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

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ABSTRACT

The National Aeronautics and Space Administration (NASA) initiated the Hi-Rate Composites Aircraft Manufacturing (HiCAM) project in 2021 with the goal of significantly increasing composite structures manufacturing rate in the commercial aircraft industry. The technologies currently under investigation include resin infusion and automated fiber placement (AFP) of novel thermoset materials and thermoplastic composites. Thermoplastic composites offer attractive solutions to rapid manufacturing due to their ability to be formed and consolidated quickly. NASA is particularly focused on assessing composite structure manufacturing utilizing an in-situ consolidation AFP of thermoplastics (ICAT) process employing a recently developed laser heating system. Two semi-crystalline polyaryletherketone thermoplastic tape materials were characterized to ascertain the ICAT process parameters at AFP placement speeds approaching 423 mm/s. The required laser power settings were determined at Electroimpact, measuring material temperatures utilizing a forward looking infrared (FLIR) thermal imaging camera and thermocouples. The material temperature, tool temperature, and placement speed were varied for resulting consolidation quality assessment. The resulting temperature data were also utilized to calibrate thermal analysis models under development at NASA. The experimental temperature data confirmed analytical results. An overview of the HiCAM project as well as initial data from ICAT process characterizations are described.

Keywords: thermoplastic composites, automated fiber placement, laser heating
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1. INTRODUCTION

1.1 NASA HiCAM Project

Modern commercial aircraft such as the Boeing 787 and Airbus A350 contain approximately 50% composite structure by weight and can fly much farther than their predecessors, saving both fuel costs and opening new service markets to airline customers. The next generation of aircraft are envisioned to continue to incorporate significant amounts of composite materials to produce the efficiency required from modern aircraft. The National Aeronautics and Space Administration (NASA) initiated the Hi-Rate Composites Aircraft Manufacturing (HiCAM) project in 2021 under the NASA Advanced Aeronautics Vehicles Program (AAVP) with the goal of significantly increasing the manufacturing rate for aerospace composite structure used on commercial aircraft. The work is inspired by the growing worldwide demand for personal and business air travel via commercial transport aircraft. To meet this growing demand, commercial aircraft manufacturers must double production rates within the next 20 years while still meeting strict regulatory structures and materials performance requirements established by the Federal Aviation Administration (FAA) and other international regulatory organizations. Due to the attractive strength-to-weight ratio and improved maintainability due to a higher resistance to fatigue and corrosion [1], carbon fiber reinforced polymer (CFRP) composites are one of the leading material candidates for large primary structure, such as wing and fuselage on these future commercial aircraft. However, the rate of commercial composite structure (shipsets) production will need to increase to 4 to 6x current rates to meet the anticipated demand for additional and replacement of existing single-aisle commercial aircraft. During a workshop in 2019 hosted by NASA in Washington. D.C. and attended by the U.S. Aerospace industry and academia, multiple technologies were identified as being the most impactful to increasing the rate for manufacturing composite structure on future commercial aircraft [2]. The high-payoff technical focus areas that can accelerate the implementation of rapid manufacturing methods by the aviation industry include:

- Development of increased and improved composite structure unitization and bonded structural concepts to reduce part count, assembly steps and mechanical fastening.
- Development of fast curing thermoset (TS) resins tailored for out-of-autoclave (OOA) processes including automated fiber placement (AFP) w/vacuum bag only (VBO) curing and resin infusion with VBO curing.
- Development of in-situ consolidation of continuous carbon fiber reinforced thermoplastic tape by defining relationship of tape quality requirements and process parameter optimization for quality part production.
- Evaluation of thermoforming continuous reinforcing structures (stringers, frames, etc.) to wing/fuselage skin curvatures.
- Development of advanced in-process monitoring and real-time nondestructive inspection (fiber placement/foreign object debris/autonomous defect recognition) and cure monitoring of material state (chemistry required for mechanical properties) methodologies.
- Development of robust process modeling and simulation technologies that can be used to predict defects and material properties for varying process parameters.
- Development of advanced test methodologies for lower cost/rapid certification of new materials/processing methods and model development validation.

As a result of these identified focus areas and further input from the commercial aircraft airframe and engine manufacturers, NASA has partnered with the United States aerospace industry and academia through the Advanced Composites Consortium (ACC) to develop manufacturing and composite materials technologies to reach the goal of a 4 to 6x increase in manufacturing rates over the existing aircraft rates. Under the HiCAM project the ACC has expanded to include: original equipment manufacturers and Tier 1 suppliers (Boeing, Raytheon, Northrop Grumman, Lockheed Martin, Spirit Aerosystems, GE Aviation, Aurora Flight Sciences, Advanced Thermoplastic Composites), material suppliers (Toray, Hexcel, and Solvay), automated equipment manufacturer (Electroimpact (EI)), software developers (CGTech, Collier Aerospace, Convergent Manufacturing Technologies US), government agencies (NASA, FAA) and academia (Wichita State University, University of South Carolina). The NASA HiCAM project currently has collaborative research teams (CRTs) investigating technology focus areas, or tasks, to compare qualitatively and quantitatively with the baseline, or state-of-the-art (SoA), manufacturing rates for fabricating composite fuselage and wings. These CRTs are comprised of NASA and ACC subject matter experts investigating the following proposed CFRP structure materials and manufacturing technologies:

- non-destructive evaluation (NDE), including in-situ inspection during the fabrication process
- rapid cure resin infusion thermoset resins
- stitched resin infusion of wing and fuselage including unitization of structural elements to the skin using stitching technologies
- thermoplastic forming of continuous reinforcing elements such as stringers, frames, and spars
- thermoplastic assembly of reinforcing structural elements via welding technologies such as induction, ultrasonic, and resistance
- thermoplastic automated fiber placement (TP-AFP), including, in-situ consolidation AFP of thermoplastics (ICAT) and TP-AFP with post-consolidation in an oven or autoclave.
- high-rate thermoset AFP, including increased lay-down rates exceeding the SoA of 1058 mm/s (2500 in/min), and introducing new rapid-cure thermoset slit-tape materials to reduce the autoclave cure cycle.

In addition to the composites materials and manufacturing technologies listed above and currently under investigation, the HiCAM project also includes significant efforts in defining the rates of the current manufacturing processes based on the proposed design for a Boeing 737 type commercial aircraft replacement including factory footprint and recurring and non-recurring costs. These variables are considered in developing methodologies to accurately compare the new, or proposed, manufacturing technologies to the baseline to determine which of these proposed technologies, after development, can attain the goal of a 4 to 6x increase in shipset rate. While each of these proposed technologies possess significant merit and address issues identified as focus areas at the NASA manufacturing workshop, one area that NASA is currently focused on demonstrating potential as part of the ongoing qualitative and quantitative analysis is the ICAT process to fabricate carbon-fiber reinforced thermoplastic wing and fuselage structure out-of-autoclave (OoA). Thermoplastic matrix composites offer attractive solutions to rapid manufacturing due to their ability to be formed and consolidated without the lengthy autoclave cure cycle required for crosslinking, or “cure” associated with the more commonly used thermoset epoxy and bismaleimide materials. NASA and ACC partners are also investigating thermoplastic forming of structural elements, various welding technologies to assemble these structural elements, and thermoplastic AFP to fabricate large acreage skins for wing and fuselage. Employing a recently developed laser heating system, in the ICAT process, the thermoplastic matrix carbon fiber reinforced slit-tape can be quickly and efficiently heated above the polymer melt temperature and fusion-bonded, or consolidated, ply-by-ply over rigid, heated tooling in an automated fashion utilizing existing AFP robotic placement machines. Two semi-crystalline polyaryletherketone thermoplastic matrix tape materials were down-selected for initial study based on the quality of the supplied materials. The thermal properties of these thermoplastic tape materials were provided by the material suppliers to estimate the ICAT process parameters necessary to fabricate consolidated laminates at AFP placement speeds approaching 423 mm/s (1000 in/min). The laser power settings to achieve the desired material temperatures were determined in the Electroimpact, Inc. laser-assisted AFP lab, measuring the substrate and incoming tape temperatures utilizing FLIR thermal imaging cameras and thermocouples during an initial ICAT process characterization study.

In this initial study the ICAT process material temperature, tool temperature, and placement speed were varied to determine the resulting consolidation quality and down-select processing parameters for further test panel fabrication. The resulting temperature data from the trials were also utilized to calibrate thermal analysis models under development at NASA to understand the transfer of heat into and out of the ply boundary welding region during the ICAT process. Once validated, accurate thermal models are anticipated to be effectively utilized to reduce trial-and-error processing experiments to fully optimize the ICAT process parameters as they relate to autohesion, crystallization and, ultimately, laminate performance. The experimental temperature data will be used to confirm the analytical results, indicating that the substrate and incoming tape surfaces are quickly heated above the polymer melt temperatures at the incident laser regions and then quickly cool as the material is compacted at the nip-point zone under the center of the AFP machine (head) compaction roller.

