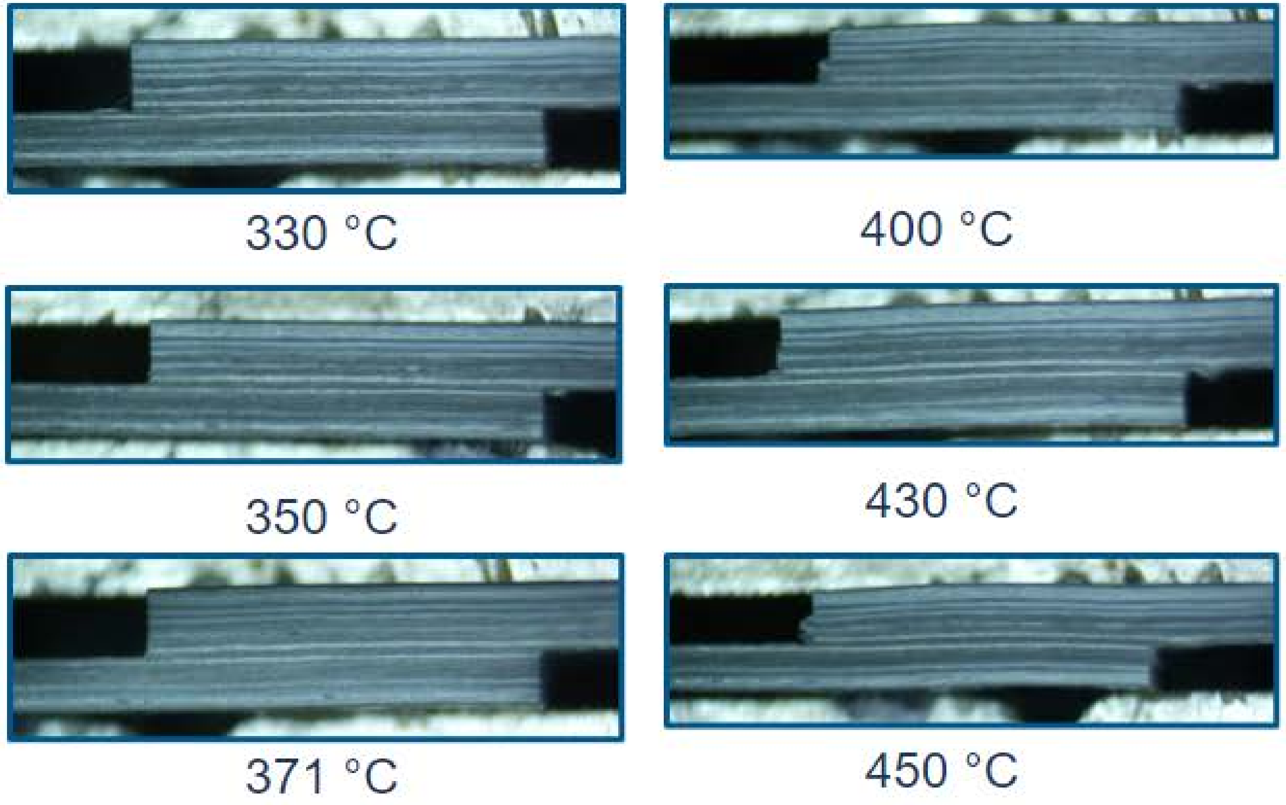
Ultrasonic Inspection

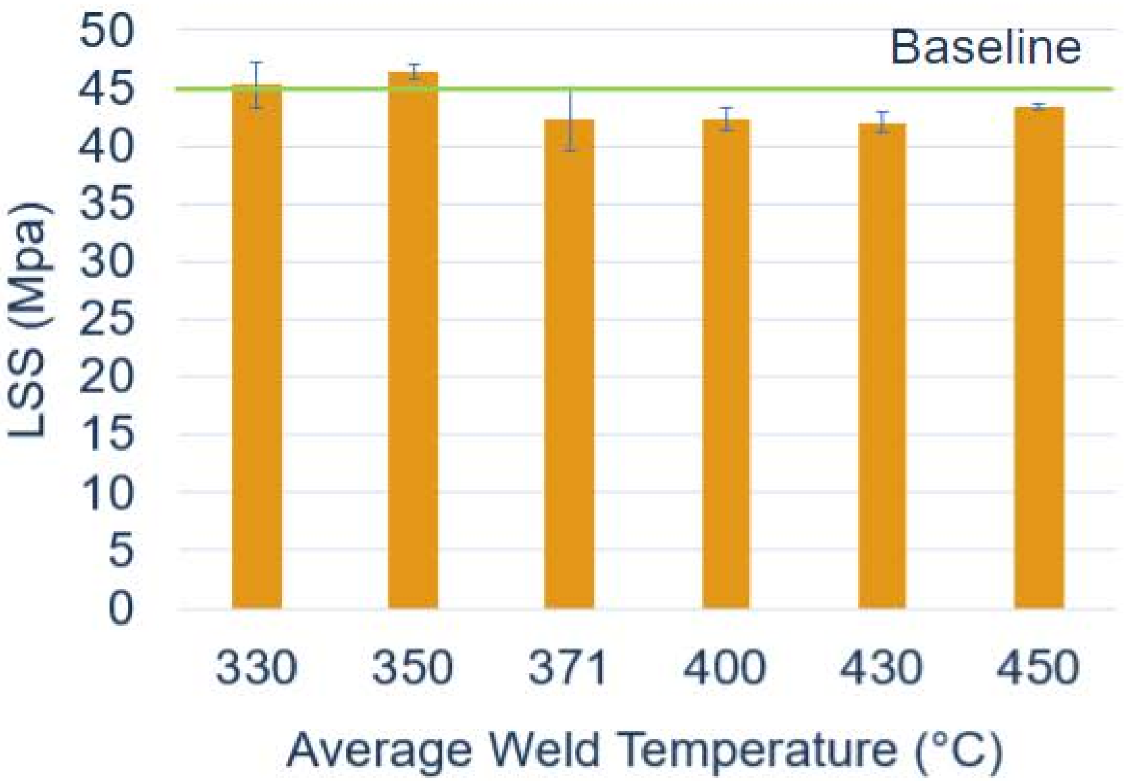


DSC Results

Represents Nominal Processing Temperature, Pressure, and Cooldown Rates

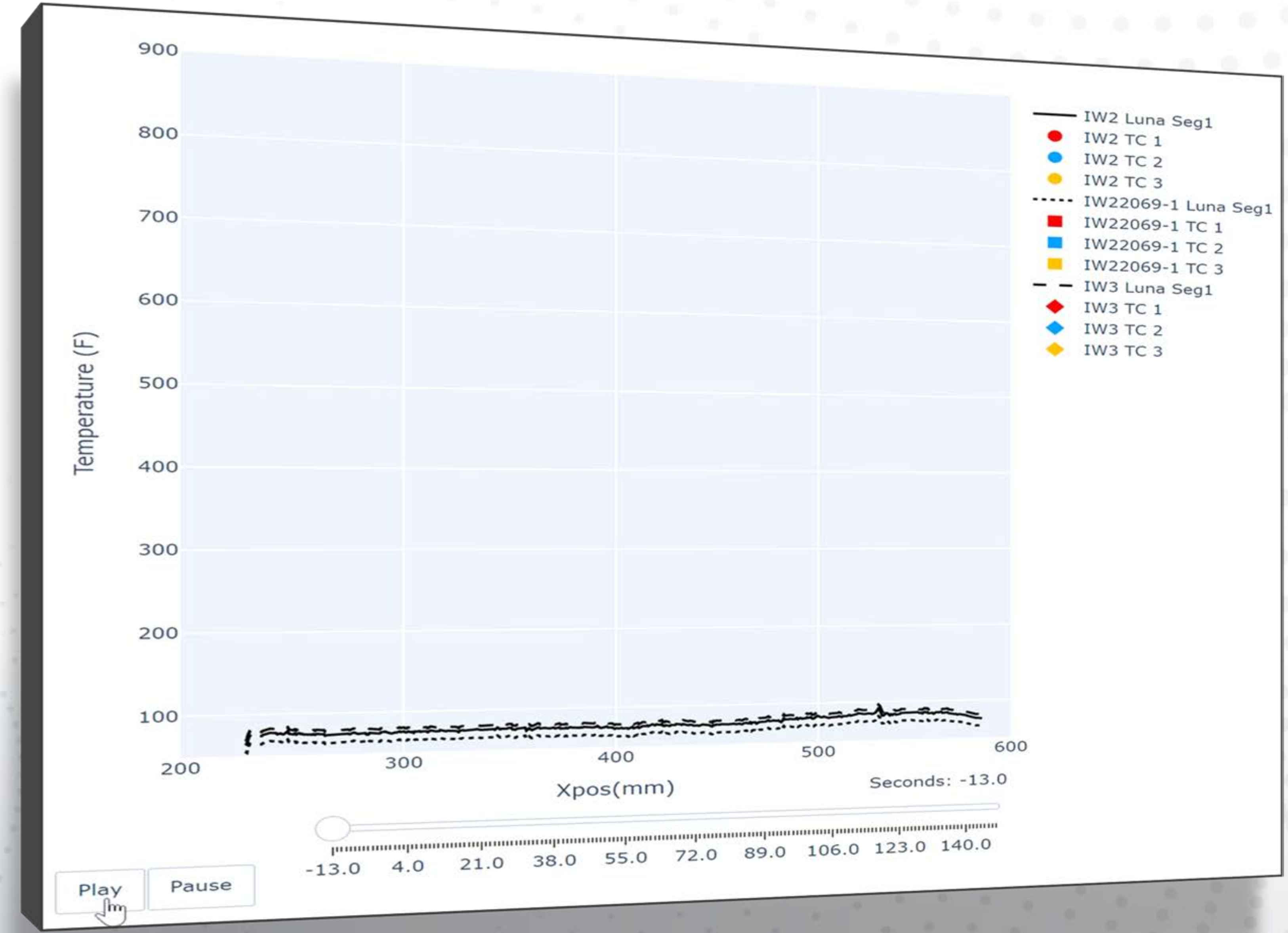
Temperature Process Parameters





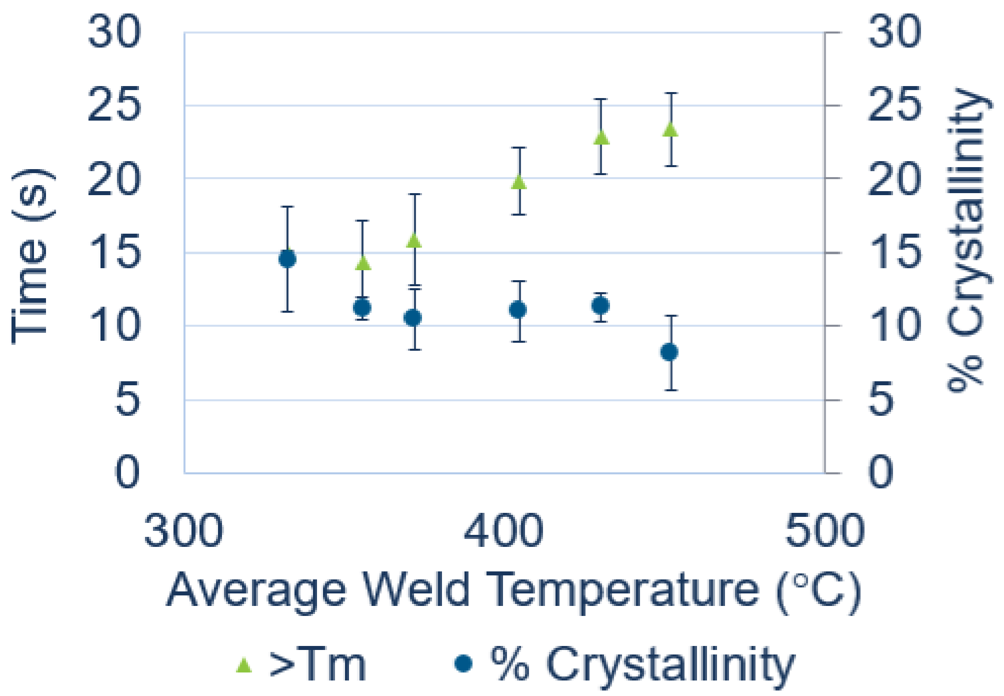
Slight knockdown (10%) most likely due to specimen deformation. Deformation will be mitigated with improved tooling.

Temperature Process Parameters - Luna



Temperature Results

Parameter	Temp (°C)	LSS (MPa)	% Crystallinity
Baseline	Autoclave Cycle	45.5 ± 4.8	23.0 ± 2.0
Temperature	330	45.3 ± 1.9	14.5 ± 3.6
	350	46.4 ± 0.6	11.2 ± 0.8
	371	42.3 ± 2.7	10.5 ± 2.1
	400	42.4 ± 1.0	11.0 ± 2.1
	430	42.0 ± 0.9	11.3 ± 1.0
	450	43.4 ± 0.3	8.2 ± 2.5



