Thermoplastic Composite High Rate Fuselage Manufacturing Demonstrator

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ABSTRACT

Spirit AeroSystems, Inc., has designed and built a thermoplastic composite fuselage manufacturing demonstration article as part of the Hi-Rate Composites Manufacturing (HiCAM) project. Compared to previous demonstration articles, this one is larger (1.2 m x 2.6 m) and features additional complexity that will be present in the next commercial composite aircraft such as thickness tailoring and compound curvatures in the fuselage skin. Skin thickness range from 7mm to 2.5 mm is thicker than any existing demonstrators consolidated using vacuum bag only. Technologies featured include Automated Fiber Placement, Automated Stiffener Forming, stamp forming, Co-Fusion, and induction welding. In collaboration with HiCAM partner companies, comprehensive evaluation criteria were established as goals to demonstrate MRL 4. Evaluation criteria include dimensional requirements on: laminate thickness variation, feature position, and surface profile tolerances on interface surfaces. Additional evaluations include Non-Destructive Inspection, coupon mechanical testing, and photomicrographs to verify the internal composite laminate structure. The material is based upon work supported by NASA under award No 80NSSC22M0194, any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Aeronautics and Space Administration.

Keywords: thermoplastic composites, induction welding, stamp forming, automated fiber placement
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1. INTRODUCTION

As the demand for air travel increases so to must the capacity to manufacture aircraft. Within the NASA HiCAM project, manufacturing systems have been designed to produce composite single aisle sized aircraft at a rate of 80 per month. This rate represents a 6-8X improvement over current rates. The Boeing 787 is being produced in rates of around seven airplanes per month (APM) [1] and using the Airbus A320 as an example of a state-of-the-art single aisle aircraft the 2024 delivery rate averaged out at 47.6 APM [2]. To meet the objective of HiCAM not only does the industry need to increase production rates beyond what it can do for mostly metal airframes it must also invest in tooling, equipment, and knowledge if it wishes to produce composite airframes at 80 APM. To do so cannot be achieved with minor variations and improvements. Cost modeling of a greenfield factory to produce fully Thermoplastic Composite aircraft at 80 APM shows a 43% cost savings opportunity compared to the HiCAM baseline aircraft which uses 2020 state of the art materials and manufacturing methods.

To show this thermoplastic manufacturing concept as viable, Spirit is building a Readiness Level (RL) 4 demonstration article as part of the HiCAM project [3]. The design of the RL4 demo article is shown in Figure 1. The demonstration article is representative of the forward fuselage section of an aircraft incorporating longitudinal and radial stiffening elements, variable skin thickness and compound curvature. The rates for detailed part fabrication and assembly as well as the costs of equipment and tooling used on the demonstrator are used to refine the estimates in the aforementioned cost model.

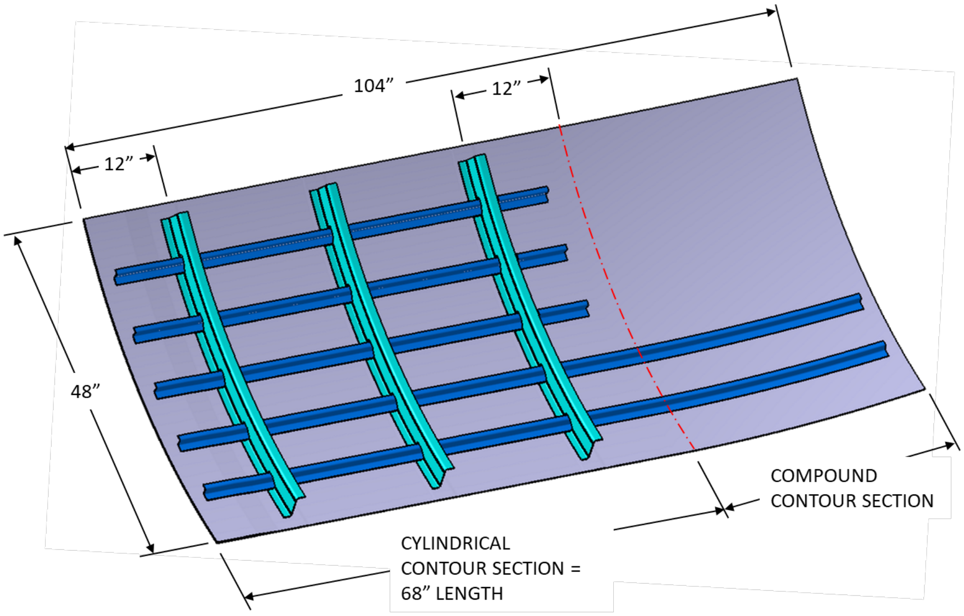


Figure 1. Spirit AeroSystems fuselage stiffened skin Readiness Level 4 demonstrator panel

This demo article is an exciting way to demonstrate US manufacturing capability and technology. All components on the panel are made from semi-crystalline thermoplastic unidirectional prepreg tape utilizing Intermediate Modulus plus fibers. The skin varies in thickness from 7 mm to 2.5 mm, the radius is 1.98 m at the aft end and transitions to 1.9 m over the final 0.9 m in length, and is 4.6 m^2 in acreage making it the largest thermoplastic skin produced in the United States. The stringers and frames are welded to the skin to demonstrate assembly without fasteners and without adhesive bonding. Several technologies are proved out to RL4 by the manufacture and evaluation of Spirit’s demo article. Those technologies are: laser assisted thermoplastic Automated Fiber Placement (AFP), stamp forming, and thermoplastic welding. Within the umbrella of welding Spirit is demonstrating induction welding (IW) and their patented Co-Fusion [4] method. Subsequent sections of this paper discuss the part fabrication challenges, features of the parts relevant to derisking full scale production, assembly methods, and lastly the evaluation of the assembly.

