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

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ABSTRACT

The National Aeronautics and Space Administration (NASA) project Hi-Rate Composites Aircraft Manufacturing (HiCAM) aims to significantly increase commercial aircraft composite structures manufacturing rate. Thermoplastic composites offer attractive solutions to rapid manufacturing due to their ability to be formed and consolidated quickly. NASA has a particular interest in assessing composite structure manufacturing utilizing an in-situ consolidation automated fiber placement (AFP) of thermoplastics (ICAT) process employing current state-of-the-art laser heating systems. Three semi-crystalline polyaryletherketone (PAEK) thermoplastic tape materials were characterized to ascertain the ICAT process parameters. The required laser power settings were determined at Electroimpact, Inc.®‡, 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 quality of the resulting test panels was evaluated by both non-destructive evaluation as well as destructively by photo-microscopy. The effect on interlaminar strength was determined by short beam strength testing. Test results of carbon fiber laminates fabricated by ICAT using polyetheretherketone (PEEK), polyetherketoneketone (PEKK), and low-melt polyaryletherketone (LM-PAEK) at various placement temperatures and placement speeds are presented.

Keywords: thermoplastic composites, laser heating, automated fiber placement (AFP), in-situ consolidation AFP of thermoplastics (ICAT)

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‡ *Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the hardware used in this study. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government nor does it imply that the specified equipment is the best available.*

1. INTRODUCTION

Aircraft manufacturing is a cornerstone of the United States economy. Commercial aircraft were the largest single category of export from the United States in 2019 [1]. Worldwide, the market for single-aisle aircraft is projected to grow by $36.9 billion from 2021 ($85.7 billion) to 2027 ($122.6 billion), making production of this type of aircraft crucial to the United States economy [2].

Composites have tremendous potential in airframe construction. They are attractive to aircraft manufacturers and designers because of their favorable mechanical properties and resistance to corrosion [3]. These properties enable the construction of aircraft that are significantly lighter, and therefore more fuel efficient. This will both lower the cost of air travel and improve environmental outcomes [4,5].

Small aircraft have long incorporated composite materials, but commercial transport aircraft made with composites have only entered production relatively recently [6]. Passenger aircraft with a large proportion of their airframe constructed using carbon fiber reinforced composites are currently being manufactured, but composites are considered harder to manufacture and more costly compared to metallic airframes [7]. New manufacturing technologies and processes are vital to ensure that production of next generation aircraft can keep up with demand.

In 2021, the Hi-rate Composite Aircraft Manufacturing (HiCAM) project was initiated by the National Aeronautics and Space Administration (NASA) to investigate technologies for rapid production of commercial airframes using composite materials. HiCAM aims to advance multiple technologies to technology readiness level (TRL) 6-7 by the year 2027. One area being investigated is automated fiber placement (AFP) of thermoplastics. During this process, polyaryletherketone (PAEK) thermoplastic prepreg (pre-impregnated carbon fiber) tape is placed robotically (Figure 1 and 2). The current state-of-art (SoA) AFP process uses thermoset prepreg tapes, which must be processed in an autoclave after placement. Switching to a thermoplastic matrix provides several benefits including the potential to eliminate the need for autoclave processing and thus increase manufacturing rates [8].

In-situ consolidation AFP of thermoplastics (ICAT) presents many advantages, but with engineering challenges which have yet to be solved [8]. Maximizing the speed that the robot applies composite tape (layup speed) is critical to making the process economically viable. Effective consolidation also requires large amounts of thermal energy because of the higher melting temperature of the semi-crystalline PAEK materials. Therefore, lasers are a popular heating solution for their high-power output, ability to tightly focus the heating zone, and uniform power distribution [9-13].

In this effort, three semi-crystalline PAEK thermoplastic tape materials were evaluated to ascertain the potential of their use in an ICAT process utilizing SoA AFP equipment. The required laser power settings were determined, and the material temperature, tool temperature, and placement speed were varied for resulting consolidation quality assessment. The quality of the resulting test panels was evaluated by both non-destructive evaluation as well as destructively by photo-microscopy. The effect on interlaminar strength was determined by short beam strength testing.