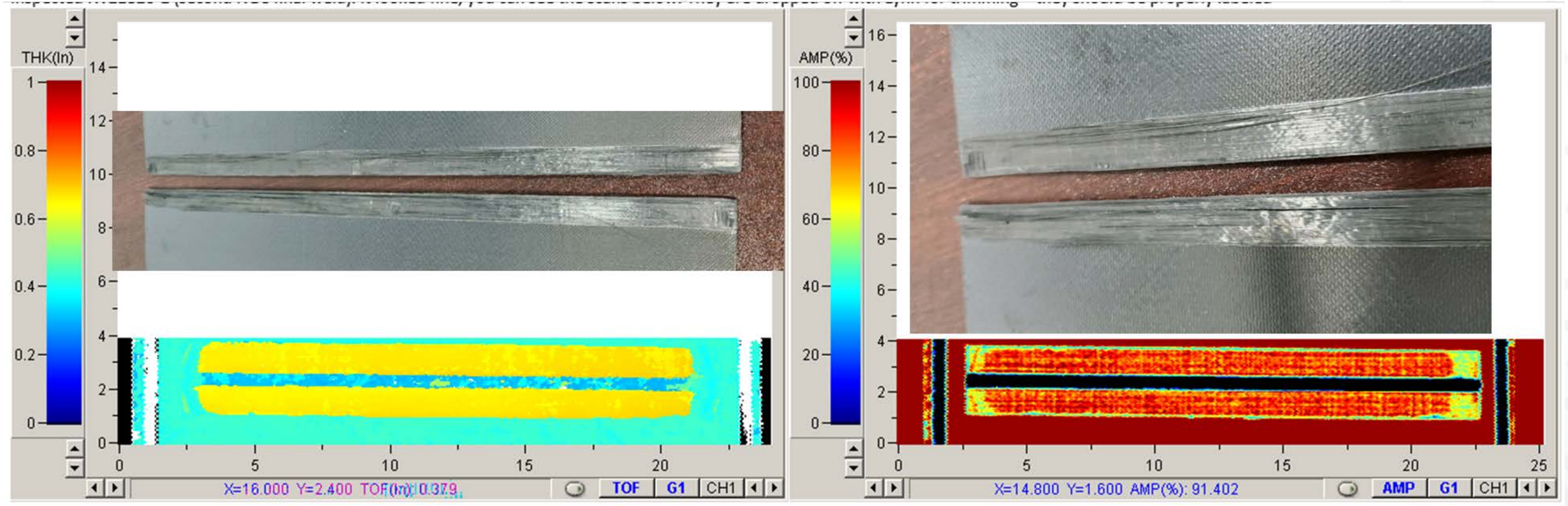
Weld Rate: 6.35 mm/s

<10% Reduction in LSS vs. Baseline

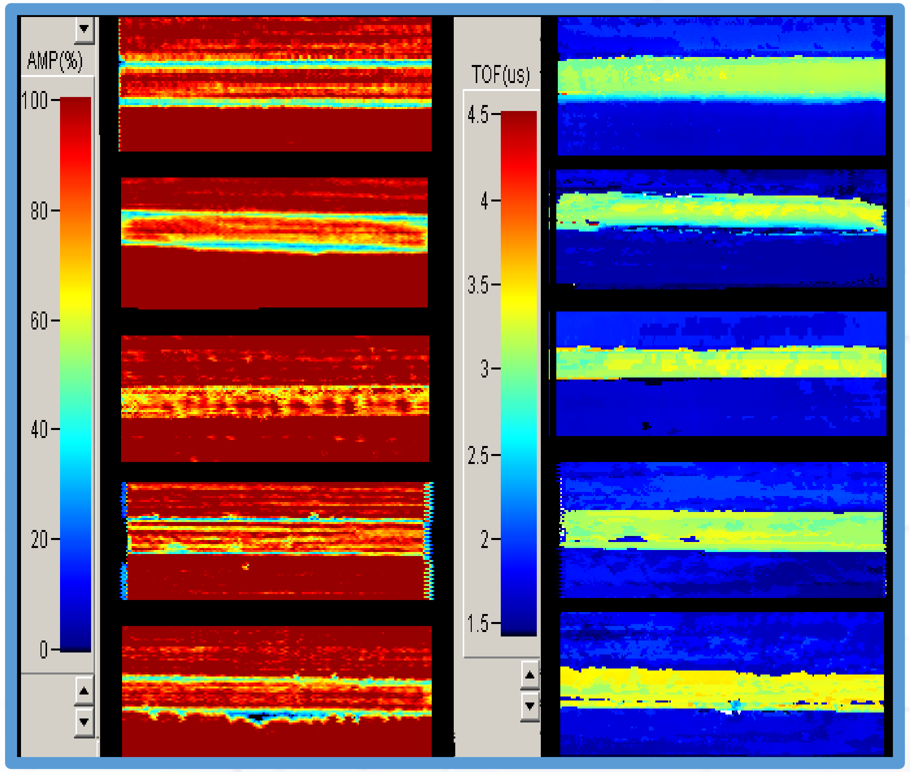
Do not see major knockdown at temperatures > 371 °C.
All specimens had low crystallinity.