1.2 In-situ Thermoplastic AFP Background

Thermoplastic composites are being utilized more in transport and mechanical applications as they offer several advantages compared to thermoset composites including recyclability, long out-life and ambient storage, good mechanical and chemical performance, low volatile organic compound emission during the manufacturing process and shorter processing times. Another advantage is their ability to be joined by fusion bonding which is useful to join two parts without the disadvantages of mechanical fasteners.

During the heated head-automated thermoplastic-tape placement (HH-ATP) process previously developed at NASA Langley Research Center (LaRC), an incoming carbon fiber/thermoplastic composite tape was fusion bonded, or welded, to a previously placed and consolidated layer under heat and pressure locally applied to the interface (Figure 1). By placing additional layers in different directions, a part with desired thickness and properties can be fabricated [3]. The placement process of thermoplastic composite tapes is understood to involve the following general steps:

1) The incoming and substrate thermoplastic matrix tape plies are heated above the material melt temperature, T_M, (for semi-crystalline polymers) or the glass-transition temperature, T_g, (for amorphous thermoplastic polymers).
2) A compaction load is applied to the viscous material to establish intimate contact at the ply interface between incoming and substrate tape plies. The amount and time of application of the

compaction step is also dependent on the surface roughness of the supplied tape material [4-7].

3) With the viscous plies in contact, the polymer molecules reptate across the boundary in the autohesion process; the plies must be in contact but not necessarily under compaction load for adequate autohesion, or fusion bonding [6].
4) The fusion-bonded plies cool below the polymer T_g, freezing the laminate properties until the next AFP pass.

Consequently, development of residual stresses is unavoidable due to disparate thermal characteristics of matrix and fiber materials and due to non-uniform heating and cooling. From the product quality standpoint such as interlaminar strength, and dimensional accuracy, these stresses should be kept within allowable limits. As another quality requirement, a laminate should be void free and well consolidated for reliable use in a structure as a load bearing part. Achievement of adequate fusion bond, or autohesion between individual plies is critical [5] for structural performance. Incomplete welding results in high void content, which seriously degrades the mechanical performance of the composite. In addition, prolonged times at excessively high process temperatures may lead to thermal degradation and decomposition of the thermoplastic matrix. Selection of optimized processing parameters is required to deliver quality composites by HH-ATP.

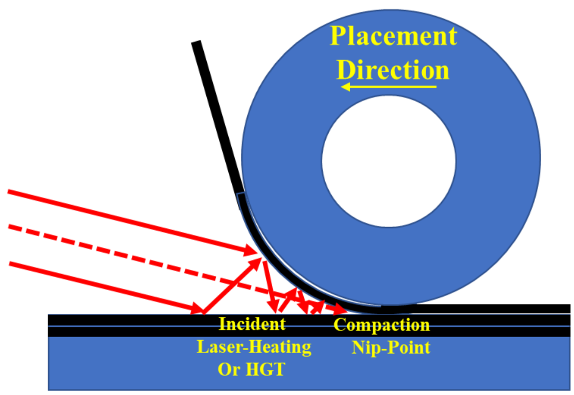
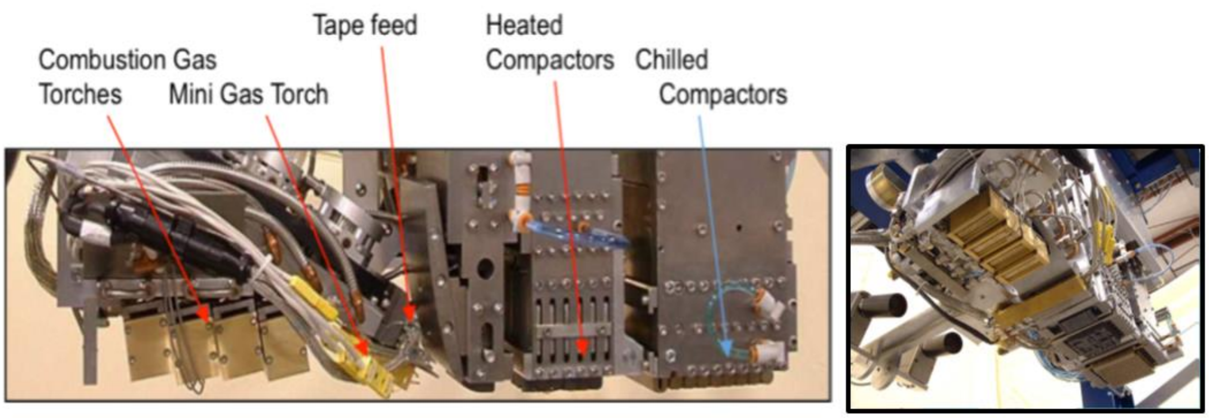


Figure 1. Simplified schematic of the HH-ATP Process.

The Advanced Materials and Processing Branch (AMPB) at NASA LaRC has developed aerospace capable thermoplastic composite materials and the accompanying thermoplastic composite processing techniques. Under a NASA Small Business Innovative Research (SBIR) Phase II contract completed in 2007, Accudyne. Inc. (Newark, DE) designed and fabricated a developmental version HH-ATP placement head (Figure 2) with the capabilities to conduct material evaluation and process development experiments of in-situ consolidation of thermoplastic ATP placing both commercial-off-the-shelf (COTS) CF/thermoplastic supplied tape as well as LaRC developed materials. The NASA LaRC HH-ATP facility utilizes a high-rail gantry system providing 1.8 m (~6 ft) of linear motion, a 1 m x 1 m (~3 ft x 3 ft) flat tool controlled by X and Y direction stepper motors, and a heated tape placement head. The HH-ATP process is fully automated with process and machine control software developed by Accudyne. Coordinated gantry/head motion together with the on-head tape consolidation process enables the fabrication of open section flat laminates without requiring an autoclave. As described in the processing steps above, the equipment was designed so that the deposition head preheats the CF/thermoplastic tape and the pre-placed, or substrate, laminate to the melting temperature using hot gas torches (HGT), welds them together under heat and pressure until the composite material is fused and consolidated in place and maintains pressure while cooled to temperatures below the T_g [3]. Figure 2(a) shows the processing elements used in the thermoplastic composite fabrication including: 1) four gas combustion torches (HGT) to preheat the pre-placed composite "substrate" layers to near the process temperature, 2) a mini-HGT to rapidly heat both tape surfaces at the contact, or "nip-point", to the process temperature where compaction load is applied via a line-compactor to establish intimate contact between the incoming and substrate tape plies using up to 800 N (~180 lb.), 3) immediately following the "nip-point", a heated conformable area-compactor capable of applying force of up to 1330 N (~300 lb) over an area of 11.4 cm x 10 cm (4.5 in x 4 in), and 5) a chilled area conformable area-compactor that can apply forces of up to 2200N (~500lb) at 10°C over an area of 12.7 cm x 10 cm (5 in x 4 in). Figure 3(b) provides a view of the head from the perspective of the flat placement tool. The conformable "area-compactors" are comprised of vertical heated shims capable of applying uniform load to both flat part surfaces or to parts with pad-ups and pad-downs [3]. This novel approach of using conformable area-compactors requires a travelling sheet of brass shim stock between the head compaction elements and the placed thermoplastic tape to prevent material sticking and allows the heated and cooled compactors to conform up to the approximate contour of a basketball [3], i.e., double curvature with a radius of about 12 cm (4.8 in). These conformable area-compactors provide an increased area of compaction force in comparison to the single flexible roller commonly utilized during AFP of thermoset tapes (see Figure 1) and provides a larger area, or more importantly longer heated-compaction time to the thermoplastic tape to fusion-bond the incoming tape to the substrate tape ply.



(a) (b)

Figure 2. LaRC HH-ATP head process elements including front-view of torches, tape feeder mechanism, and three heated and chilled compactors (a) and bottom-view perspective (b).

