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IN-SITU CONSOLIDATION AUTOMATED FIBER PLACEMENT OF THERMOPLASTIC COMPOSITES FOR HIGH-RATE AIRCRAFT MANUFACTURING

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High-Rate Composites for Aircraft Manufacturing (HiCAM)

- NASA HiCAM Project in partnership with the Advanced Composites Consortium (ACC) is investing in composites primary structure manufacturing development to address U.S. industry needs:

Boeing & Airbus market outlook for single-aisle aircraft:

- By 2040, >43,000 deliveries
- Replace 80% current & double fleet size
- Single-aisle, 2nd decade demand ~150 per month

Historic aircraft production rates per month:

Metals (B737, A320) :	60	1.3x = 80
Composites (B787, A350) :	10-14	6x = 80

Increased Emphasis on Sustainability:

- Reduced emissions (weight, drag)
- Reduced operating costs (fuel, acquisition, maintenance)

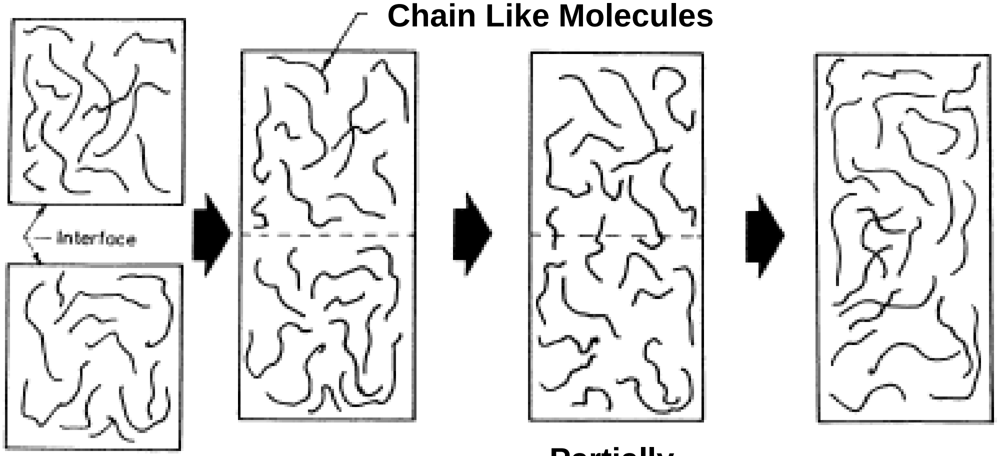
Market drivers: earlier deliveries (high production rate), cost reductions & performance improvements.

Thermoplastic Composites Processing

- Polyaryletherketone thermoplastic matrix composites offer comparable or better performance as an aerospace composite material to conventional thermosets (epoxies):
  - Glass transition temperatiure, Tg ≥ 130 °C
  - Shorter processing times (no crosslinking “cure” cycle)
  - No out-time limitation (no freezer storage required)
  - High solvent resistance

HiCAM is currently investigating aircraft manufacturing through forming, assembly, and automated fiber placement (AFP) of carbon fiber (CF) reinforced polyetheretherketone (PEEK), polyetherketoneketone (PEKK), and low-melt polyaryletherketone (LM-PAEK) thermoplastic polymers.

Thermoplastics Polymer Autohesion



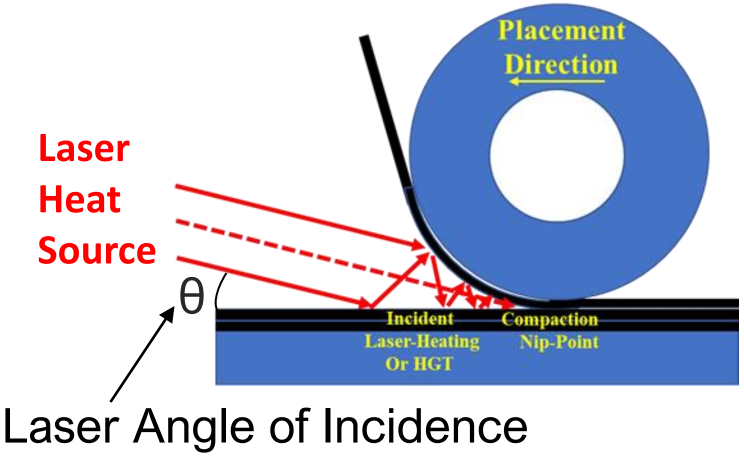
Thermoplastic Fusion-Bonding (Autohesion) Phenomenon[1]

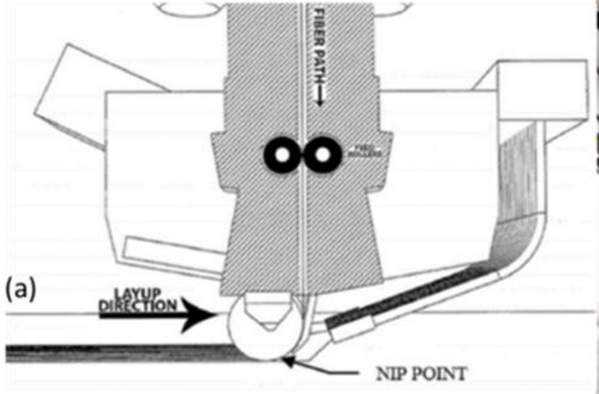
- **Regardless of process, strength development in thermoplastics occurs due to autohesion, or reptation (diffusion), of the polymer molecule across the inter-ply boundary**
  - The interfacial bond strength is a function of the processing temperature, contact pressure, and contact time.
  - Above the crystalline melt temperature, interfacial bond strength increases with time due to interdiffusion (reptation) of mobile molecular chain ends across the interface. [Review: de Gennes (1971), Tierney and Gillespie(2006)]
  - After intimate contact is established, interpenetration and re-entanglement of the polymer molecule(s) occurs and ultimate cohesive strength is achieved, the time required is dependent on the polymer molecular weight and crystallinity.