UT Inspection & Destructive Analysis

Edge to edge welding & joint exhibits fiber breakage at weld interface



Weld Rate Process Parameters



Baseline

0.05 in/s

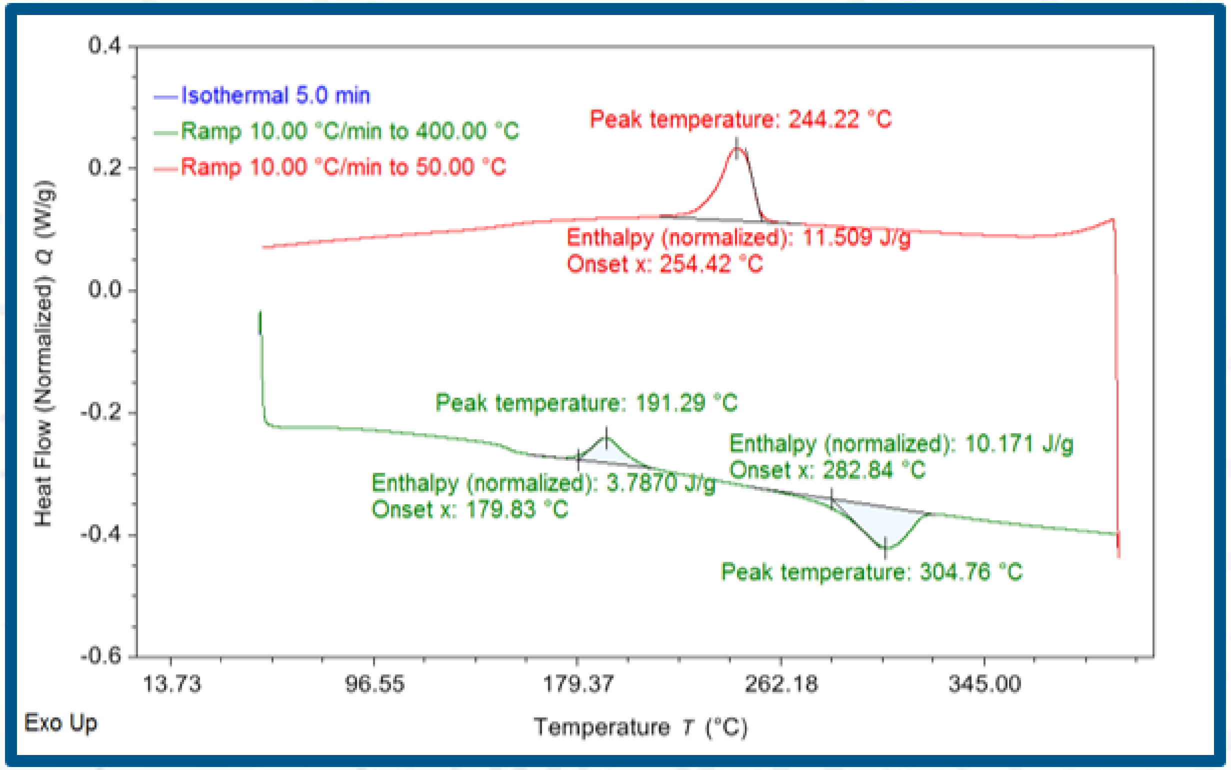
0.1 in/s

0.25 in/s

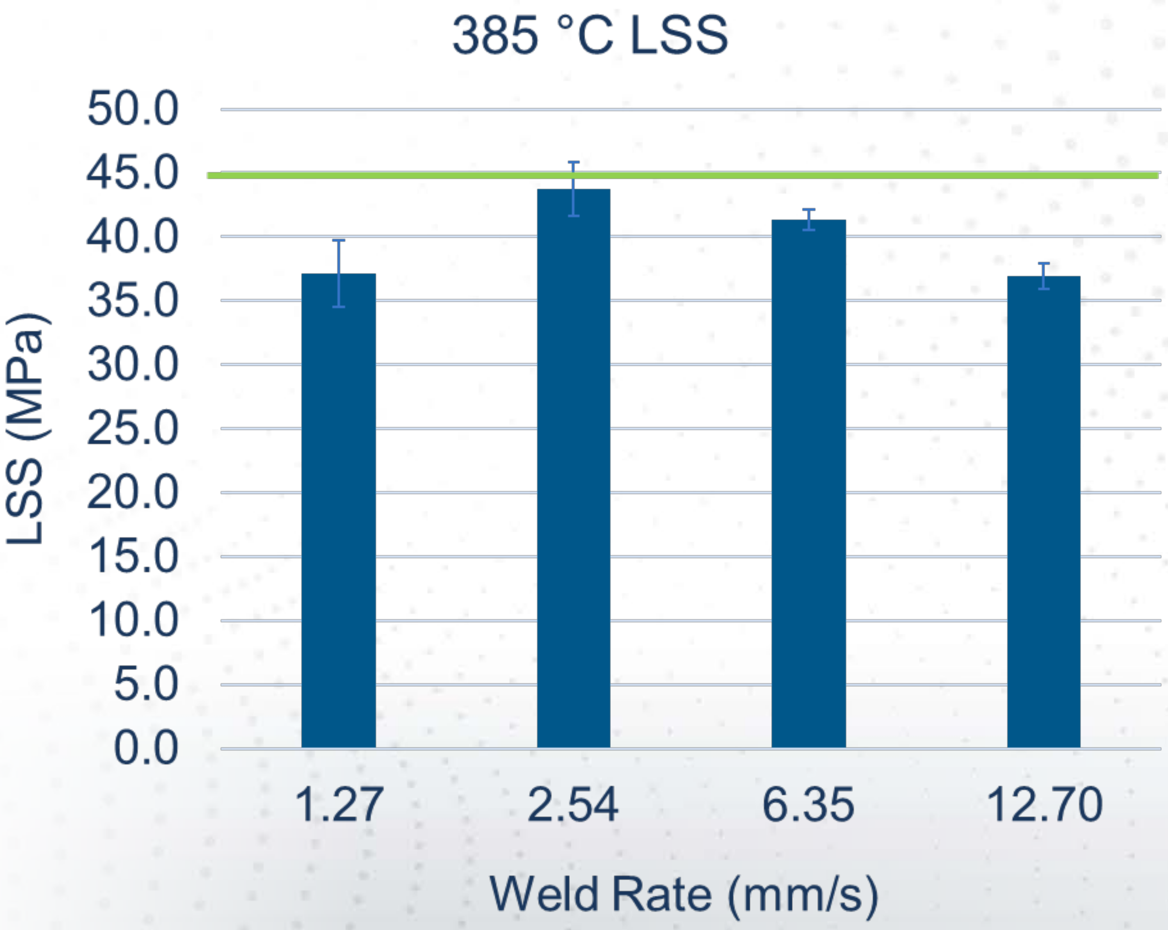
0.5 in./s

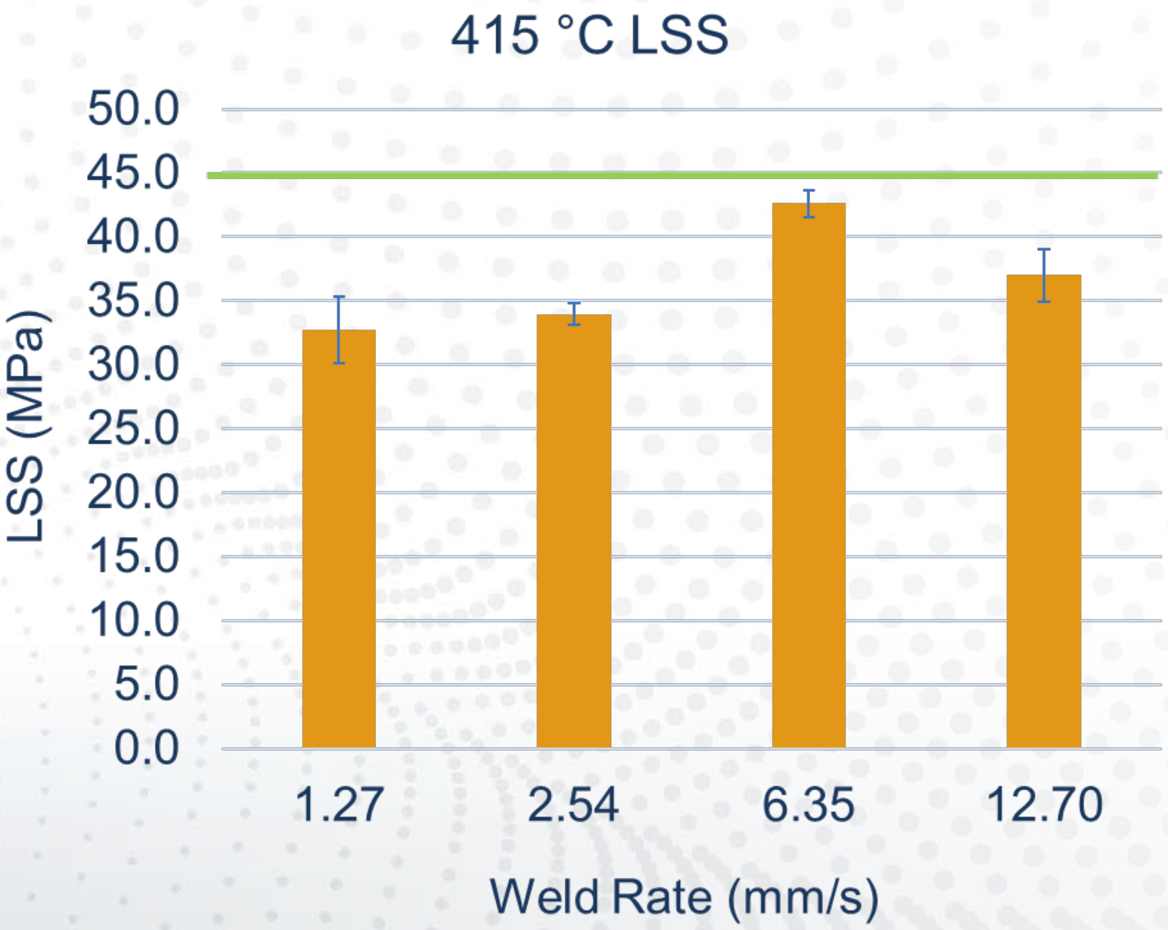