The equipment arrangement described above provides a highly capable solution for conformable compaction that has been demonstrated to investigate the in-situ process of flat and simple contour CF/thermoplastic parts fabricated from various LaRC amorphous and non-optimum commercially available semi-crystalline CF/thermoplastic tape materials. However, the HH-ATP equipment configuration is unlikely to serve as a solution to replace existing production capable AFP heads, because the area-compactors would not conform to complex-contour parts or tight radii associated with a wing skin or spar, respectively. The developmental HH-ATP head was used at Accudyne to study the heated and cooled compaction process of multiple CF/thermoplastic materials including: the amorphous thermoplastic, LaRC 8515 polyimide with a T_g of ~270 °C; and various other semi-crystalline polyaryletherketones, including : polyether ether ketone (PEEK), polyether ketone ketone (PEKK), as well as PIXA, PIXA-M, PIXA-M1, Avimid® K3B, Avimid® R1-16, and PETI-5 tape. Despite the poor quality of most of the supplied tape in these previous studies [3,6], the low-warpage, HH-ATP fabricated laminate quality was excellent; OHC strengths following in-situ placement using the LaRC HH-ATP head were 76 to 94 percent of those from in-situ placed, post-consolidated autoclaved laminates [3]. The measured mechanical properties of in-situ placed laminates were almost equal to laminates post-autoclave-consolidated after in-situ placement. Based on the results at the time it was concluded that to reach mechanical properties equivalent to autoclave processed laminates, HH-ATP would benefit from further equipment, process, and especially incoming tape material quality development. In work performed in 2008 [7] three versions of AS4/ PEEK tape were acquired from multiple industry suppliers and characterized to assess their potential use with the HH-ATP process. One of the explanations for the property disparity, especially in the lowest performing materials, was the quality of the supplied CF/thermoplastic tape utilized in this study. At the time, the AS4/PEEK (APC-2) and an AS4/PEKK tape were supplied with quality sufficient for consolidation in an autoclave with an elevated temperature and pressure cycle. An autoclave cycle provides sufficient time under pressure and above the melt temperature for the viscous polymer to flow sufficiently to establish intimate contact, fusion between plies, and for porosity found in these supplied materials to be evacuated from the laminate, or at a minimum, the porosity already present in the supplied tape does not expand under autoclave pressure. The level of quality of these supplied tape materials was insufficient to fabricate quality laminates during the more rapid HH-ATP process, where intimate contact, fusion-bonding, and void consolidation between the incoming and substrate ply occurs in seconds as opposed to longer times (up to 1 hour) in an autoclave process. The microscopy of the 7.62 cm (3 in) wide AS4/PEEK tape supplied for the lowest performing laminates tested are shown below in Figure 3. The 7.62 cm wide tape was cut into smaller sections and the sections of tape stacked in potting solution prior to polishing and photomicroscopy. In other words, each of the images in Figure 3 are of three sections of stacked tape, not a processed composite laminate. The significant improvements in commercially supplied tape quality are discussed further in the results section of this paper.

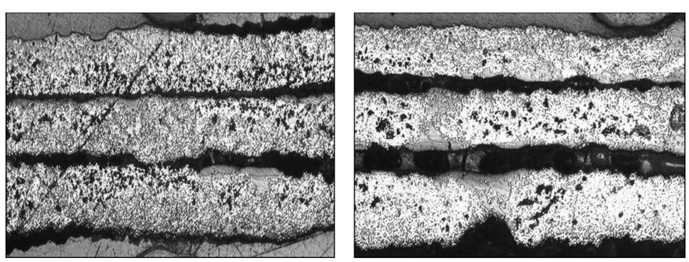


Figure 3. Photomicroscopy of CF/thermoplastic tape supplied and utilized for previous HH-ATP studies (2007) by Accudyne Inc, and NASA, showing excessive porosity and surface roughness.

1.3 Laser Assisted Thermoplastic AFP

As discussed above, the NASA and Accudyne developed approach to HH-ATP of thermoplastic composites is not likely to meet the rigors of the composites structure production environment. The current approach in industry for AFP of thermoplastics appears to be the retrofit [8,9] of highly capable existing AFP heads developed for placement (tacking) of thermoset tape materials at temperatures ranging from 25 to 70 °C and at advertised speeds of up to 1270 mm/s (3000 in/min).

Thermoplastic AFP processing requires much higher tape heating temperatures (300–400 °C) than thermoset AFP and ideally the tape material heating occurs directly ahead of the compaction roller nip-point where the incoming material meets the pre-placed substrate tape (Figure 1). As an alternative to the HGT heating source discussed above, lasers and flash lamp technologies have been developed and added to existing AFP machine heads to quickly heat the materials to these higher temperatures (Figure 4). Laser systems inherently have very quick response times to commands from the AFP head CNC control. Also, because the spot size is precisely controlled, residual heat is minimized and warm-up and cooling dwell times are reduced. Some commercially available systems such as LaserLine® result in a fixed heating spot, or line, across the entire width of the course being placed. Electroimpact, Inc® is developing laser heating systems for thermoplastic and thermoset AFP processing, which incorporates multiple diode laser spots sized according to the width of the tape, which allow the control of the heating of individual tows of material [9]. There are many good examples of laser heaters with fixed spot sizes that can produce individual heating sources for 6.4 mm (0.25 in) pitch or 12.7 mm (0.5 in) pitch AFP tows that can fit onto existing commercially available AFP processing heads. A laser, with a variable spot size, matched to the AFP tows, enables AFP processing on production parts with tow drops contained within the engineering edge of parts (EEOP). A Variable Spot Size (VSS) laser was developed and produced by Electroimpact® using individual diode laser heat sources for each tow. These designs offer laser spot sizes for up to 1.27 cm (0.5 in) wide tows and 16 lanes. This VSS laser provides 220 Watts/cm (560 Watts/in) of power targeting thermoset materials (VSS-LP-H16). Each spot measures 12 mm wide by 12 mm long and delivers 280 Watts for a total of 4,480 Watts of power. Optics were designed to achieve a precise spot size with distinct edges to prevent overlaps or gaps in the power delivery. When coupled with the VSS laser, a dynamically responsive machine can take advantage of this system development and achieve high speeds for both on-part and off-part heating. The VSS system developed for ICAT currently provides 629 Watts/cm (1600 Watts/in) of power over a course width of 5.08 cm (2 in) or a total of eight 0.64 cm (0.25 in) laser spots (round or square) for a course containing eight 0.64 cm (0.25 in) wide tows of slit-tape.

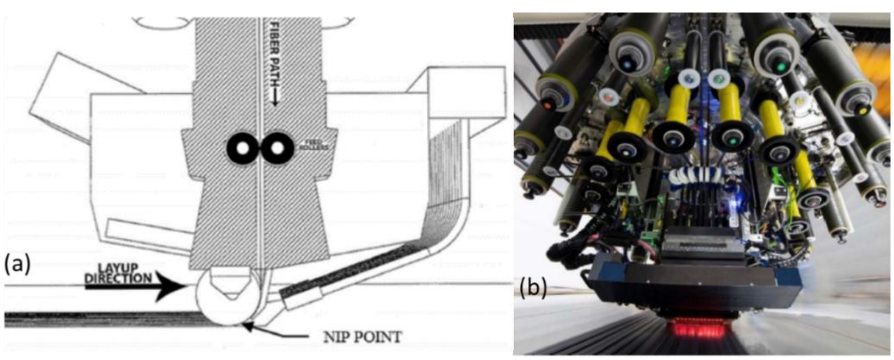


Figure 4. Electroimpact VSS-HP laser assisted AFP head concept (a), and digital photo of the VSS-HP laser heating system mounted and running on a 16-tow, 1.3 cm (0.5 in) tow width AFP head (b).

In comparison to the LaRC HH-ATP head, the laser-assisted thermoplastic AFP head places the laser-heated tape using a single compaction roller designed by Electroimpact with a solid metal core, over-wrapped with a flexible high-temperature material to provide conformable compaction at the elevated placement temperatures. Therefore, the objective of this work was to determine the temperature profile of the laser-assisted AFP head at, or above, the melt temperature of the thermoplastic materials and determine the capability of this system to fabricate quality thermoplastic carbon fiber reinforced plastic (CFRP) laminates by the ICAT process at manufacturing rates exceeding the baseline process of thermoset AFP followed by an autoclave cure.

2. MATERIALS AND METHODS

2.1 Materials

For this initial evaluation of the laser assisted ICAT process, two commercially available semi-crystalline polyaryletherketone thermoplastic / carbon fiber tape materials were investigated. Cetex® TC-1200 containing PEEK and T800GC-24K carbon fiber was supplied by Toray® with a fiber areal weight (FAW) of 245 g/m^2 and resin content (RC) of 34 wt.%. Toray reports a T_M of 343 °C and a T_g of 143 °C. The other 0.64 cm (0.25 in) wide slit-tape investigated was the "low-melt", polyaryletherketone (LM-PAEK®) thermoplastic AE-250® with IM7-12K carbon fiber tape supplied by Victrex® with FAW of 148g/m^2 and a RC of 34 wt.%. Victrex® reports a T_M of 305 °C and a T_g of 147 °C for AE-250. These two thermoplastic materials from the polyaryletherketone family were selected for the initial ICAT processing trials because the PEEK polymer has been well-characterized by both industry and academia and the new PAEK polymer offers the opportunity to investigate a more novel commercially available high-performance thermoplastic material and processing with different thermal requirements. The width tolerances of the slit-tape were determined and provided to the materials suppliers by Electroimpact® according to their experience with placing thermoplastic slit-tape. The quality of the slit-tape received from Toray and Victrex® were evaluated by photomicroscopy prior to ICAT processing trials. Multiple specimens were obtained along the length of the rolls of 0.64 cm (0.25 in) wide slit-tape by cutting with a fresh razor blade. The tape specimens were potted using an acrylic compound supplied by Buehler and the ends polished with high-grit sandpaper and suspensions of alumina on polishing pads supplied by DACE Technologies®. The digital images collected from photomicroscopy of the supplied tapes are discussed in the results section.