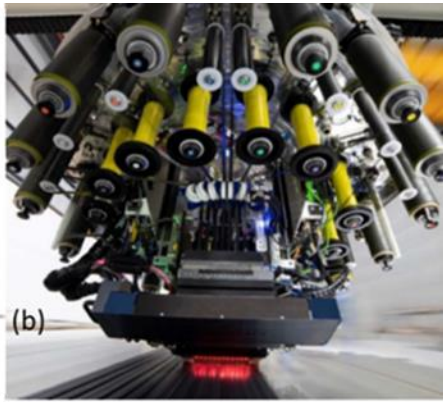
[1]Image Reference: A.C. Loos and P.H. Dara: “PROCESSING OF THERMOPLASTIC MATRIX COMPOSITES.” NASA/Contractor Report–NASA Grant NAG1-343; DOI: 10.1007/978-1-4613-1893-4_143

In-situ Consolidation AFP of Thermoplastics (ICAT)

- **ICAT is an automated composite fabrication process where ply cohesion can be achieved in-situ during AFP of the CF/thermoplastic tape on rigid tooling.**
  - ICAT process tape heating via the Electroimpact Variable Spot Size - High Power (VSS-HP) laser heating system mounted on a 16-tow, 6 - degree of freedom (DoF) AFP head.
    - Four individually controlled 0.64 cm (0.25 in) wide round (elliptical) spots.
    - Lasers were focused on the substrate tape at an incident angle. $\theta \approx 16°$.
    - Power capability up to 63,000 m*kg/s^3 (1600 watts/in.), or 400 J/s (watts) per each 0.64 cm wide slit-tape.
    - Placed 2.54 cm wide courses at tape temperatures up to 500 °C and speeds up to 400 mm/s on a flat, heated tool.
    - Tape temperature at the nip-point is measured by a FLIR camera mounted on the placement head.
    - Compaction load of 1.1 kN (250 lbf) was utilized for all panels placed and applied via the AFP machine high-temperature capable, flexible nip roller.

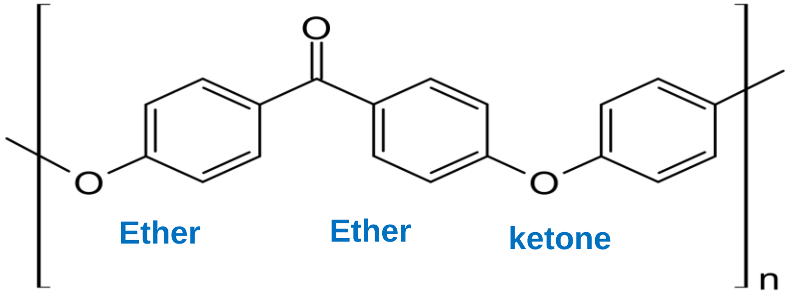




(b)


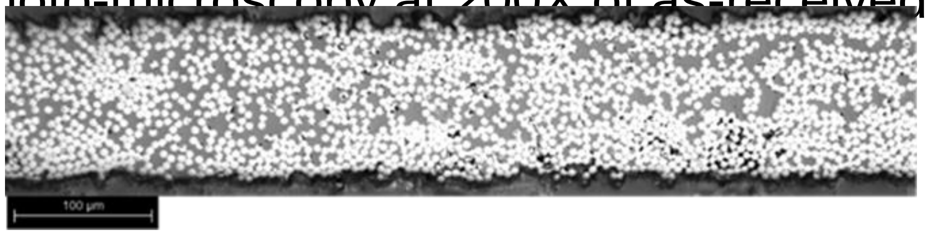
Note: All images in this slide were created/ photographed by the NASA and Electroimpact co-authors of this work.

CF/Polyaryletherketone slit-tape Materials



PEEK Polymer Molecule Repeating unit Chemical Structure[2]

- The 0.64 cm (0.25 in) wide slit-tape carbon fiber (CF)/ Polyaryletherketone semi-crystalline thermoplastic materials studied were:
  - PEEK: Toray TC1200® with T800GC®-24K CF; tape fiber areal weight (FAW) = 145 g/m^2, resin content (RC) = 34 wt.%.
  - LM-PAEK: Victrex IM7/AE250® with IM7-12K CF; FAW = 148 g/m^2; RC = 34 wt.%. According to Victrex the LM-PAEK (AE-250) polymer molecule chemical structure is similar to PEEK, but currently proprietary.
- Photo-microscopy at 200X of as-received slit-tape:



Toray TC1200® T800/PEEK

Victrex LM-PAEK IM7/AE250®

[2]Image Reference: S. Najeeb and J.P. Matinlinna: "Nanomodified Peek Dental Implants: Bioactive Composites and Surface Modification—A Review," International Journal of Dentistry; September 2015; DOI: 10.1155/2015/381759

Material Characterization Snapshot

In support of the ICAT process assessment, material characterization is ongoing to understand the relationship between process and material behavior:

- % volume (Vol) crystallinity by differential scanning calorimetry (DSC)
- Complex Viscosity by parallel plate rheology
- Polymer decomposition by thermal gravimetric analysis (TGA); isothermal in Air
- In table below T_M = melt temperature and Tg = glass transition temperature