Amplitude (%)   Time of Flight

Ultrasonic Inspection

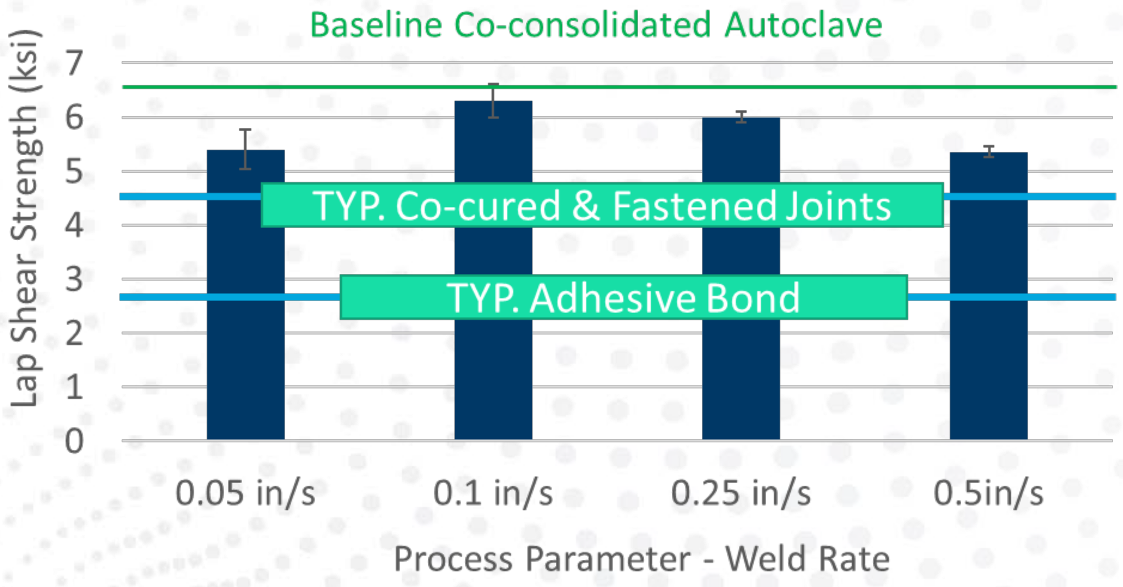


Weld Rate Comparison



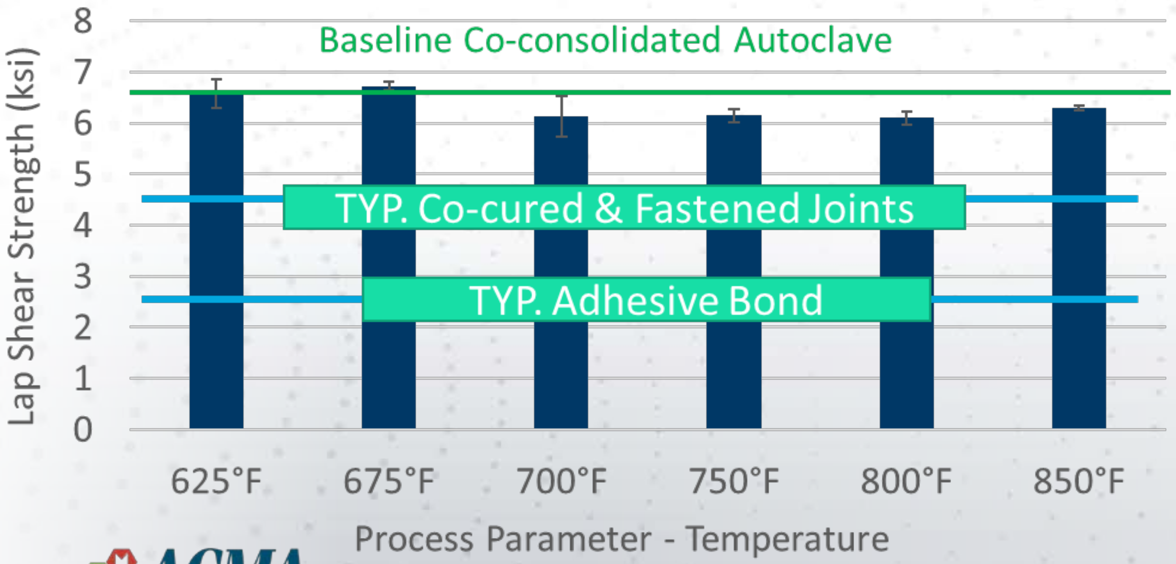


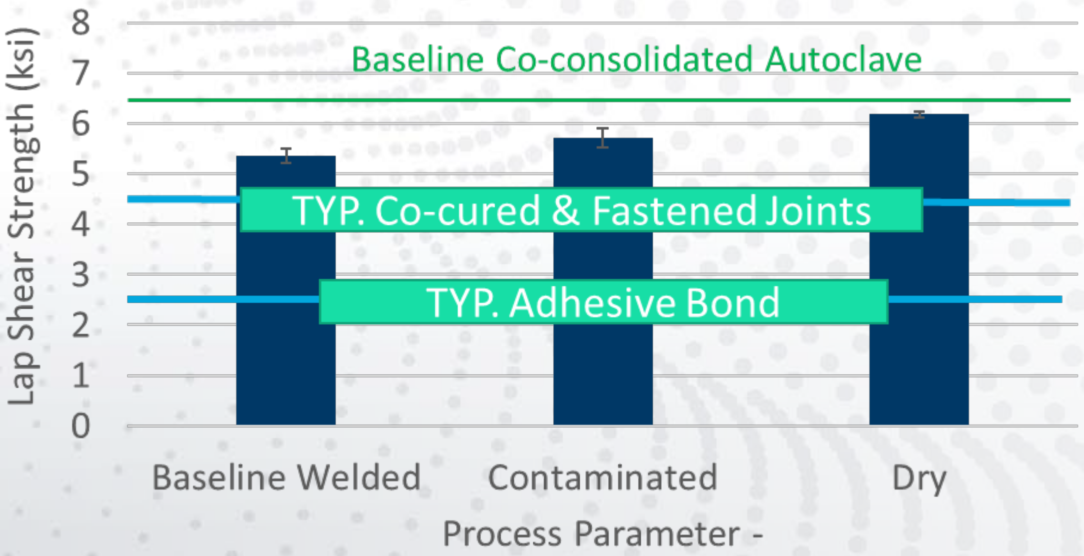
Parameter - Evaluations



<10% Reduction in joint strength compared to vs. Baseline pristine autoclave consolidation.