2.2 ICAT Process Characterization Trials

Utilizing the supplied 0.64 cm (0.25 in) PEEK and AE250® (LM-PAEK®) carbon fiber slit-tape, two laser-assisted ICAT processing characterization experiments were conducted by the staff at Electroimpact using their thermoplastics AFP developmental head. While EI has developed a variable spot sized laser heating system offering both round (elliptical) and square (rectangular) spots, the more mature round spot VSS-HP system was selected for the trials reported in this work. Utilizing the 16-tow, 0.64 cm (0.25 in) tow width AFP head mounted on the KUKA Titan robot arm shown below in Figure 5. The laser heating system included 4 round collimated laser spots with a total power of 630 Watts/cm (1600 Watts/in), or up to 400 Watts of power for each 0.64 cm (0.25 in) tow of material placed. The focused energy and resulting tape temperature were measured to be within +/- 10°C of the target temperature using a FLIR camera (Teledyne FLIR, LLC®, Model: FLIR A35 FOV 25, 60 Hz, ver. 2017) mounted on the AFP head and focused on the incoming and substrate tape surfaces just ahead of the start of the nip-point of the head compaction roller. The four laser spots were aligned and mounted at an angle of incidence such that the elliptical spots provide approximately 60% of the light energy to each of the 0.64 cm wide substrate tape and 40% of the energy to the incoming tape being placed. Using four round spots to heat the material resulted in a 2.54 cm (1.0 in) wide course being placed with each pass of the AFP head on the flat heated tool.

Figure 5. Electroimpact® VSS-HP laser-assisted thermoplastic AFP Developmental Head.

Both processing builds were conducted by AFP of the thermoplastic slit-tape material on a flat-heated tool supplied by Wenesco® and shown in Figure 5 beneath the AFP head on the larger coupon table. The heated tool surface was covered by a 1 cm (0.375 in) thick aluminum vacuum plate and a 0.051 mm (0.002 in) thick layer of Kapton® film was vacuumed to the surface of the aluminum plate to serve as the tool medium for placement of the test panels and to allow for easy release of the panels from the tool.

2.2.1 Initial ICAT Process Characterization Experiment

The first ICAT processing characterization trial was conducted to verify the heating capability of the Electroimpact® VSS laser heating system. An abbreviated processing design of experiment (DoE) was performed to determine, or improve the understanding of, the relationship between the ICAT processing parameters of material temperature, tool temperature, and placement speed on the quality of the interface formed between the tape plies during the process. The compaction load of 1.1 kN (250 lbs) was selected and fixed based on input from Electroimpact® and their experience with placing thermoplastic laminates for other customers. This value is high in comparison to the compaction loads used during thermoset AFP to tack plies but well within the capability of commercially available AFP heads. To conserve the slit-tape materials, the flat panels placed in the first ICAT processing trial were only six plies thick $[0°/0°/+45°/-45°/0°/0°]_1$ and were intended to provide 0° on 0° plies for thermocouple placement and measurement while also providing off-axis plies, which are assumed to be the worst-case scenario for heating and establishment of intimate-contact during placement. The processing parameters studied in this first ICAT processing trial are listed in Table 1.

Table1. Processing Parameters of the First ICAT Processing Characterization Experiments.

Slit-tape Material	Supplier Reported Melt Temperature (^{O}C)	2% Mass Loss Decomp Temperature (^{O}C)	Supplier Reported Glass Transition Temperature, Tg (^{O}C)	Trial #	Tape Target Temp (^{O}C)	Compaction Load (kN)	Tool Temp (^{O}C)	Placement Speed (mm/sec)
PEEK (Toray TC1200)	343	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
PAEK (VICTREX AE-250/IM7)	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

Each run, or trial, listed in Table 1 corresponds to an ICAT placed 15.24 cm x 10.16 cm (6.0 in x 4.0 in) six-ply unsymmetric, unbalanced panel. For the PEEK material processing trials, the maximum tape heating temperature of 500 °C was targeted to be well below the reported 2 % mass-loss decomposition temperature of 575 °C [10], while high enough to maintain the tape surface temperature above T_M through the compaction zone beneath the AFP head roller. Likewise, the maximum laser heating of the surface of the LM-PAEK® material processing panels was maintained at or below 450 °C based on the understanding of its degradation occurring at 557 °C [11]. The onset of polymer decomposition is suspected to be well below the 2% mass-loss temperature reported and hence the reason for ongoing thermal characterization of this material property at NASA. The heated tool used in these processing experiments has a maximum temperature capability of up to 300 °C and for these initial trials the tool temperature was varied but kept in the lower range with the idea that lower tool temperatures would be more acceptable to the production floor at an aircraft OEM. However, higher tool temperatures may be required and investigated in future experiments to determine effects on polymer crystallization and resulting mechanical properties. The temperature of the substrate ply heated by the incident laser spot is understood to scale linearly with the heated tool temperature. The uniformity of the tool surface temperature was measured prior to placing the first ply using the FLIR camera mounted on the Electroimpact AFP head. The resulting eleven panels were intended for cross-section and evaluation by photomicroscopy and the results of this first trial were used to determine the processing parameters to fabricate thicker mechanical test panels in the next ICAT processing experiment trials discussed below.

The second set of ICAT process characterization experiments conducted as a part of this current work were intended to fabricate mechanical test panels utilizing the processing parameters identified from the photomicroscopy results of the panels fabricated in the first set of experiments. The photomicroscopy results are discussed in Section 3. In the second set of process experiments, two 50.8 cm x 25.4 cm (20 in x 10 in) by 24 ply quasi-isotropic $[45°/0°/-45°/90°]_{3S}$ panels were fabricated using the same flat, heated tooling and AFP head with four round spots, collimated, diode lasers at the Electroimpact thermoplastic development lab. The PEEK panel was fabricated using a laser heating target temperature of 500 °C, a tool temperature of 120 °C, and a placement speed of 100 mm/s (236.2 in/min). The LM-PAEK® panel was fabricated using a laser heating target temperature of 450 °C, a tool temperature of 80 °C, and a placement speed of 400 mm/s (944.8 in/min). The compaction load applied by the AFP roller for both panels was 1.1 kN (250 lbs). In addition to fabricating the two mechanical test panels, temperature data was collected again during the second ICAT processing characterization experiments to validate the predictions of the thermal models under development.

2.2.2 ICAT Processing Trials Temperature Measurements

In addition to fabricating thin laminates to determine the placement quality, the ICAT processing trials were also intended to collect experimental temperature data to calibrate the physics-based thermal models under development. During both sets of trials, a FLIR camera mounted on the front of the placement head measured the temperature of the substrate and incoming material prior to the nip point. The FLIR camera was used to validate the substrate temperature matched the tape target temperature for the placement trials. During the first set of trials, a thermocouple data acquisition (DAQ) system (NI® cDAQ-9174, CompactDAQ chassis equipped with a NI 9212 8-Channel Module) capable of simultaneously measuring 95 samples/s/channel was used to collect temperature measurements at the maximum sample rate during each ply laydown. During the first set of trials, it was observed that 95 samples/s was not adequate to accurately capture when the peak temperature occurred and resulted in sparse data points during heating and cooling of the material. For example, at 400 mm/s processing speeds, most of the heating and cooling took place in ~0.3 s. During this time, only 28 temperature measurements could be captured. For these reasons, prior to the second set of trials, a new DAQ was acquired (DATAQ® DI-2008) where up to two thermocouples could be measured at 2000 samples/s/channel. This system was used for the thermocouples on the surface of the substrate as the robot placed material on top of them. All thermocouples already in the material were connected to the 95 samples/s/channel DAQ. The thermocouples utilized were 40 AWG, J-type from Omega® (5TC-TT-J-40-36). These thermocouples were selected based on their small diameter (0.0799 mm (0.0031 in)) that results in a low thermal mass and fast response time. The thermocouple locations in the ply stack are listed in Table 2.

Table 2: Thermocouple locations in ply stack.