Supplied Tape	Avg. Tg (°C)	Avg. T_M (°C)	Quasi-Equilibrium Vol Crystallinity (%)	Incoming Tape Vol Crystallinity (%)	Resin Complex Viscosity at 450 °C (Pa*s)	Decomposition Time to reach 0.5% mass loss at 500 °C (s)
PEEK TC-1200®	139	343	37.4	19.3	124.0	210.0
LM-PAEK IM7/AE250®	146	306	21.6	8.28	131.0	223.0

Dictates minimum ICAT processing temperature

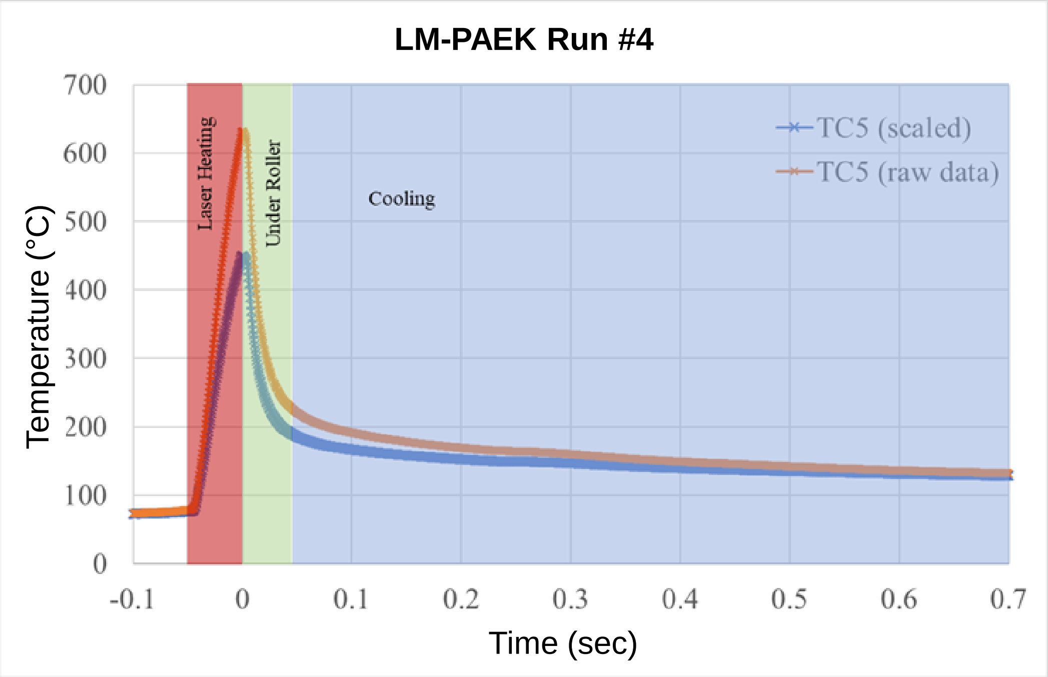
Dictates maximum ICAT processing temperature

ICAT Process Screening Experiment

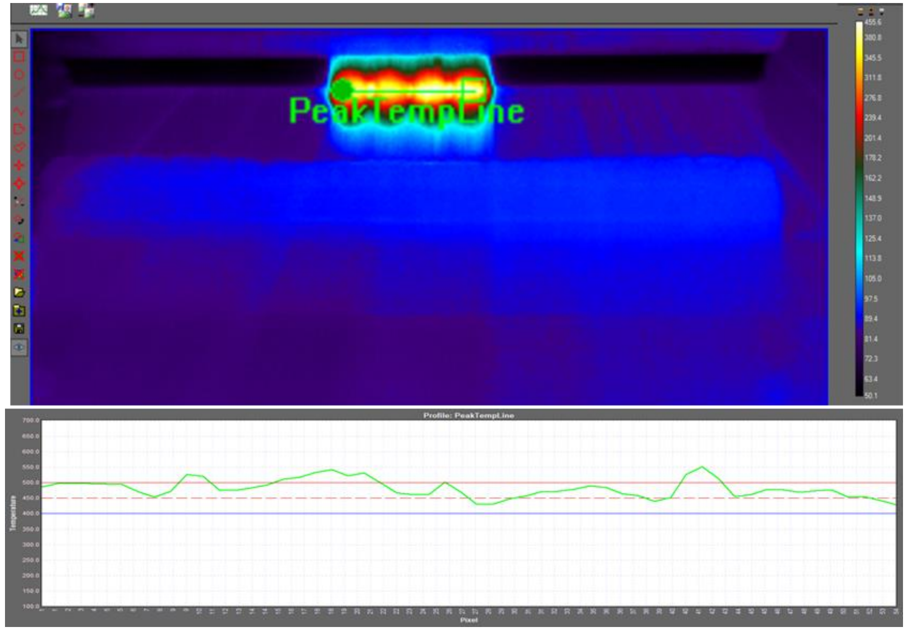
- **To better understand the ICAT process a screening design of experiment (DoE), varying process laser temperature, placement speed, and tool temperature, was run at Electroimpact using the new VSS-HP laser heating system, placing Toray TC1200®(PEEK) and Victrex AE250®/IM7 (LM-PAEK) 0.64 cm wide slit-tape:**
  - Thirteen "screening" panels were fabricated; 15 cm x 10 cm, six plies thick [0°/0°/+45°/-45°/0°/0°]
  - Temperature measured by a forward looking infrared (FLIR) camera focused on the substrate and incoming tape just ahead of the compaction roller and thermocouples welded to the surface of the 0° substrate plies #1 and #5.