2. EXPERIMENTATION

2.1 AFP Equipment

Fabrication was performed at Electroimpact® in Mukilteo, WA, USA with a six-axis Kuka Titan® robotic arm with an Electroimpact® developed Q16 placement head. The AFP head was configured to place 2.54-cm wide courses comprised of four 0.635-cm wide carbon fiber/thermoplastic matrix tapes (Figure 1) onto a custom, 9.5-mm thick, aluminum tool that was heated by a uniform hotplate supplied by Wenesco®. Electroimpact® 400 W per lane, 976-nm wavelength, VSSL-HP (Variable Spot Size Laser-High Power) laser was mounted to the AFP head and used to heat both the incoming and substrate tape, simultaneously. The laser used four spots (one for each tow), which could be controlled individually. A conformable compaction roller was used to apply force to the incoming and substrate heated tapes. Panels were placed on a layer of high-temperature polyimide release film (DuPont™ Kapton®) attached to the heated tool to prevent sticking. A schematic diagram of the layup process can be seen in Figure 2, where the angle of incidence (θ) is approximately 16 degrees.

Figure 1: Electroimpact® six-axis AFP robot arm (Image Credit: Electroimpact, Inc.®).

Temperature was measured during layup with two separate systems. A forward-looking infrared (FLIR) camera supplied by Teledyne FLIR® was mounted to the AFP head. This camera monitored the temperature distribution on the incoming tape and the substrate during the layup process. Calibration of the FLIR camera was achieved by pointing it directly down at a layer of prepreg material on the heated tool and determining the correct emissivity value to match temperatures measured by surface mounted thermocouples (TCs). Further improvements/validation of the FLIR emissivity calibration process are needed since the calibration was performed at lower temperatures than those observed by the FLIR camera during processing. The emissivity value of the FLIR was found to be 0.8 for the composite materials.

J-type, 40 AWG, TCs (5TC-TT-J-40-36 from Omega®) were also used to monitor substrate temperature throughout layup. TCs were "welded" onto the surface of the substrate tape by melting the surface polymer using a hand-held soldering iron. "Welding" the TCs prevented them from moving during layup and minimized protrusion of the TC bead from the substrate surface. A DATAQ® DI-2008 data acquisition (DAQ) system was used to collect temperature data at a rate of 2 kHz, which made it possible to observe the evolution of the substrate temperature over a very short time period (~1.5 s) with relatively high fidelity.

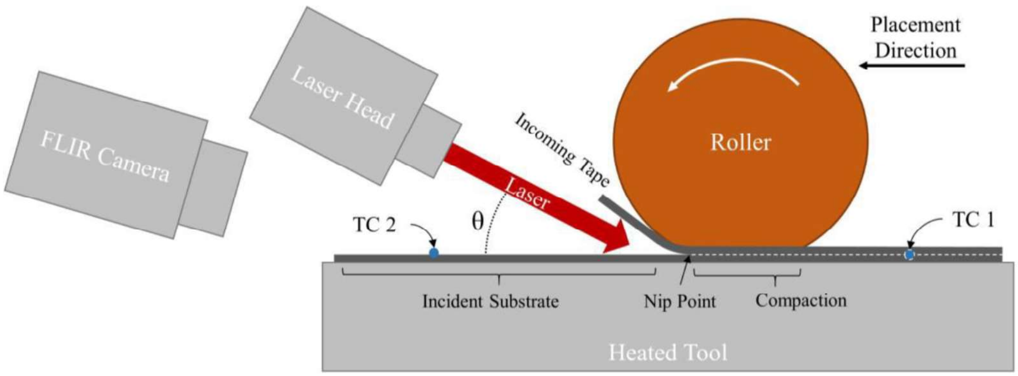

Figure 2: Schematic diagram of laser-assisted AFP.

2.2 Materials and Experiment Design

The materials used in this study included: an IM7 carbon fiber/polyetherketoneketone (PEKK) thermoplastic tape supplied by Hexcel® with an areal weight of 194 gsm and 34 wt.% resin content, a T800 carbon fiber/polyetheretherketone (PEEK) thermoplastic tape supplied by Toray® with an areal wight of 145 gsm and 34 wt.% resin content, and an IM7 carbon fiber/low-melt polyaryletherketone (LM-PAEK) thermoplastic tape supplied by Victrex® with an areal weight of 148 gsm and 34 wt.% resin content. Thermal properties are shown in Table 1. NASA conducted parallel-plate rheology of the neat resins, PEEK, PEKK, and LM-PAEK, provided by the suppliers and used in their respective carbon fiber (CF)/thermoplastic tapes. As shown in Figure 3, at the supplier recommended autoclave consolidation temperature for PEEK of 390°C , the PEKK resin has a significantly higher viscosity than the PEEK and LM-PAEK.