Thermocouple (TC) #	TC Location
TC0 and TC1	Between tool and ply 1
TC2 and TC3	Between ply 1 and ply 2
TC4 and TC5	Between ply 14 and ply 15
TC6 and TC7	Between ply 22 and ply 23
TC8 and TC9	On top of ply 24 (final ply)

2.3 ICAT Process Thermal Model Development

The relevant material thermal properties were obtained from the suppliers and the open literature such as polymer degradation and crystallization kinetics. In addition, the ICAT process will be optimized by understanding the physics underlying the heating, compaction (intimate contact), and autohesion (fusion-bonding) of the plies during the in-situ fabrication process. As a first step in this physics-based approach, thermal models have been developed based on a one-dimensional (1D), or through-the-thickness, closed-form analytical solution of the relevant system of equations as well as a 2D approximation of the thermal response using the finite difference method.

2.3.1 Analytical Thermal Model Development

A heat transfer analysis of the laser heated thermoplastic tape was performed to assess the temperature profile during the in-situ AFP consolidation of the thermoplastic composite. Also, the temperature measurements from the ICAT process builds were compared to the model predictions. A simple one-dimensional thermal analysis, sufficiently representative of the laser heat transfer process of the tape in the vicinity of the nip point of the consolidation roller, is considered here in order to provide a quick estimate of the temperature range expected in the in-situ thermoplastic panel builds. However, a two- or three- dimensional heat transfer finite element approach would provide a more precise and detailed thermal profile in the long-run. The governing equation (Eq. 1) for one-dimensional heat transfer problem can be stated as

$$\frac{\partial T}{\partial \tau} = \alpha \frac{\partial^2 T}{\partial y^2}, \qquad \tau = \frac{x}{V} \tag{1}$$

where α is thermal diffusivity as a function of material characteristics such as thermal conductivity, density and specific heat; T is the temperature through the thickness direction y; V is the roller head speed, and τ and x and are the time and location on the tape surface, respectively. The boundary conditions on the problem include the heat flux on the tape top surface, and an insulation boundary on the far side of the substrate.

The substrate tape layers built up on the tool can be considered sufficiently large compared to the thin thermoplastic incoming tape that is placed as a new substrate layer. Therefore, the substrate layers can be idealized as a semi-infinite solid for seeking a solution to the thermal model of the heated substrate tape. The predominant mode of heat transfer into the tape is by conduction [12]. Therefore, a closed form solution can be readily obtained for the temperature on the tape surface as well as the temperature through the thickness of the substrate y (Eq. 2), for any time duration of laser exposure [14] at the given heat flux on the tape surface.

$$T(y,t) = T_i + \frac{2q_0''\sqrt{\alpha t}}{k} i\,erfc\left(\frac{y}{2\sqrt{\alpha t}}\right) \tag{2}$$

where T_i is the initial temperature of the material; T is the final temperature at depth y and time t; k and α are the thermal conductivity and diffusivity of the material; *ierfc* is the complementary error function; and the laser heat flux q_0'' is a function of the laser power and absorptance of the material. The heat flux on the tape surface at the roller nip point can be calculated [12] for a known incident angle of the laser beam on the substrate. A one-dimensional transient solution is sought for the thermal response of the tape in the vicinity of roller nip point. The heat penetration depth in this semi-infinite substrate model of undefined depth is seen as a function of the square root of the thermal diffusivity and elapsed time. This means that the thermal penetration depth depends on the time of exposure of the material beyond its initial temperature. For a certain fraction of exposure time there exists a critical depth at which the substrate will not feel the effect of laser heat moving at the speed of the roller head.

However, a sharp increase in tape surface temperature can be expected with a high intensity laser. As the tape section approaches the roller nip point, a section would no longer be under the laser spot, and the absence of heat flux results in immediate cooling of the tape. The temperature sustained in the tape after a fraction of exposure time just before undergoing consolidation at the nip point is critical to the formation of crystallinity and bonding of the incoming tape. Although, more detailed consideration of thermal contact of the tape with the roller and substrate at the nip point are possible, the cooling response of a tape is readily obtained from a simplified solution [14] of the heat transfer differential equation for conduction.

2.3.2 Finite Difference Thermal Model

A thermal model was developed using a two-dimensional, explicit finite difference method, and Euler method for solving the time-dependent heat equation over a two-dimensional grid. This is perhaps the simplest numerical method for solving the 2D time dependent heat equation, chosen for its straightforward implementation (enabling easy modification and control over boundary conditions) and its well-defined stability criteria. The time-dependent heat equation (Eq 3) can be modeled as:

$$\frac{\partial T}{\partial t} = \alpha_x \frac{\partial^2 T}{\partial x^2} + \alpha_y \frac{\partial^2 T}{\partial y^2} \qquad (3)$$

Where T is the temperature and α_x and α_y are the thermal diffusivity coefficients in x and y, chosen based on the heat capacity and direction-dependent thermal conductivity coefficients as well as the grid spacing in x and y.

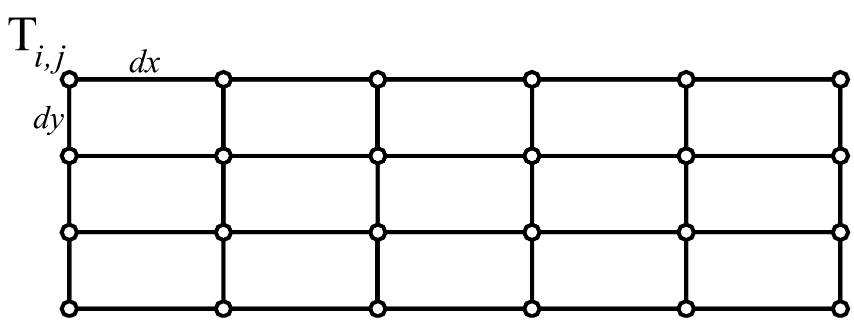


Figure 6. Representation of the finite difference modeling approach.

In this method, a 2D grid is created for each thermal domain T, Figure 6. The size of the grid elements and the timestep are determined to maintain stability for the Euler method according to the criteria for each dimension and each region:

$$\frac{2\,\alpha_x\,\mathrm{d}t}{(\mathrm{d}x)^2} < 1 \qquad (4)$$

and

$$\frac{2\,\alpha_y\,\mathrm{d}t}{(\mathrm{d}y)^2} < 1 \qquad (5)$$

Additionally, the grid element dy is chosen to be about the same order of magnitude as the surface smoothness deviations and no smaller than the distance between each fiber in the tows (below which point the composite assumption breaks down and fiber and resin would need to be treated as separate regions).

One domain is used for the substrate, another for the current tape layer being applied, and a third for the thermal condition of the roller itself, Figure 7.

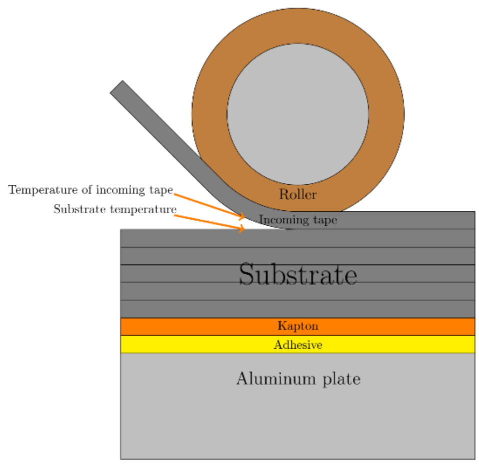


Figure 7. Schematic of the finite difference model boundaries in relation to the nip-point materials.

The domain for the roller is approximated as a slab of the same length as the circumference of the roller, and all three domains are set to this length. The boundary condition on the bottom (i.e., the tool surface in contact with the substrate) is set to a constant temperature (i.e., the tool temperature), enforced each time step. The boundary condition of the inside of the roller is also a constant-temperature condition set at or near room temperature. Side boundaries are set to insulating. The boundaries between the three domains are set as a region of adjustable thermal conductivity, set to zero when the surfaces are not in contact and set to some value between zero and one when in thermal contact. Convection and radiation are not used in the current implementation, but this could be added as a boundary condition. First-order estimates show single-digit percentage impacts on the heat distribution during the actual simulation. However, convection and radiation over longer periods (such as between passes of the head) can create a thermal gradient in the substrate and roller, particularly for thicker parts.

Laser energy for welding the tape to the substrate is added as a constant flux to both the top surface elements of the substrate and the bottom surface elements of the incoming tape. The ratio between the two fluxes can be varied. While nominally this is modeled as a constant flux for the duration of the laser pass, the flux can follow any arbitrary positive function, such as an increasing ramp or an increasing ramp followed by a decreasing ramp. The length of the laser pass on the top and bottom can be adjusted. No sophisticated optics are modeled, but a separate optical model could be used to provide a function for the laser input power.

On each time step, any thermal energy from the laser is input into the substrate and tape grid elements according to a vector representing the current position of the laser impinging region. Temperature conditions at constant-temperature boundary conditions are enforced. Grid elements within each region exchange heat with elements immediately adjacent. The vectors representing the distribution of intimate contact are advanced to correspond to the position of the roller. Grid elements on the edges of regions exchange heat with elements of regions adjacent according to the degree of intimate contact set.