Slit-tape Material	Supplier Reported T_M (°C)	2% Mass Loss Decomp Temperature (°C)	Supplier Reported Tg (°C)	Trial #	Tape Target Temp (°C)	Compaction Load (kN)	Tool Temp (°C)	Placement Speed (mm/sec)
PEEK (Toray TC1200®)	335	575	143	1	400	1.1	120	250
				2	450	1.1	120	250
				3	500	1.1	120	250
				4	500	1.1	80	250
				5	500	1.1	120	400
				6	500	1.1	120	100
				7	400	1.1	80	170
LM-PAEK (VICTREX IM7/AE-250®)	305	557	147	1	400	1.1	120	250
				2	450	1.1	120	250
				3	450	1.1	80	250
				4	450	1.1	80	400
				5	450	1.1	80	100
				6	350	1.1	80	170

ICAT Laser Heating Cycle



Temperature cycle during ICAT of LM-PAEK at tape temperature of 450°C, Speed of 100 mm/s and tool temperature of 80°C



Example FLIR Temperature measurement at the the Nip-Point during ICAT of LM-PAEK using four round VSS-HP laser spots

- Temperature data from thermocouples (TCs) and data acquisition system collecting data at 2000 samples/s/channel.
- The red curve “raw data” indicates an issue when using TCs to measure the temperature of the tape surface. When the laser is incident on the TC bead, it overshoots the surrounding material.
- To account for this, the maximum temperature of the tape was collected using FLIR data at the start of the nip-point and the thermocouple time-trace was then compensated to the appropriate peak temperature based on the FLIR measurement. A linear scaling function was used for both the heating and cooling phases.
- At the high-speed (400 mm/s) ICAT processing condition, the tape surface polymer is above the melt temperature for only 0.05 sec.

Results of ICAT Screening Experiment: PEEK

ICAT process Screening Experiment at Electroimpact varying Laser Target Temperature (LT), Tool Temperature (TT) and Placement Speed (V) for the 0.64 cm (0.25 in.) wide CF/PEEK slit-tape material:

LT = 400°C, TT = 80 °C, V = 170 mm/s (402 in/min)

LT = 450°C, TT = 120°C, V = 250 mm/s (591 in/min)

LT = 500°C, TT = 120 °C, V = 400 mm/s (945 in/min)

LT = 400°C, TT = 120 °C, V = 250 mm/s (591 in/min)

LT = 500°C, TT = 80 °C, V = 250 mm/s (591 in/min)

LT = 500°C, TT=120°C, V = 100mm/s (236 in/min)

Poor Intimate Contact
(red arrows)

ICAT Process Recipe Selected
for the PEEK short beam strength (SBS) test panel fabrication

Results ICAT Screening Experiment: LM-PAEK

LT = 350°C, TT = 80°C, V = 170 mm/s (402 in/min)

Poor Contact (red arrow)

LT = 450°C, TT = 120°C, V = 250 mm/s (591 in/min)

LT = 400 °C, TT = 120°C, V = 250 mm/s (591 in/min)

LT = 450°C, TT = 80°C, V = 250 mm/s (591 in/min)

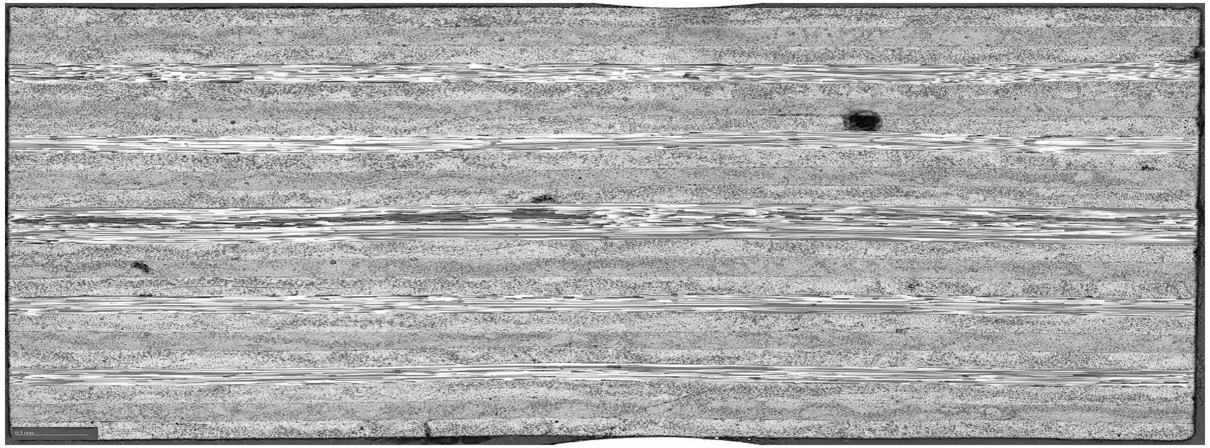
ICAT Process Recipe Selected for SBS test panel fabrication

LT = 450°C, TT = 80°C, V = 400 mm/s (945 in/min)

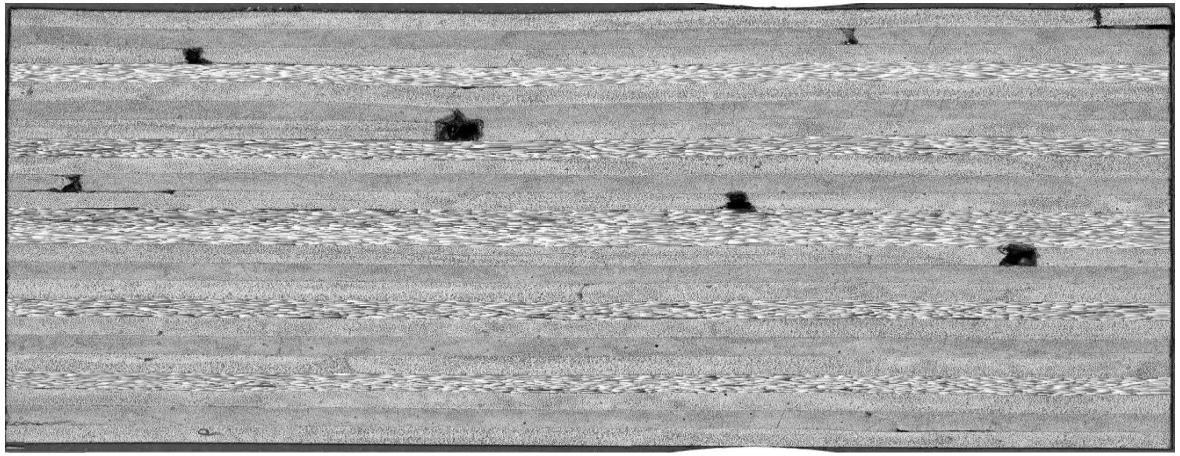
ICAT Short Beam Strength (SBS) Test Panels