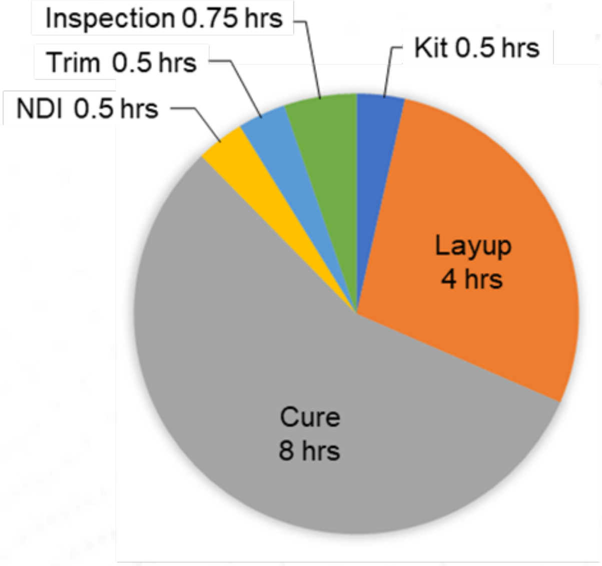
Qarbon welding joint strength exceeds thermoset co-cured autoclave strength





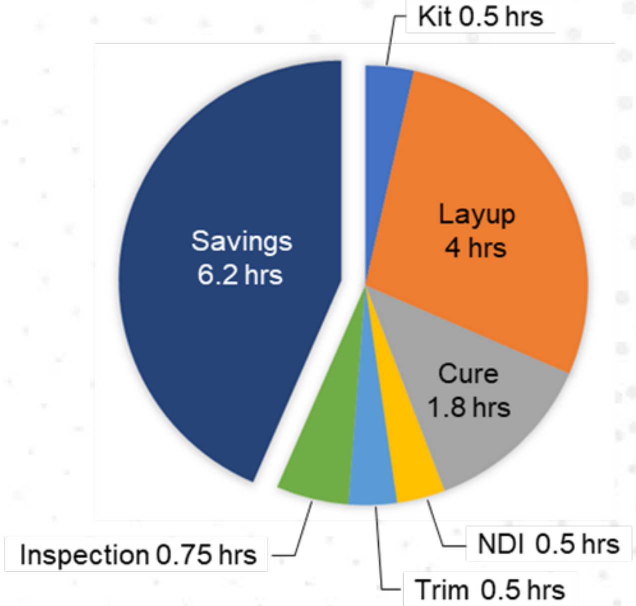
Thermoplastic savings – Manufacturing sanity check

Autoclave Thermoset Process



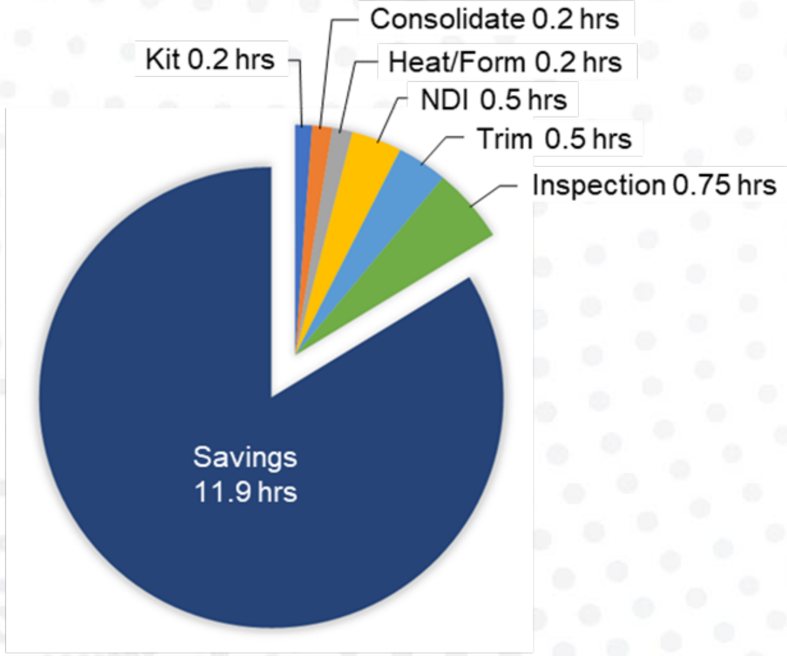
Total Process: 14.25 hrs.

Out-Of-Autoclave Thermoset Process



Total Process: 8.05 hrs.

Thermoplastic Process



Total Process: 2.32 hrs.

THERMOPLASTIC MANUFACTURING COST SAVINGS OUTWEIGHTS PARTIAL AUTOMATION IN THERMOSET

THERMOPLASTIC SAVINGS - PRODUCTION OF 2,500 ANNUAL SHIP SETS

(10 SS PER DAY!)

- 39% reduction in manufacturing floor space
- 87% reduction in detail part tooling
- 64% reduction in manufacturing labor
- Increased repeatability (reduced defects)

TS T1 = 2,298 labor hours

TS T1000 = 622 labor hours

Out of autoclave materials doesn't save significant time

RECURRING LABOR SAVINGS IN THERMOPLATICS

TP T1 = 817 labor hours

TP T1000 = 241 labor hours

Out of autoclave materials doesn't save significant time

Tooling *Non-recurring*

- TS = 860 detail part layup tools, 16 1st stage assembly jig, 28 2nd stage assembly jig
- TP = 96 press molds, 10 sub-assembly jigs, 14 final assembly jigs

Factory *Non-recurring*

- TS = 499K sq foot manufacturing facility
- TP = 309K sq foot manufacturing facility

Capex *Non-recurring*

- TS = 85 pieces of major equipment to meet rate requirements
- TP = 60 pieces of major equipment to meet rate requirements

Capex

- TS = $142M
- TP = $88M

Savings = ($54M)

RE Labor

- TS = $169M
- TP = $65M

Savings = ($104M)

Factory

- TS = $87M
- TP = $50M

Savings =($37M)

Tooling

- TS = $42M
- TP = $10M

Savings =($32M)

NRE Reduction = $123M   RE reduction = $104M/Year

Induction Welding “ENABLING” New Aerostructure

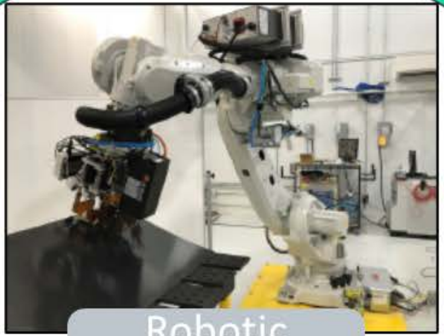
- Fusion joining of structure
  - Removes fasteners from assembly
  - Manufacturing cost reduction
  - Joint strength exceeds common methods
  - Weight savings opportunity
- World beating capability
  - Dis-similar thickness joint
  - One side only access
  - Reduced tooling requirements
  - Scalable for primary structure

Ready for platform specific requirements

Patented technology that is proven, repeatable, predictable and remarkable

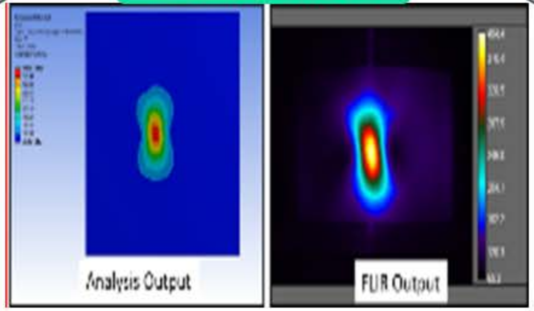
World Record

Curved Structure



Robotic Automation

Predictable



Questions - ?