Table 1: Thermoplastic slit tape material thermal properties.

Thermoplastic Tape	Supplier	Trade Name	Fiber Areal Weight, gsm	Polymer T_g, °C	Polymer T_m, °C	2% Decomposition Temperature, °C
T800/PEEK	Toray	Cetex® TC1200	145	140	343	575
IM7/LM-PAEK	Victrex	AE™250	145	145	309	550
IM7/PEKK	Hexcel	Hexply-Kepstan® PEKK	190	162	332	575

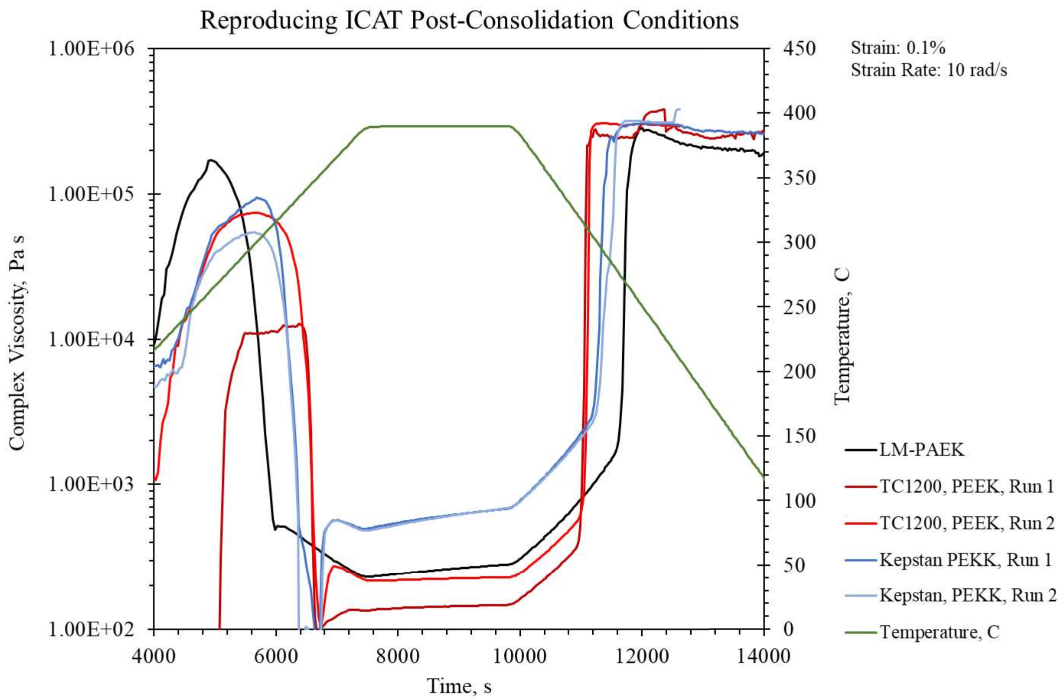

Figure 3. Parallel plate rheology of PEEK, LM-PAEK, and PEKK neat polymers using the supplier recommended PEEK autoclave processing temperature (390°C).

Five, 50.8 cm × 25.4 cm (20 in. × 10 in.), composite panels with 24-ply, quasi-isotropic layups, $[45/0/\text{-}45/90]_{3S}$, were fabricated with the processing parameters shown in Table 2. Preliminary processing trials on smaller panels were performed to understand the thermal response with a wide range of layup speeds and determine the final processing conditions used in this work. The laser power used for each panel was empirically determined to produce the desired target surface temperature of the prepreg tape as measured by the FLIR camera for each layup speed. The peak temperature was selected to balance maximizing time above melt (higher temperatures preferred) while minimizing/preventing decomposition (lower temperatures preferred). The first ply of all five panels was placed with a layup speed of 150 mm/s and laser power of 85 W based on previous placement studies, demonstrating these parameters ensured adherence of the prepreg tape to the Kapton® film. Therefore, the values for layup speed and average laser power in Table 2 only describe plies two through twenty-four.

Table 2: Panel fabrication parameters.