Using the ICAT process parameters identified in the screening experiments, one PEEK panel and one LM-PAEK panel were fabricated with quasi- lay-up: $[45°/0°/-45°/90°]_{3S.}$ After ICAT processing, each resulting panel was cut into three sections using a wet-saw resulting in:

- **PEEK and LM-PAEK "ICAT panels"**
- **PEEK and LM-PAEK "ICAT + vacuum-bag oven (VBO) post-consolidation panels"**
- **PEEK and LM-PAEK "ICAT + autoclave post-consolidation panels"**



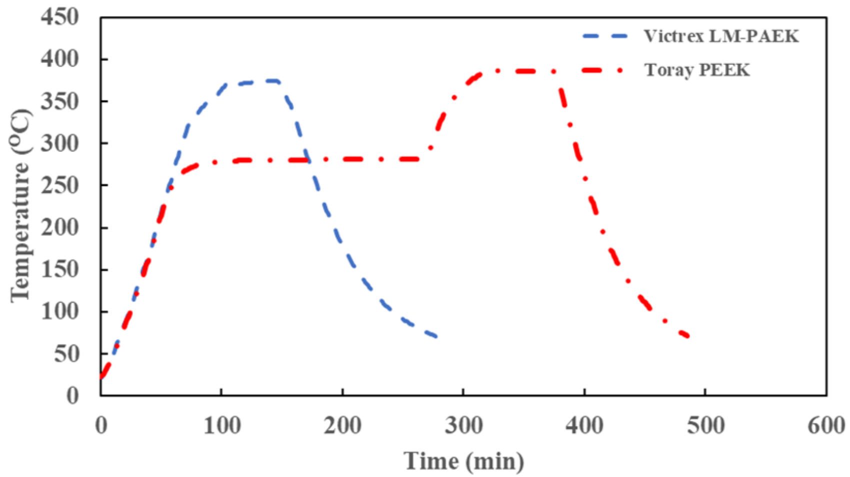
ICAT Fabricated PEEK Panel



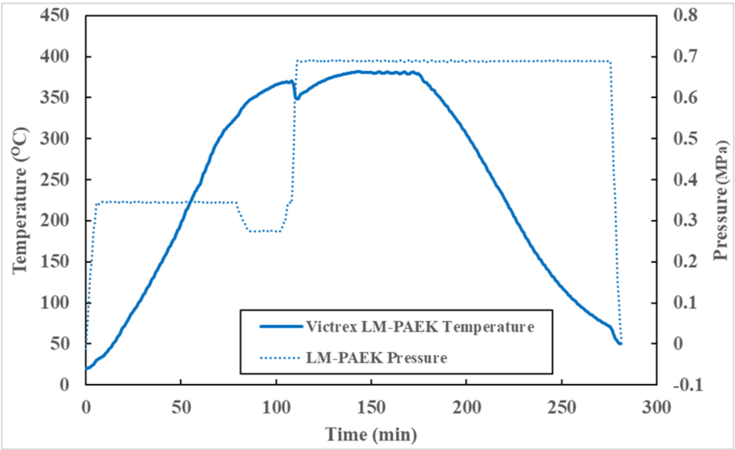
ICAT Fabricated LM-PAEK Panel

Panel Post-Processing Cycles

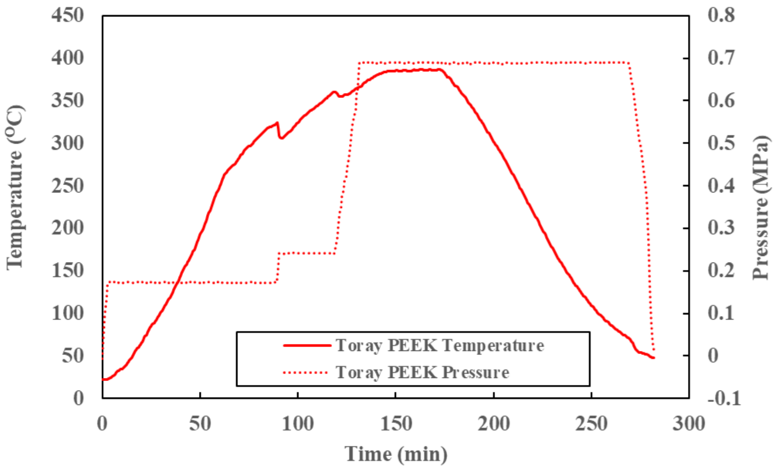
The VBO and Autoclave post-consolidation cycles used were recommended by the materials suppliers Toray and Victrex:



Vacuum Bag Oven Cycles



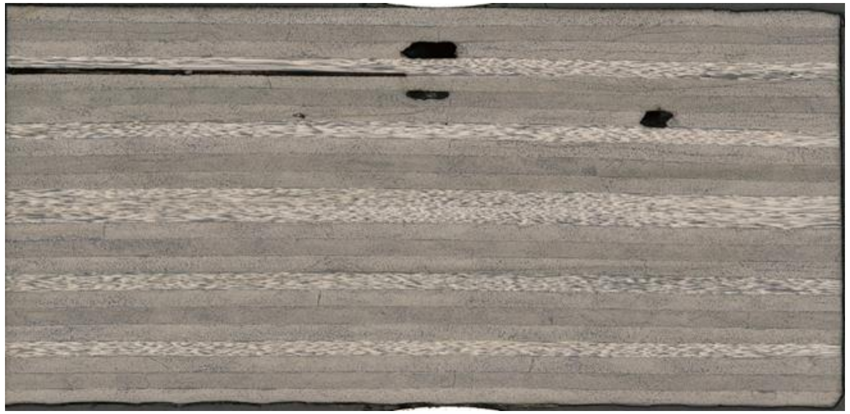
LM-PAEK Autoclave Cycle



PEEK Autoclave Cycle

Post-Processed Panel Photo-microscopy

PEEK ICAT + Oven post-consolidation



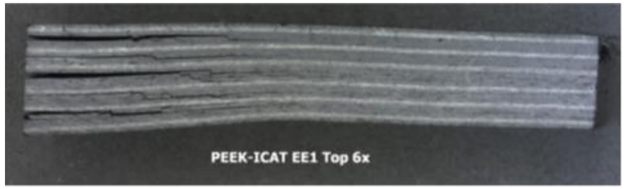
LM-PAEK ICAT + Oven post-consolidation

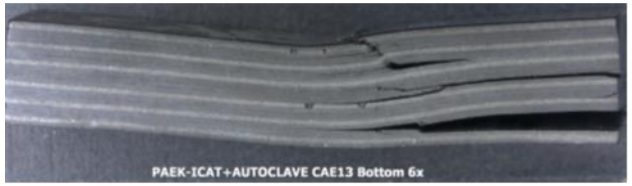
PEEK ICAT + Autoclave post-consolidation

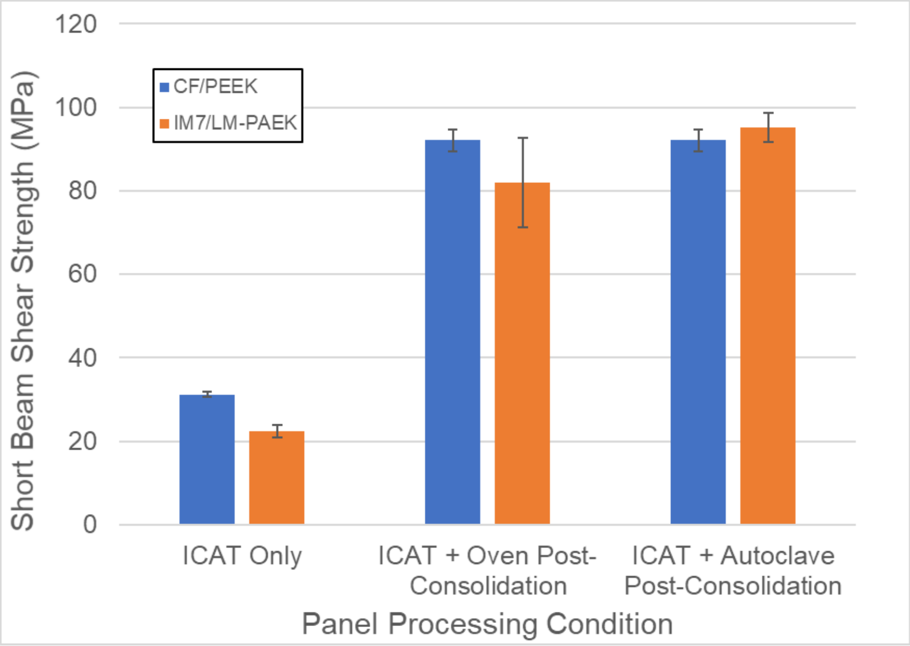
LM-PAEK ICAT + Autoclave post-consolidation