3. RESULTS

3.1 Supplied Tape Quality Evaluation

The quality of the supplied thermoplastic tapes currently available from Toray and Hexcel were evaluated. As a part of that ongoing effort, cross-sections were taken from the supplied Toray TC1200® and the Victrex AE250/IM7® slit-tape. The specimens were potted, polished, and photographed using a digital microscope at 100X magnification. Figures 8 and 9 show the results of the photomicroscopy for the TC-1200 and AE250/IM7 slit-tape, respectively.

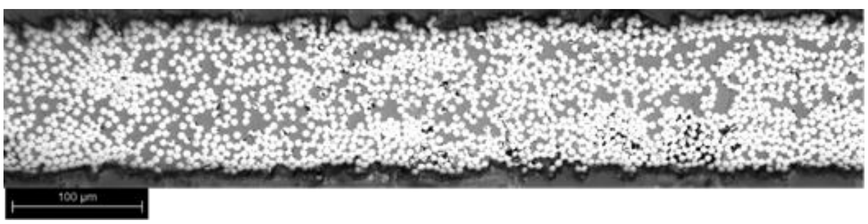


Figure 8. Photomicroscopy of Toray TC-1200 slit-tape.

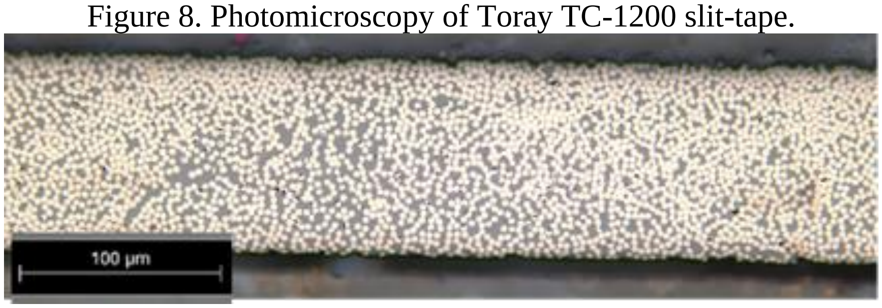


Figure 9. Photomicroscopy of Victrex AE250/IM7 slit-tape.

The photomicroscopy indicates that both tape materials have a uniform distribution of fiber and resin and no porosity, although the dark regions found at the base of the TC-1200® tape image (Figure 8) may indicate dry-fibers. These are not the only quality considerations for optimized tape utilized in the ICAT process. Surface roughness [4] and volume, or thickness, of surface polymer will also likely affect the degree of intimate contact [5] and fusion-bonding of the plies in the processed laminate. However, in comparison to the APC2® tape supplied to NASA previously for the HH-ATP trials (Figure 3), the quality of the tape supplied for this study is markedly improved.

3.2 ICAT Processing Trials Temperature Measurements

During the first set of trials, it was observed that the thermocouples would heat to a higher temperature than the surrounding material when under direct heating from the laser (i.e., when thermocouple located on surface of substrate prior to material being placed on top of the thermocouple). Because of this, a combined FLIR-thermocouple temperature measurement compensation technique had to be employed to obtain a valid temperature profile prior to the nip-point (heating phase) after the robot had passed by. The FLIR camera, which could only measure the temperature profile up to the nip-point because of line of sight, was utilized to validate that the target tape temperature was reached. The thermocouple time-trace was then compensated to the appropriate peak temperature based on the target tape temperature and/or FLIR measurement. A linear scaling function was used for both the heating and cooling phases. For the heating phase, the substrate temperature prior to heating was held constant and all measurements after this up to the peak temperature were linearly scaled down. For the cooling phase, a point along the cooling trace where the temperature of the thermocouple could be assumed to be the same as the material (approximately 1 s after peak temperature) was held constant and all measurements prior to this up to the peak temperature were linearly scaled down. The effect of this scaling function can be seen in Figure 10.

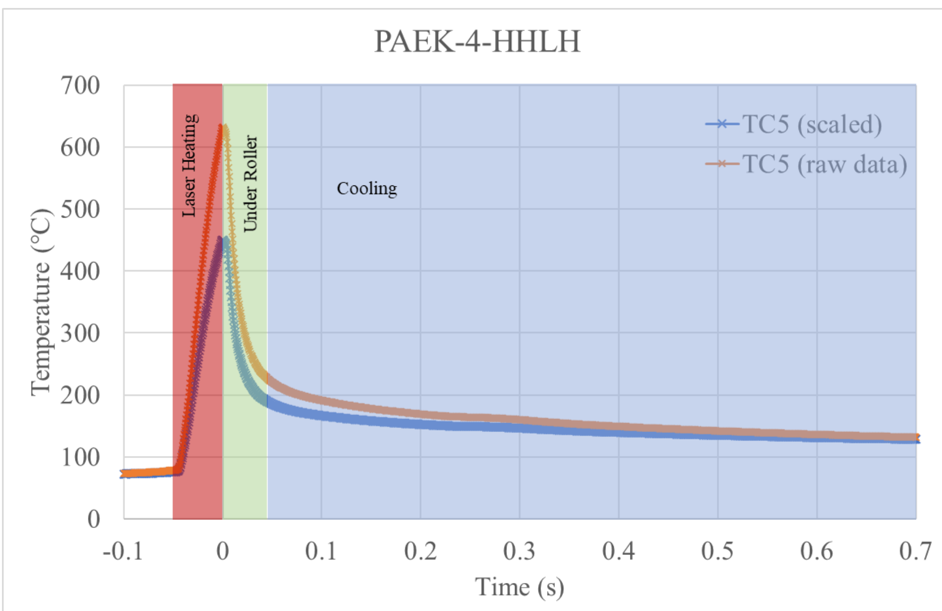


Figure 10. Raw and scaled temperature data from thermocouple #5 (TC5) (located between plies 14 and 15) during the second set of PAEK-4 trials.

Figure 11 details the combined FLIR-thermocouple compensated temperature measurements from the six embedded thermocouples from the second set of PAEK-4 ICAT processing characterization experiments. To align the data, the time of peak temperature has been shifted to t = 0 s. The temperature measurements were recorded when the thermocouple was on the surface of the material (i.e., the ply where material was placed on top of the thermocouple). In addition to the repeatability of the data, it was observed that the thermocouples closer to the bottom of the panel (TC2 and TC3 located between plies 1 and 2) cooled faster than the thermocouples located near the middle and top of the composite panel (TC4 and TC5 located between plies 14 and 15 and TC6 and TC7 that were between plies 22 and 23). This a result of the composite material acting as an insulator as compared to the heated aluminum tool plate that acts as a heat sink.

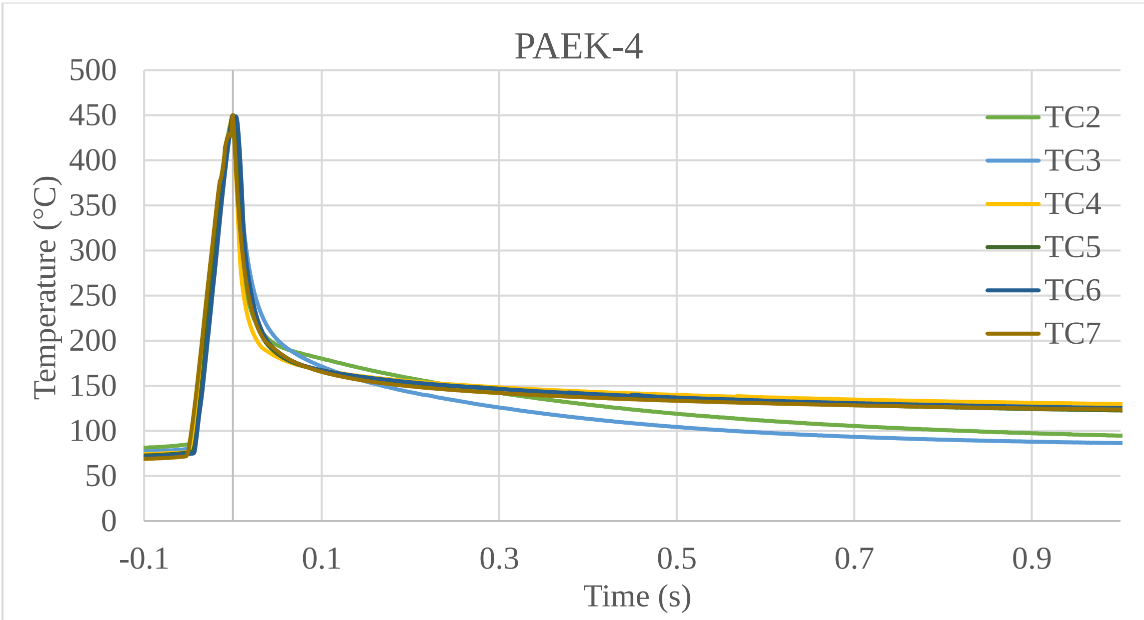


Figure 11. Scaled temperature data from all embedded thermocouples during the second set of PAEK-4 ICAT process characterization experiments.