Panel	Layup Speed (V), mm/s	Average Laser Power, W	Tool Temperature (TT), °C	Target Peak Surface Temperature (ST), °C
IM7/PEKK-A	25	61	180	525
IM7/PEKK-B	50	89	180	525
IM7/PEKK-C	100	133	200	550
T800/PEEK	100	185	120	500
IM7/LM-PAEK	400	365	80	450

After ICAT processing in the laser-assisted AFP lab at Electroimpact®, the resulting panels were cut into three sections at the NASA Langley Research Center (LaRC) using a wet-saw resulting in an "ICAT-only", an "ICAT + Vacuum-Bag-Oven (VBO)" post-consolidation panel and an "ICAT + autoclave" post-consolidation panel. The VBO panel sections were post-processed under a vacuum bag in an oven, and the last section from each panel was post-processed in an autoclave at elevated temperature and pressure. All post-consolidation cycles were performed with the panel placed under a breather cloth and Kapton® vacuum bag without the use of a caul plate. Full vacuum of 101 kPa was employed for the entire temperature cycle, whether in an oven or an autoclave. Post processing utilized vendor recommended temperature and pressure cycles.

3. RESULTS AND DISCUSSION

3.1 Photomicroscopy

Photomicrographs of the PEEK and LM-PAEK "ICAT-only" test panels, "ICAT + VBO" post-consolidation panels, and "ICAT + autoclave" post-consolidation panels are shown in Figure 4 and 5, respectively. The photomicrographs displayed in Figure 6 through 8 are of the PEKK panel sections at the three post processing conditions. All photomicrographs were taken at a 100X magnification. Note legend key of Layup Speed (V), Tool Temperature (TT), and Target Peak Surface Temperature (ST) from Table 2 used throughout the figures presented.

Figure 4: Photomicrographs of T800/PEEK Panel (ST = 500°C, TT = 120°C, V = 100 mm/s).

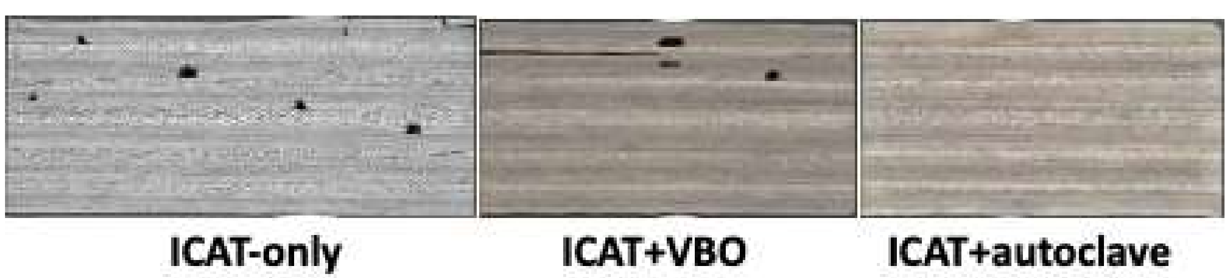

Figure 5: Photomicrographs of IM7/LM-PAEK Panel (ST = 450°C, TT = 80°C, V = 400 mm/s).

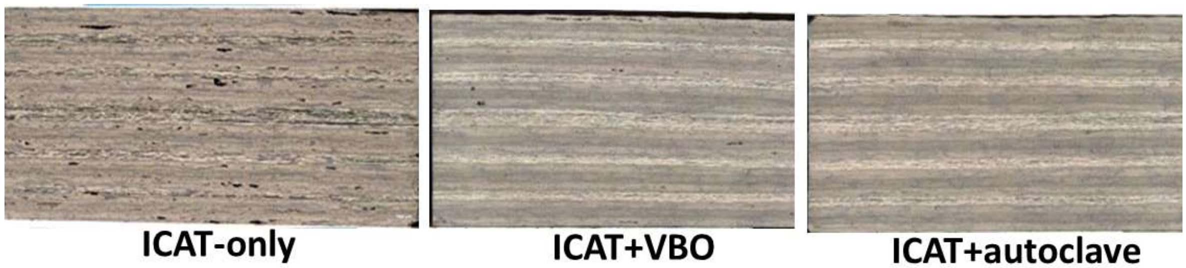

Figure 6: Photomicrographs of IM7/PEKK Panel A (ST = 525°C, TT = 180°C, V = 25 mm/s).