Short Beam Strength (Ambient) Testing Results

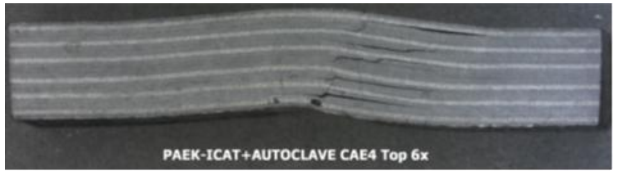
Valid ILS Failures

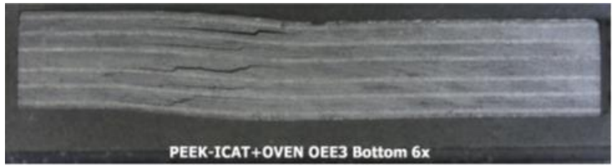






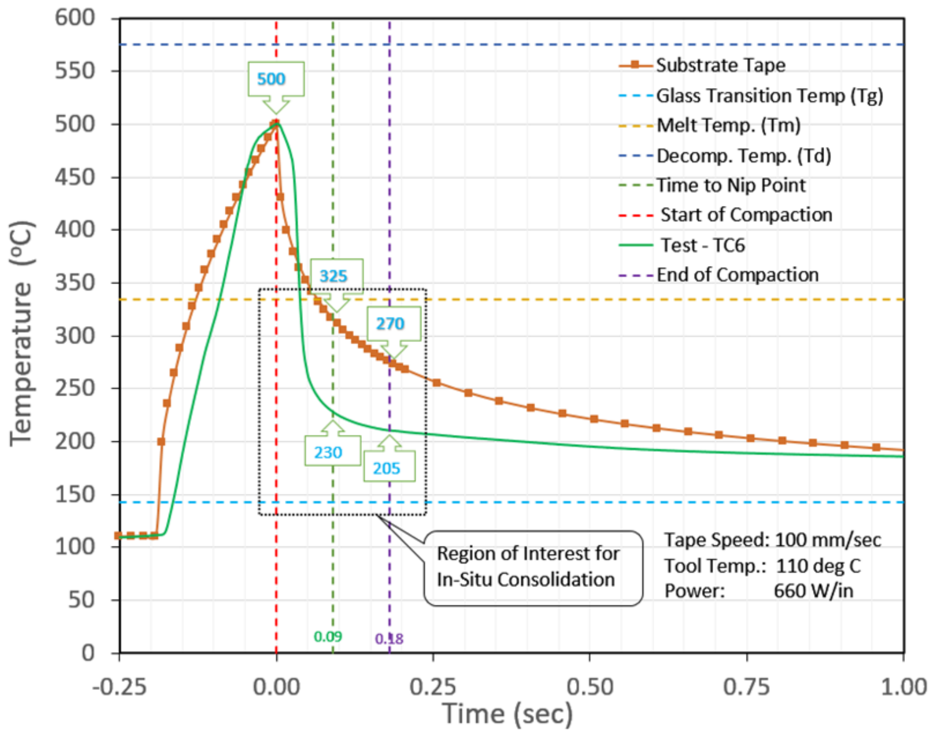
Invalid Failure Modes



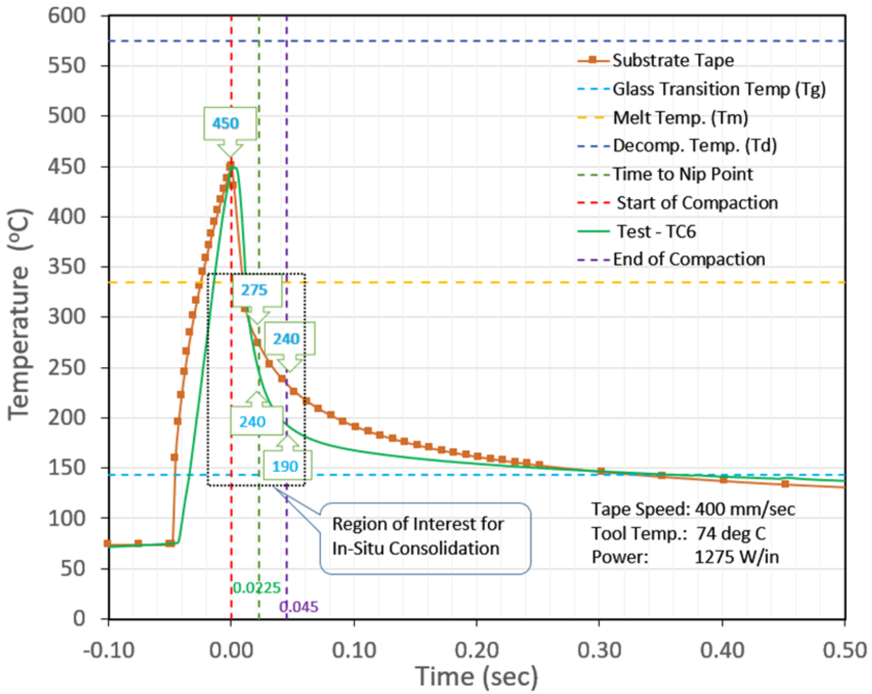


- The average values reported are calculated from five valid SBS failures, according to ASTM D2344. Images at 6X resolution of Valid Interlaminar Shear (ILS) failures and invalid Flex/Compression Failures are shown.
- The ICAT-only coupons failed with a short beam shear strength (SBSS) of only 30 % to 35 % of the autoclave post-consolidated panels, indicating that an insufficient degree of autohesion (reptation) is occurring during the ICAT process at the placement speeds used in this study.
- The CF/PEEK “ICAT + Autoclave post-consolidation” SBSS values are consistent with values found in the literature and comparable to the average value found for CF/LM-PAEK material post-consolidated in the autoclave.
- The equivalence of the CF/PEEK “ICAT + Oven Post Consolidation” to the Autoclave post-consolidation panels indicate that this material may be suitable for Out-of-Autoclave (OoA) processing.
- The low value of the CF/LM-PAEK “ICAT + oven post-consolidation” material is accompanied by a relatively high Coefficient of Variation (CoV) > 10 % in comparison to all the other coupon sets with CoVs < 5 %, indicating that more testing is required for this material and processing condition.

ICAT Thermal Modeling Closed-Form (1-D)