3.3 Analytical Predictions of ICAT Heating and Cooling Compared with Experimental Data

Several ICAT processing cases were analyzed comprising of high, low, and medium ranges of tape temperatures, roller head speed, tool temperatures, for a prescribed maximum consolidation load. The analyses focused on the PEEK and PAEK tape materials. The transient thermal response calculations were performed in Excel spreadsheets and the code was run with inputs on laser beam section size, incidence angle, material absorptance, conductivity, density, and tape thickness. The temperature response of the tape on the substrate was calculated for the duration of heating from the laser exposure, as well as for the cooling duration of the tape past the roller nip point. The results are plotted in Figures 12 and 13. These two plots are for the two extreme conditions from various cases-- high tape surface (500 °C) temperature with high tool temperature (110 °C) and low speed (100 mm/s) in the case of PEEK, and tape surface temperature (450 °C) with low tool temperature (74 °C) and high-speed (400 mm/s) in the case of PAEK. The maximum temperature desired on the tape top surface was obtained by scaling the available power. A sharp increase in heating response of the tape surface above its initial temperature on the substrate is indicated in the figures, where heating at a surface location begins at the time of incidence of laser spot and terminates at the time it is extinct as it reaches the roller. The compaction of the tape under the elastomeric roller begins and ends at the leading and trailing edge of the roller footprint (approximately 18 mm in length). The time point for the start and end of compaction and nip point of the roller are shown (red, purple, and green lines). Also, the T_g and T_M of interest are shown in the plot, marking the region of interest for in-situ consolidation for maximum crystallinity and fusion-bonding depending on the temperature sustained in the tape. After the end of compaction, cooling of the tape by conduction is gradual and continues for a long time, until the tape reaches the initial temperature of the substrate (controlled by the heated-tool).

The thermocouple sensed temperature results from test on the second build of the thermoplastic panel are also shown in the figures for both PEEK and PAEK cases. The time points at the maximum temperature (peak) of the laser heating from the analysis and test are matched so that temperature response from both can be compared.

It is seen that the predicted temperature response agrees with the test results at the peak with similar temperature rising trends. On the cooling segment, more gradual cooling trend is predicted as compared with the test results showing steep cooling, which may be attributed to additional dissipation of heat by way of conduction into the roller, as well as by way of convective heat transfer into the room environment. Also, the temperature cooling response of the tape under the roller nip point are based on one dimensional heat flow into the substrate only. The heat transfer upon contact of the substrate tape with the incoming tape under the roller must be addressed for more accurate prediction of the cooling response.

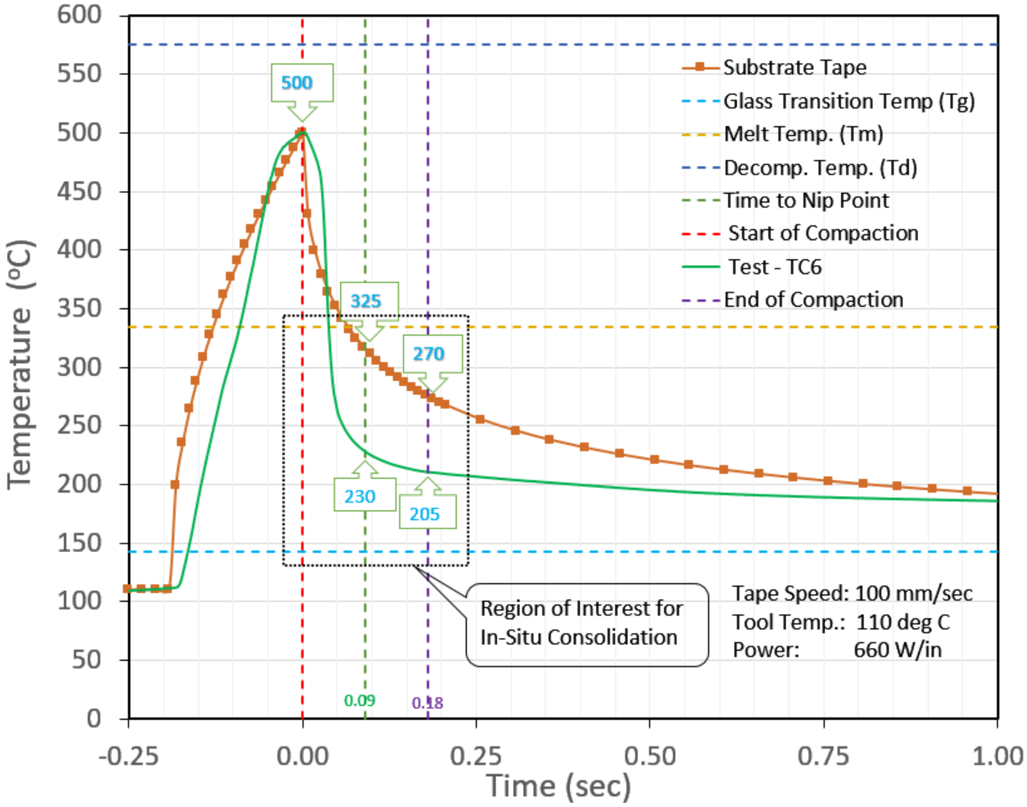


Figure 12. Comparison of analysis and experimental test temperature responses of the thermoplastic tape on substrate for the low speed case of PEEK/TC1200® material.

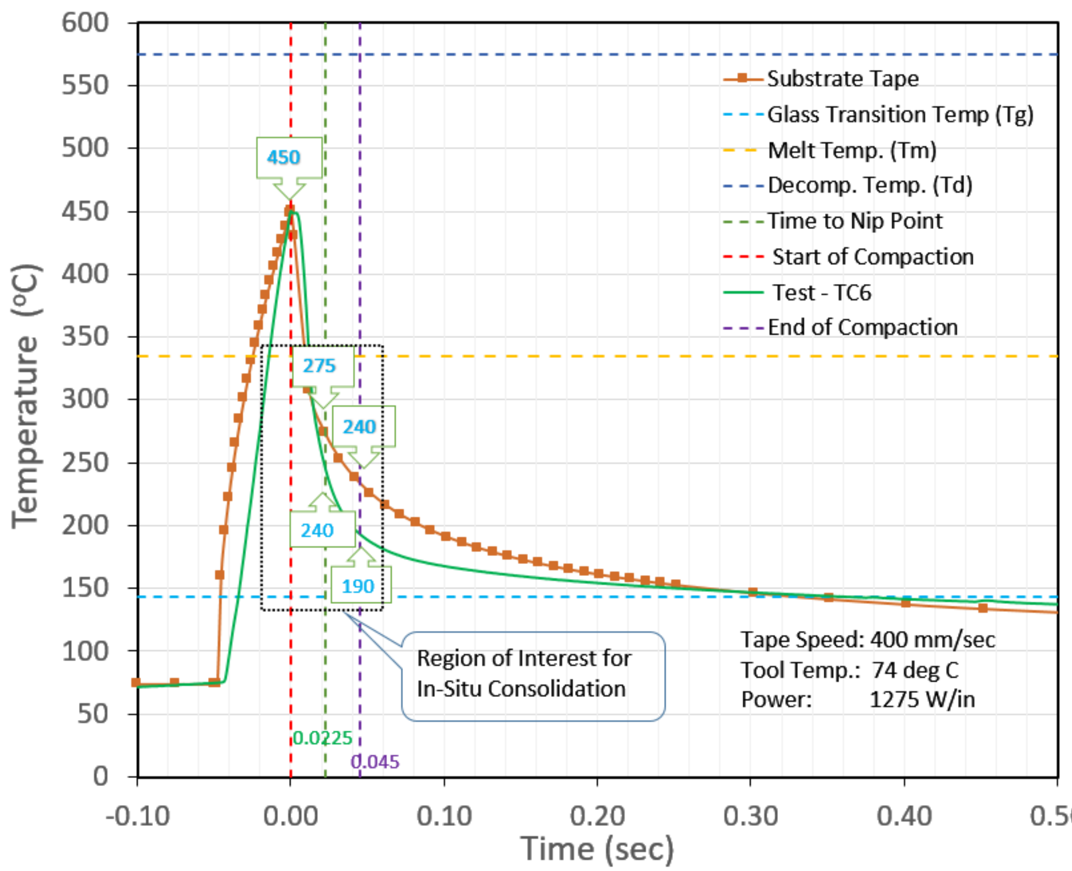


Figure 13. Comparison of analysis and experimental test temperature responses of the thermoplastic tape on substrate for the high speed case of PAEK/AE250® material.