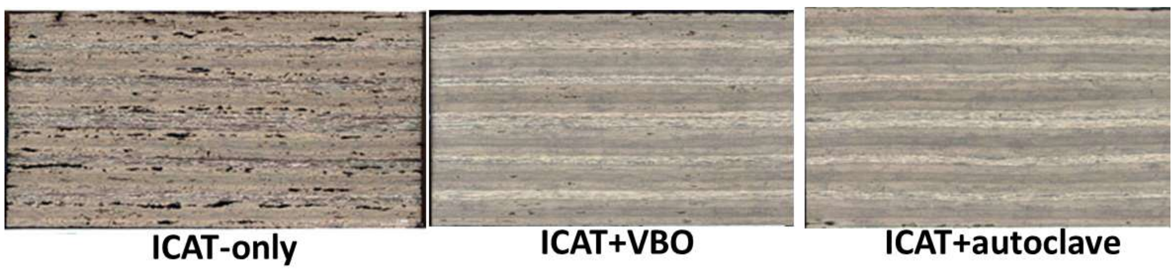

Figure 7: Photomicrographs of IM7/PEKK Panel B (ST = 525°C, TT = 180°C, V = 50 mm/s).

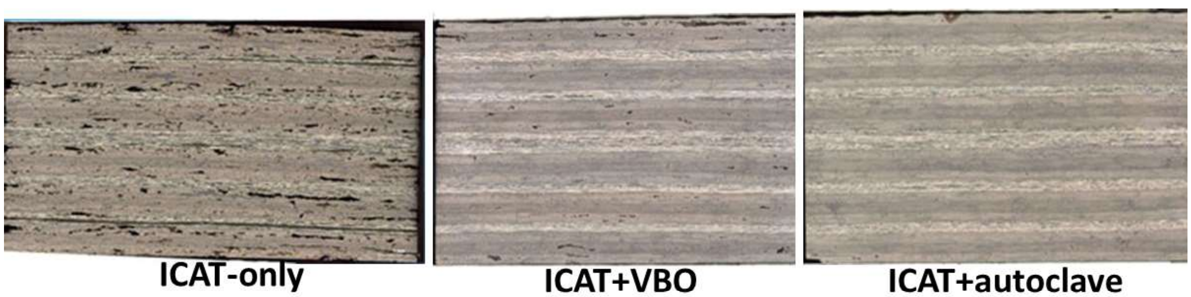

Figure 8: Photomicrographs of IM7/PEKK Panel C (ST = 550°C, TT = 200°C, V = 100 mm/s).

The photomicrograph images in Figure 4 through 8 indicate higher porosity in the ICAT-only sections of all the panels with decreasing porosity evident in the VBO post-processed sections and little to no porosity in the ICAT panel section post-processed in the autoclave. Porosity of the ICAT-only IM7/PEKK panels appears to increase with faster layup speeds with unacceptable porosity evident at even the slowest speed of 25 mm/s.

3.2 Ultrasonic Inspection

After the post-processing of the two panel sections in autoclave and by VBO, the three sections from each IM7/PEKK Panel A, B, and C and the IM7/LM-PAEK panel were submerged together in the NASA LaRC ultrasonic inspection tank for pulse-echo C-scan using a 10 MHz signal transducer. The screen capture of the non-destructive inspection (NDI) analysis of the signal for each of the PEKK panels is shown in Figure 9 through 11. In these figures the C-scan results are presented on the left side of the screen by the color (heat) map with the yellows and reds indicating higher percentages of the ultrasonic signal passing all the way through the laminate thickness and then back to the sensor; an indication of low to no porosity, or ply disbond. Also, in Figure 9 through 11, for the purpose of comparison all three panel section scan results are included in the same figure with the "ICAT + VBO" on the bottom, followed by the "ICAT-only" panel section and the "ICAT+ autoclave" section on the top, as labeled.

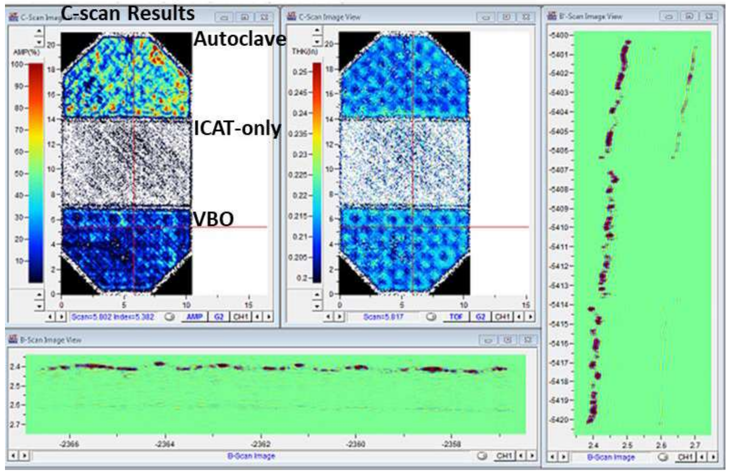

Figure 9: NDI results of IM7/PEKK Panel A (ST = 525°C, TT = 180°C, V = 25 mm/s).