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QARBON AEROSPACE

Thermoplastic Composites Conference

Bonding and Joining Panel Session

Mario Valverde

Bristol Composites Institute, University of Bristol

Overview

- What challenges are we facing in bonding?
- What can we do?
- Understanding the bonding process
- An overmoulded ribbed plate case study

What challenges are we facing in bonding?

- How do we deploy these parts and technologies into industry?
  - Certification requirements
  - Is there confidence in the technology?
  - History of thermoplastics is short (but growing!), Fig. 1.
- How do we accurately evaluate the bond quality?
  - Which methods are appropriate?
  - What metrics do we use?
    - Benchmark?
  - We cannot see the created interface during processing
    - Novel techniques to visualize the joining process, Fig. 2.

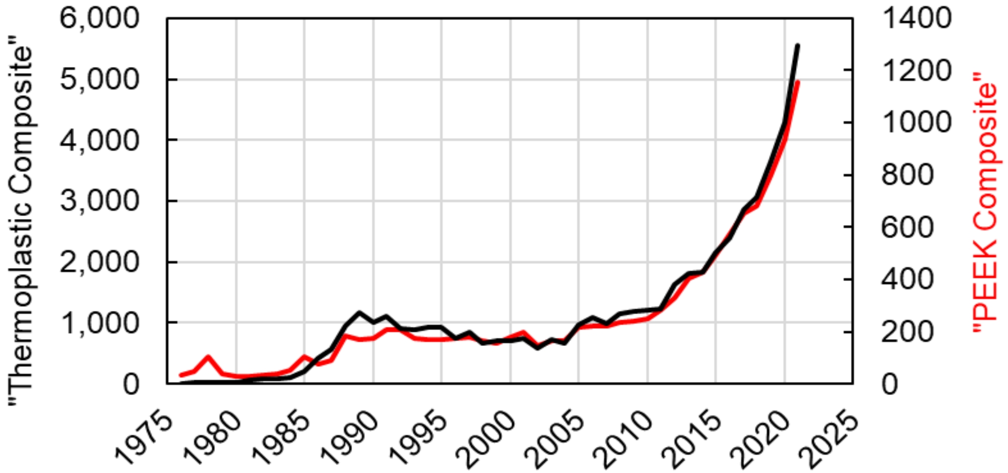

Fig.1: Annual publications on “thermoplastic composites” and “PEEK composites”.

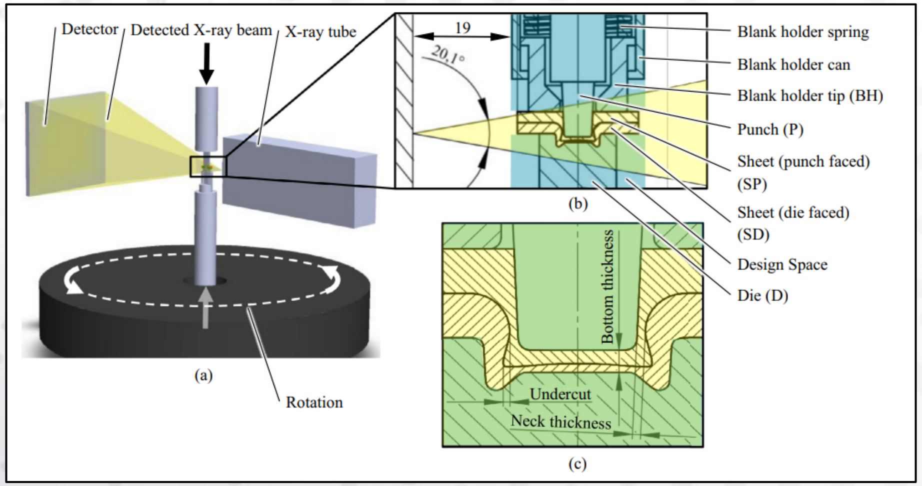

Fig.2: Schematic test set-up for in-situ CT of a clinch joint [1].

What can we do?

- Encourage R&D projects with a variety of stakeholders
  - Suppliers, tooling, manufacturer, end-user, academia…
  - This fosters knowledge transfer
  - Risk mitigation can be addressed early on in project
- Development of simulation techniques to support experimental campaigns and Industry 4.0 trends
- Modular lab-scale equipment, Fig. 3.
  - Simple to integrate and operate
  - Allows for large-scale data capture
  - Cost-effective