The low and high-speed cases of PEEK and PAEK, differ in targeted maximum (peak) temperature. However, both cases show similar heating and cooling trends, as well as sustained temperature in the region of interest. The compaction time duration in the PAEK case is cut by $1/4^{th}$ of the PEEK case due to placement speed. The thermocouple material conductivity in contrast with the thermoplastic material conductivity and the resulting response to laser exposure could be another factor affecting the results, which necessitates detailed calibration of the thermo-couple measurements.

Convective and radiative cooling have approximately the same heat flux for a 61 cm by 61 cm heat plate with an 80 to 120 °C set temperature and a ~20 °C ambient temperature [14]. The results of the thermal response predicted by the finite difference model to the experimental temperature data are shown in Figure 14. For thin composite parts, convection and radiation have little impact on the steady state substrate temperature. However, for thicker components, such as the ~3 mm parts considered here, the composite material (as well as the Kapton® film on the tool surface) act as an insulating barrier. This has the effect of a temperature gradient of approximately 8 to 15 °C for the 80 and 120 °C tool temperatures, respectively. This may explain the discrepancy between the simulated results (where the substrate is assumed to be the same temperature as the aluminum tool plate) and the experimental results, which differ by about 20 °C at 1 second after the peak temperature is reached (at the nip point). The remaining discrepancy could perhaps be accounted for by the fact that the simulation assumes all unidirectional plies in the same direction (whereas the experiment used a quasi-isotropic layup pattern that would have the effect of conducting heat away faster perpendicular to the lay-up path) and the fact that the bonding between layers may not be complete, which would serve to insulate the surface from the tool. Finally, there are uncertainties in the thermal properties of the composite material. Results from literature are used instead of directly measured values. Also, the aluminum tool plate does not itself act as a perfect distributor of the heat (and therefore the temperature on the tool plate reduces towards the edges). Other sources of error include the emissivity of the composite, the ambient airflow and temperature during the layup process, and the scaling process for the thermocouple data.

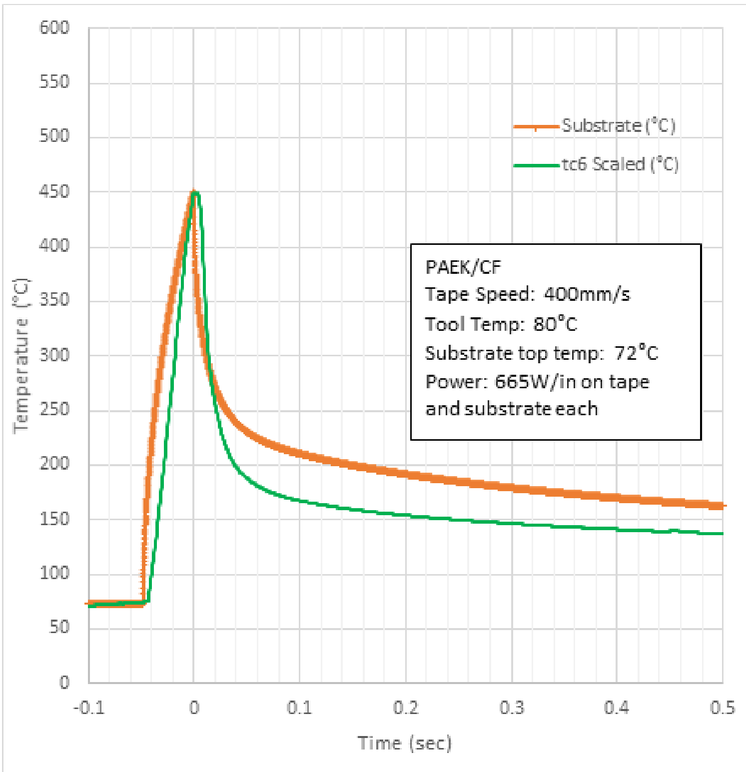


Figure 14. Comparison of finite-difference model predictions and experimental test temperature responses of the thermoplastic composite tape on substrate for test panel PAEK-4.

3.4 Microscopy Results of ICAT Process Characterization Experiments

In the first ICAT process characterization builds at Electroimpact a quantity of seven 6-ply panels were fabricated using the TC1200 PEEK slit-tape and six were fabricated using the AE250/IM7 slit-tape as described in Table 1. The purpose of this first processing experiment was to conduct an abbreviated DoE comparing the effects of tape temperature, tool temperature, and placement speed on interply quality. In addition, the results of the first processing experiment, were utilized to down select processing parameters that at a minimum resulted in intimate-contact [4,5] being established between the placed plies. Those ICAT processing parameters were used in the second ICAT processing experiment to fabricate mechanical test panels to determine the extent of autohesion [4,5,6] occurring during ICAT processing. The technique utilized to determine the degree of intimate-contact was photomicroscopy of the cross-sectioned 6-ply panels.

Figure 15. Photomicroscopy of PEEK Panel-6 from first ICAT processing experiments.

Figure 16. Photomicroscopy of PEEK Panel-1 from first ICAT processing experiments.

Figure 17. Photomicroscopy of PAEK Panel-6 from first ICAT processing experiments.

The panel quality indicated in Figure 15 resulted from ICAT processing of the TC1200® (PEEK) slit-tape using a laser heating target temperature of 500 °C, head compaction load of 1.1 kN, flat tool temperature of 120 °C and AFP head placement speed of 100 mm/s In comparison to the photomicroscopy results of the other PEEK tape processing conditions listed in Table 1, this combination of processing parameters resulted in the least number of defects such as porosity in the inter-ply regions of the six-ply laminates. The trends observed with the ICAT process of PEEK were as expected: higher laser target temperature and lower placement speeds reduced the number, and/or occurrence of inter-ply porosity. Every other PEEK panel had some degree of porosity located at the [+45°/-45°] interface or at the [0°/+45°] interface, The PEEK panel with the worst inter-ply porosity is shown for comparison in Figure 16.

In contrast, lower porosity overall was observed in the six panels fabricated using the Victrex AE250/IM7® (LM-PAEK®) slit-tape. The large defect shown in ply #2 of the PAEK panel shown in Figure 17 is likely a course gap and indicative of the need for tighter placement control or, perhaps slit-tape width tolerance, more so than an ICAT processing parameter effect. The only PAEK panel in this study where inter-ply porosity similar to Figure 16 was observed was the PAEK Panel-6-LHLL* indicating that 350 °C is too low a temperature to ICAT process PAEK tape even at low placement speeds.

In the second set of ICAT processing characterization trials, the PEEK-6 and the PAEK-4 processing conditions were used to fabricate 24-ply quasi-isotropic test panels by the ICAT process for each of the materials. After ICAT processing the resulting panels were cut into three sections using a wet-saw resulting in an "ICAT panel", an "ICAT + Vacuum-Bag Oven (VBO) post consolidation panel" and an "ICAT + Autoclave post-consolidation panel". After post consolidation steps, Short-Beam-Shear (SBS) coupons will be cut from each panel and tested to determine the resulting SBS strength for comparison to published values.

4. CONCLUSIONS

Two ICAT processing characterization experiments were conducted to investigate the effects of process parameters including tape temperature, tool temperature and placement speed on the quality of the resulting flat laminates. Based on the temperature data collected during the ICAT experiments it is concluded that the Electroimpact VSS-HP laser heating system is indeed capable of quickly heating the tape surfaces to the required, or target, temperature to melt the semi-crystalline thermoplastic materials studied. The results of the photomicroscopy of the 6-ply laminates from the first ICAT experiments indicate that intimate contact was established for the Toray PEEK tape utilizing a tape target temperature of 500 °C, tool temperature of 120 °C and placement speed of 100 mm/s ICAT processing of the Victrex LM-PAEK® tape resulted in intimate contact establishment at the more favorable processing conditions of tape temperature of 450 °C, tool temperature of 80 °C and placement speed of 400 mm/s. At this point it is inappropriate to conclude that these ICAT processing parameters are optimized. Mechanical testing of the 24-ply quasi-isotropic panels fabricated in the second ICAT processing experiments using these processing parameters is ongoing to determine if these conditions result in significant fusion-bonding, or autohesion, occurring at the ply interfaces during the ICAT process. In addition, thermal characterization, including differential scanning calorimetry and thermogravimetric analysis of both supplied materials and the ICAT fabricated test panels is ongoing to establish the effects of the processing conditions on polymer degradation and volume percent crystallinity. Both characteristics will affect the mechanical properties of the thermoplastic composite structure and, therefore, must be further understood before any further conclusions can be drawn regarding the viability of laser-assisted ICAT as a high-rate composite fabrication alternative to thermoset AFP + autoclave cure.

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