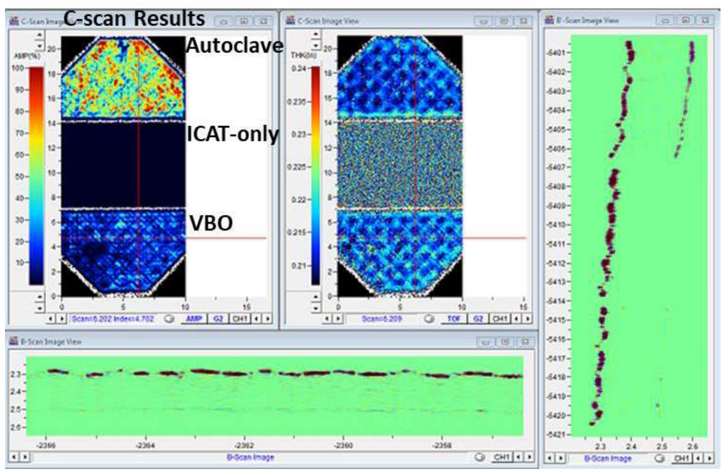

Figure 10: NDI results of IM7/PEKK Panel B (ST = 525°C, TT = 180°C, V = 50 mm/s).

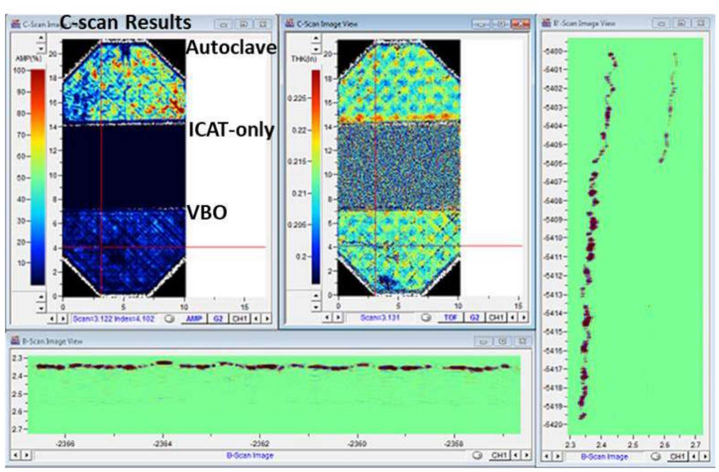

Figure 11: NDI results of IM7/PEKK Panel C (ST = 550°C, TT = 200°C, V = 100 mm/s).

The C-scan results of PEKK Panels A, B, and C and the LM-PAEK panel all indicate, with the dark color, that the porosity, or disbonds, in the ICAT-only sections are so significant that the ultrasonic signal can barely penetrate the laminate. The autoclave post-processed sections for each of the inspected panels are consistently low in porosity with the color map a mixture of blues, yellows, and reds typical of C-scan of quasi-isotropic laminates. The VBO sections indicate elevated porosity in comparison to the autoclave processed PEKK and LM-PAEK panels. Consistent with the photomicrographs shown in Section 3.1, the C-scan images of all the ICAT-only panels indicate very poor quality resulting in the need of a post-consolidation process.

3.3 Temperature Measurements

The thermal response of laser heated ICAT was investigated using FLIR and TCs to better understand fusion between layers (autohesion). Detailed explanation of the algorithm to combine FLIR and TC data is presented in [14]. The effect of AFP processing conditions on the time above melting temperature for the three PEKK panels is shown in Figure 12. As indicated in the figure as well as for the data for all the panels fabricated in this effort, the time above melt during AFP placement is below 0.5 seconds. This short time above melt is likely not enough time to allow for the development of sufficient bond strength/autohesion between plies, which is a documented relationship established in the literature [15].