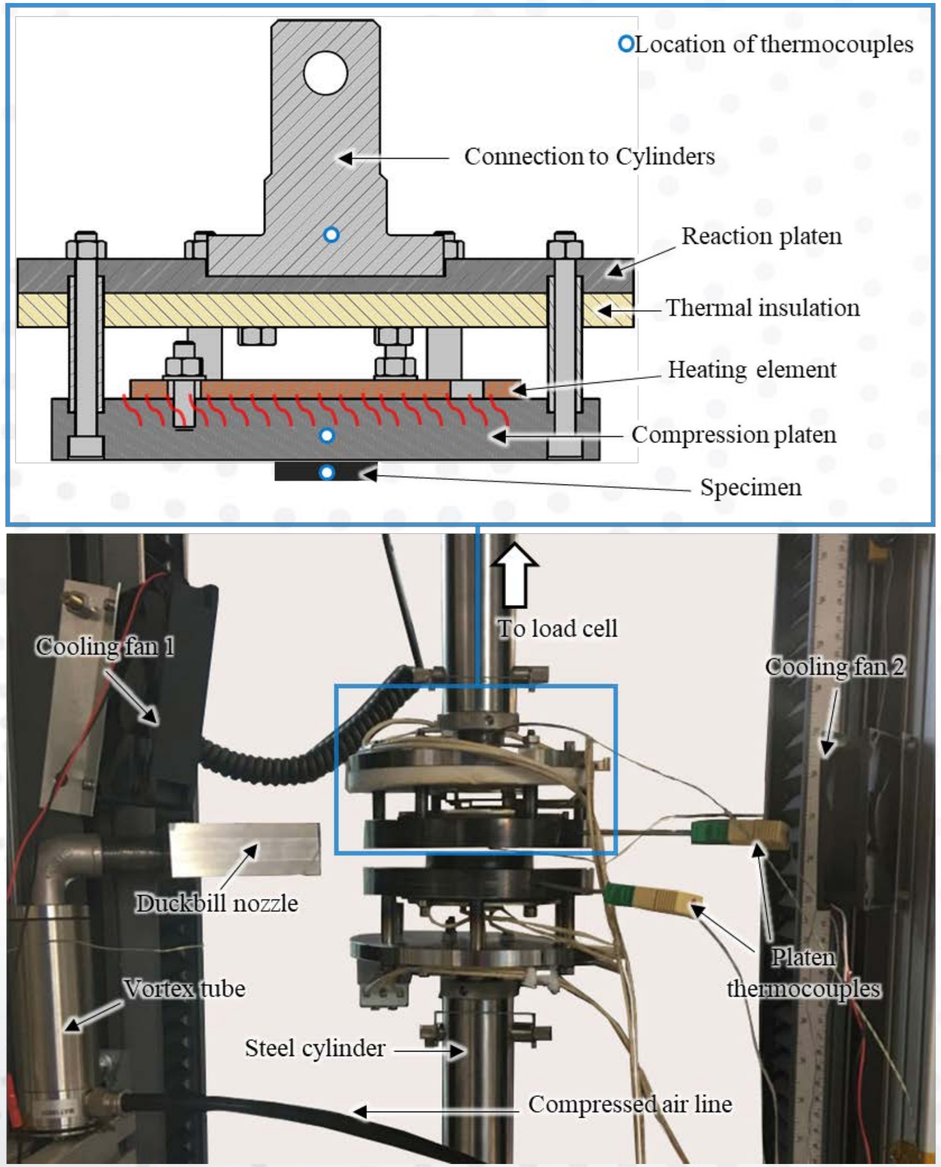

Fig. 3: Compaction test rig in universal test machine [2].

Understanding the bonding process

- What is (fusion) bonding?
  - Heat
  - Pressure
- Processing window is driven by the manufacturing technique, some examples include:
  - Automated fibre placement
  - 3D printing
  - Overmoulding, Fig. 4.
  - Many more…
- Application >> part design >> manufacturing

Fig. 4: Overmoulded component examples [3].

An overmoulded ribbed plate case study
– why it is important to understand the process

- How can we optimise the bonding of the overmoulded interface?
  - Increased pre-heating temperatures improves the bond strength, Fig. 5.
  - Also causes localised deformations, which can affect:
    - Component processability, Fig. 6.
    - Rib pull-off load, Fig. 7.
    - Overall structural performance

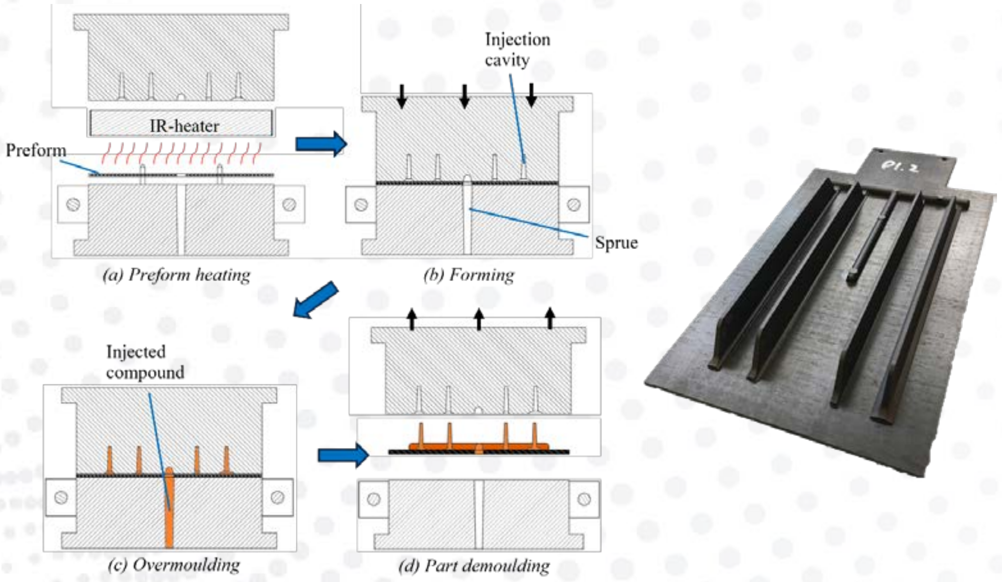

Fig. 5: Diagrams of key stages during the overmoulding cycle, showing final manufactured CF/PPS ribbed plate [4].

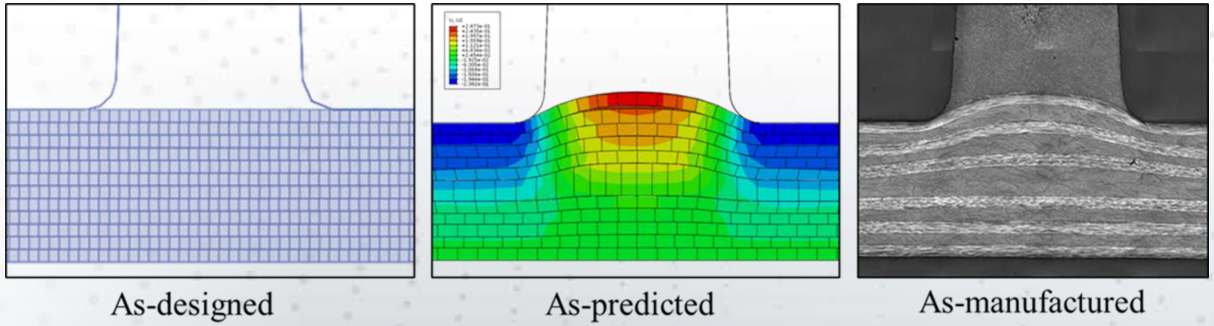

Fig. 6: As-designed, as-predicted, and as-manufactured overmoulded interface of a ribbed plate specimen [4].

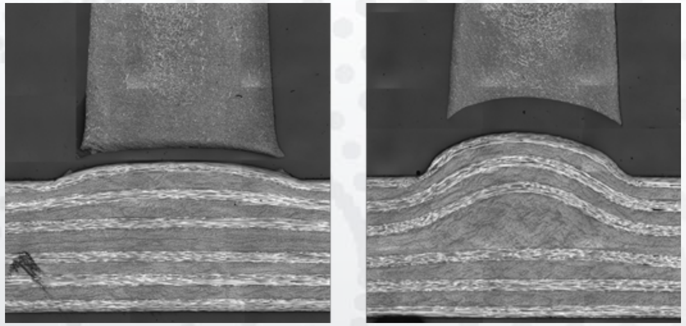

Fig. 7: Ribbed plate section micrographs showing different failure types (due to deformations) for each specimen [4].

References

1. Köhler, D., Kupfer, R., & Gude, M. (2020). *Journal of Advanced Joining Processes Clinching in in-situ CT — A numerical study on suitable tool materials*. *2*(October). https://doi.org/10.1016/j.jajp.2020.100034
2. Valverde, M. A., Belnoue, J. P., Kupfer, R., Kawashita, L. F., Gude, M., & Hallett, S. R. (2021). Compaction behaviour of continuous fibre-reinforced thermoplastic composites under rapid processing conditions. *Composites Part A*, *149*(June), 106549. https://doi.org/10.1016/j.compositesa.2021.106549
3. Valverde, M. A., Kupfer, R., Kawashita, L. F., Gude, M., & Hallett, S. R. *NCC Discover: Composites Overmoulding Conference*, Bristol, 2019, Conf. Slides
4. Valverde, M. A., Belnoue, J. P., Kupfer, R., Kawashita, L. F., Gude, M., & Hallett, S. R. *24th International Dresden Lightweight Construction Symposium,* June 2021, Conf. Slides