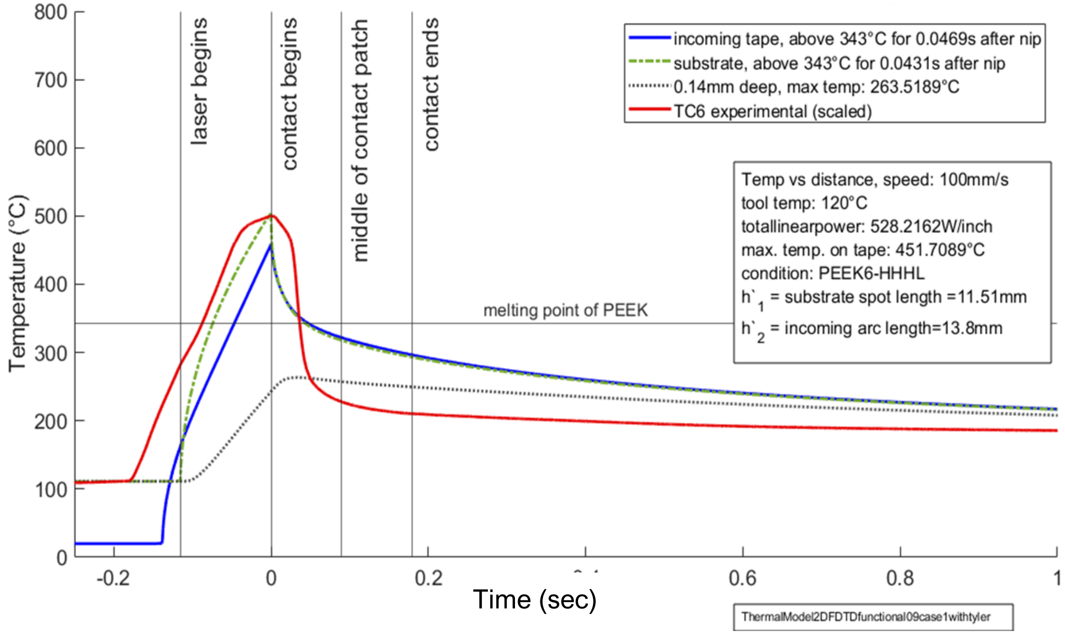
PEEK Test Panel Temperature Cycle:
LT = 500 °C, TT = 120 °C, and V = 100 mm/s



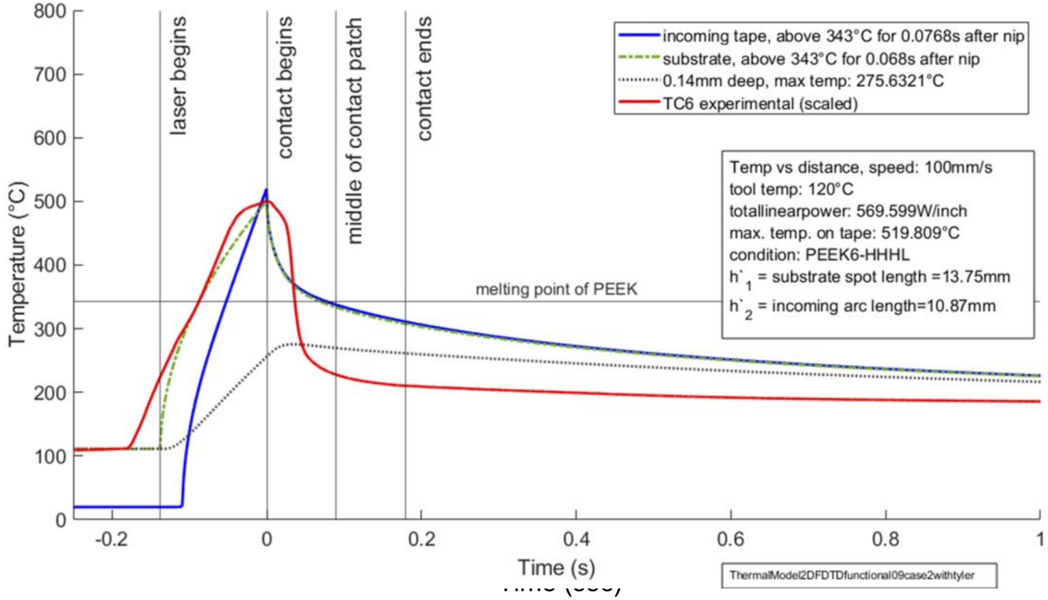
LM-PAEK Test Panel Temperature Cycle:
LT = 450 °C, TT = 80 °C, and V = 400 mm/s

- Using a 1-dimensional (1-D) semi-infinite solid closed-form numerical model (orange) the temperature trends and heat transfer are comparable to the experimental (green) for multiple processing cycles.
- This provides confidence in the temperature measuring methodology and provides a technique to conduct sensitivity analysis, varying process parameters by simulation, prior to screening panel fabrication.

ICAT Thermal Modeling: Finite Difference (2D)



PEEK Panel Thermal Cycle: LT = 500 °C, and V = 100 mm/s
Angle if Incidence = 16°



PEEK Panel Thermal Cycle: LT = 500 °C, and V = 100 mm/s
Angle if Incidence = 13°

- Using a 2-dimensional (2D) finite difference approximation model (green-dash) coded in MATLAB®, the temperature trends predicted are comparable to the experimental data (red) for the PEEK panel cycle. Here the effects of varying the laser angle of incidence (θ) is simulated; 16° in the plot on the left and 13° on the right.
- The two thermal models in development are part of an ongoing effort to develop physics-based models to simulate the ICAT and TP-AFP process with the goal of predicting the weld time at temperature needed to reach autoclave level mechanical properties.

Summary and Conclusions

- The Electroimpact VSS-HP laser heating system is capable of controlled heating of the surfaces of the substrate and incoming slit-tape up to 500°C at speeds up to 400 mm/s without reaching the maximum power limitation of each laser diode.
- The laser-assisted AFP process is demonstrated to establish intimate contact between the incoming and substrate tape plies for PEEK at a speed of 100 mm/s and for LM-PAEK at speeds up to 400 mm/s.
- Based on preliminary mechanical test data the placement speeds used in this ICAT process study do not provide enough time above melt temperature after intimate contact for sufficient autohesion to occur in the ICAT panels without some secondary post-consolidation step
- Future work includes conducting the same ICAT processing study using Hexcel PEKK tape as well as using slower placement speeds and decreasing the laser angle of incidence to increase the laser spot size, thereby increasing the time above T_M of the CF/thermoplastic tape surfaces as the developed thermal models predict.