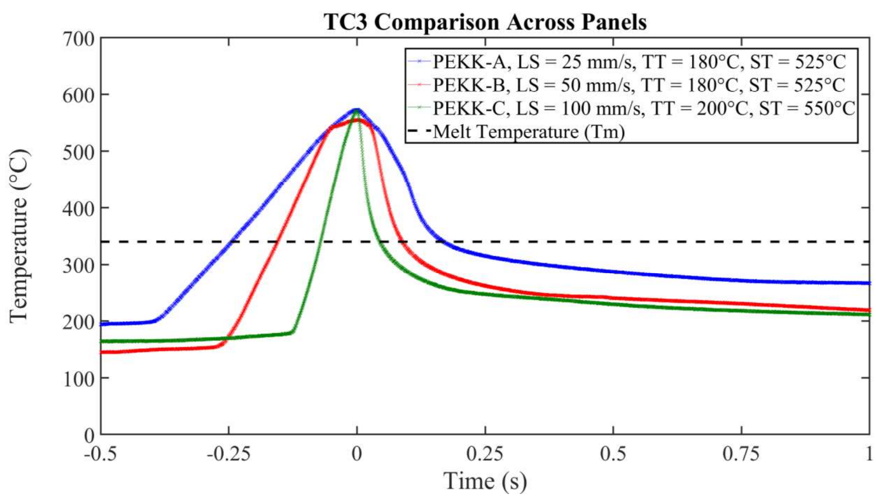

Figure 12: Comparison of times above melt temperature at TC3 located at the center ply for IM7/PEKK Panels A, B, and C.

3.4 Mechanical Testing

The PEKK, PEEK, and LM-PAEK 24-ply, quasi-isotropic test panels fabricated by NASA and Electroimpact® were tested to determine the short beam strength (SBS). ASTM Standard D2344-16 [16] was followed to determine the SBS of the "ICAT-only", "ICAT + VBO" post-consolidation, and the "ICAT + autoclave" post-consolidation laminates. Results of the SBS testing normalized to the "ICAT + autoclave" values are shown in Figure 13. The values plotted in Figure 13 are based on a minimum of five coupons, and the errors bars represent one standard deviation as a percent of the average value.

The three polyaryletherketone (PAEK) polymers were evaluated at laser target temperatures ranging from 450°C to 550°C and placement speeds ranging from 25 mm/s (59 in./min) to

400 mm/s (945 in./min). The highest performing of these materials and ICAT parameters is the T800/PEEK tape placed at ST = 500°C, TT = 80°C, and V = 100 mm/s. Although these parameters are not optimized, the resulting SBS of the T800/PEEK laminate fabricated by "ICAT-only" is less than 40% of the SBS of the same material fabricated by "ICAT + autoclave" consolidation.

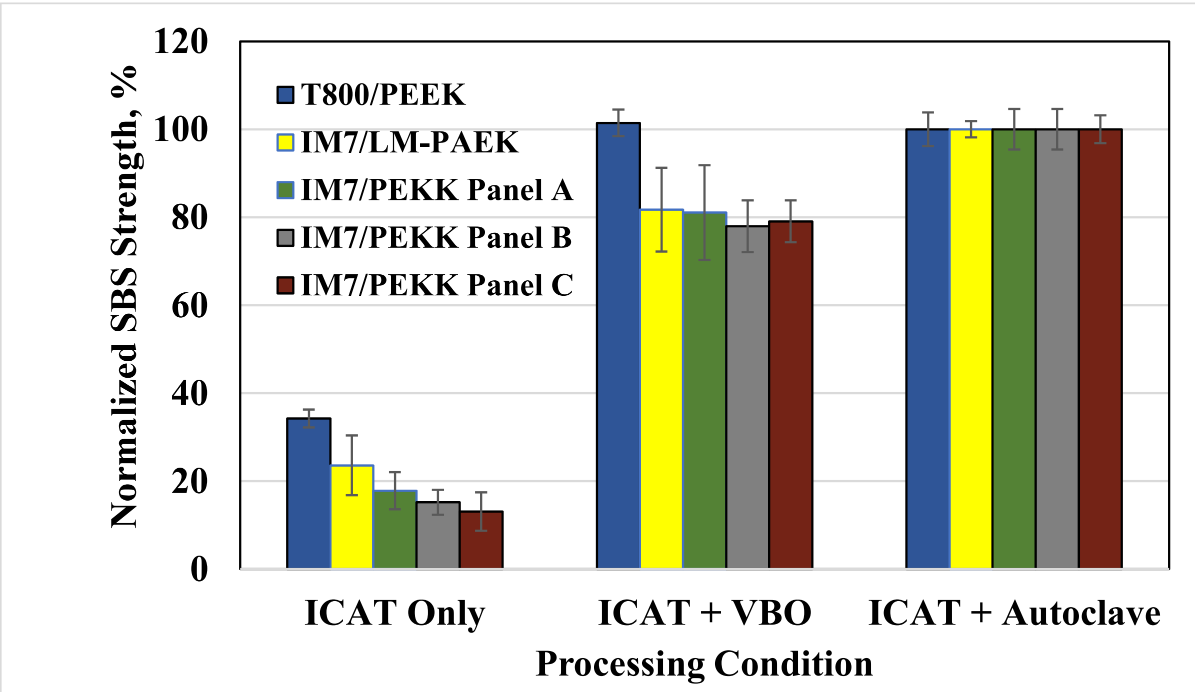

Figure 13: SBS results normalized to the "ICAT + autoclave" values from T800/PEEK, IM7/LM-PAEK, and IM7/PEKK "ICAT-only" and "ICAT + post processing" panels.

In a separate, but related, study [17], a 24-ply, uni-directional $[0]_{24}$ IM7/LM-PAEK panel was fabricated using slightly different ICAT processing parameters than used in this work and tested to better understand the higher short beam strength results reported by other groups [8]. As expected, when the ICAT process is used to fabricate unidirectional laminates, the molten thermoplastic matrix flows enough to allow the carbon fibers to migrate and "nest" within the inter-ply regions, and the SBS is significantly improved. The results from [14] indicate a SBS of the "ICAT-only" panel section that is 59 % of the "ICAT + autoclave" IM7/LM-PAEK panel section, which is very similar to values being reported by academia elsewhere [8] and which is higher than any "ICAT-only" quasi-isotropic laminates fabricated by NASA and Electroimpact®. The reason for this is further reinforced by the fact that the SBS of the "ICAT + autoclave" and "ICAT + VBO" panel sections were also significantly higher than any of the quasi-isotropic PEEK laminates consolidated by VBO and autoclave in this study. This result clearly indicates that lay-up can influence ICAT mechanical properties and initial panel quality, which was verified at NASA and reported in the literature [10, 18].

With current SoA equipment, ICAT cannot compete with the production rates of thermoset AFP + autoclave cure, where the AFP speeds can reach as high as 846 mm/s (2000 in./min). One potential solution is to develop a novel semi-crystalline thermoplastic with comparable glass transition temperature (T_g), or service temperature, and lower melt viscosity to the PAEK polymers. Another option is to modify the AFP equipment utilized to place the commercially available PAEK tapes to increase the time the tape is above melt during the ICAT process.

Although ICAT alone may not currently be viable to manufacture commercial transport aircraft at the desired rate with the equipment utilized in this work, high-rate thermoplastic AFP plus VBO processing may offer an attractive compromise. The data presented in Section 3.1, Section 3.2, and Figure 13 indicate that a post process with VBO results in better panel quality and SBS values approaching autoclaved panel sections. Therefore, a combined thermoplastic AFP process followed by an out-of-the-autoclave VBO process could be optimized to potentially meet future aircraft production needs.

4. CONCLUSIONS

NASA and Electroimpact® have evaluated the ICAT process using SoA AFP equipment augmented with a powerful diode laser heating system for three commercially available intermediate modulus carbon fiber/PAEK tape materials: T800/PEEK, IM7/LM-PAEK, and IM7/PEKK. Five 24-ply, quasi-isotropic laminates have been fabricated using various laser target temperatures ranging from 450°C to 525°C, heated TT ranging from 80°C to 180°C and placement speeds ranging from 25 mm/s (59 in./min) to 400 mm/s (950 in./min). Short beam shear strength testing of these ICAT panels in addition to sections of these panels post-consolidated in autoclave and by VBO has resulted in SBS values of "ICAT-only" less than 40% of the average SBS of ICAT panels consolidated in the autoclave after placement. Therefore, the ICAT process using current SoA equipment does not appear to be a viable process for high-rate production of primary composite structures on aircraft without hardware modification.

Further development resulting in adoption of ICAT will likely require modification of the AFP hardware beyond the current SoA for thermoset material placement. A potential modification could involve adding a second heat source that heats the tape after it is compacted under the roller to maintain the material temperature above melt until sufficient autohesion can occur that results in in-situ strength equivalent to autoclave consolidated thermoplastic laminate. Another option is to develop a thermoplastic material, either semi-crystalline or amorphous, that has equivalent mechanical properties to the PAEK matrix composites but possesses a lower melt viscosity or a lower melt temperature.

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