2. EXPERIMENTATION & RESULTS

First a brief description of each of the fabrication or joining technologies is given and then the manufacturing story is given for each part: skin, stringers, frames as well as joining stringers to the skin with Co-Fusion and then the frames to the skin-stringer panel with induction welding.

2.1 Fabrication and Joining Technologies

Thermoset AFP is widely used to manufacture large acreage components like fuselage and wing skins. The concept is similar for thermoplastics except that the material must be melted for it to fuse to the prior ply. Material is paid out in the form of slit unidirectional tape usually 6.3 mm or 12.5 mm wide. As the material is paid out, it and the prior course are locally heated just ahead of the compaction roller. The compaction roller presses the molten material into the ply beneath, cooling the material as it goes; cooling from process temperature to below melt temperature happens in a fraction of a second.

Spirit used a robotic AFP with laser heating to make skins and frame blanks in support of their RL4 demo article. The nip temperature used was 320°C. NIP temperature, compaction pressure, and laydown speed all contribute to the level of consolidation of the part coming directly off the AFP. Between the skin and the frame blanks compaction pressure, and laydown speeds were different and will be discussed in more detail within their respective part fabrication sections. However, in both instances the level of consolidation was sufficient to retain integrity for physical handling, but a mislaid tow could still be peeled off without damaging the underlaying ply. The effect of AFP parameters on part quality after consolidation was presented previously [4].

Stamp forming is a highly developed technology for manufacturing thermoplastic parts but has only been demonstrated on parts of limited complexity and size. The process begins with a pre-consolidated or AFP made blank. This blank is heated to above the thermoplastic matrix melting temperature and then quickly transferred and stamped to shape between matched metal dies. The dies are kept cooler than the blank (typically halfway between the glass transition and melt temperatures of the matrix) and the forming takes place as the dies close. This allows the part to be removed from dies after only a few minutes, while also allowing sufficient crystallinity to develop. The entire forming process is accomplished in five minutes. AFP followed by stamp forming was used to make stringers and frames for the RL4 demo article.

Co-Fusion is a patented thermoplastic composite processing method that combines skin consolidation and welding of faying stiffening elements into a single bag molding process [5]. The system utilizes a heated tool and breather/insulation under the bag in an ambient temperature room or autoclave to create a thermal gradient through the thickness whereby the skin and faying flanges melt but the protruding portion does not. As a result, the upstanding stiffening elements do not need to be tooled, instead it only needs to be stabilized to prevent leaning and support it at the correct angle. Furthermore, because of the insulation, an unheated bagging excess area, and the low temperature of the surroundings Co-Fusion can be done with much more user friendly and inexpensive standard temperature nylon bagging expendables. Co-Fusion is used to consolidate the skin at the same time as welding stringers to the skin.

During the process of induction welding thermoplastic composites, a high frequency alternating current is applied to an induction coil, which in turn creates an alternating magnetic field. This alternating magnetic field induces eddy currents both in the carbon fiber ply and between plies, forming 3D eddy currents that heat the fibers and the matrix through joule losses and dielectric heating [6]. The heat spreads locally across the laminate, melting the thermoplastic matrix. To weld components together, the faying surfaces are clamped together, and the inductive heating is applied until the matrix in the weld region melts. The joint is maintained under pressure, after the removal of the induction heating, while the weld cools until it is cold enough not to deconsolidate when pressure is removed. Welding removes all processing steps associated with fastening as well as reduces part weight by not adding reinforcement to compensate for material weakening due to holes. The impact of removing drilling from manufacturing cannot be overstated as mis-drilled holes are a top driver for scrap and rework. Induction welding was used to join the frames to the skin.

2.2 Skin Manufacturing

In preparation for AFP of the skin two activities were needed. The first was to understand the shape distortion of the skin after AFP. Being able to predict the amount of distortion allowed the fiber placement mandrel (FPM) to be shape compensated such that when the skin is taken off and distorts it matches the contour of the consolidation tool as closely as possible. The second activity needed was to build flat panels with the same thicknesses and ramps that would be in the contoured skin.

Spirit's experience with the ASPERA panel (CAMX 2023 Award for Composites Excellence (ACE) winner for Manufacturing: Materials and Process Innovation) revealed Thermoplastic skins made by AFP will distort or warp away from the tool [7]. Figure 2 shows a guess and check process to estimate the needed radius of a FPM to produce a panel with the same 1.98 m radius as ASPERA. In the case of the ASPERA skin it was laid up in a female tool with a 5.76 m (227") radius (circled in blue) and warped to about a 1.98 m (78") radius (circled in yellow). The purpose of this new FPM was to study the warp of skins made on a male FPM with thickness and curvature that were present in the RL4 Demo skin. Assuming the same 67 mm (2.6") deflection from the layup surface (circled in blue) it was determined a FPM with a radius of 1.2 m (48.9") (circled in green) would be needed. This assumption turned out to be safe but may not extend to much thicker parts or ones with a much different desired radius.

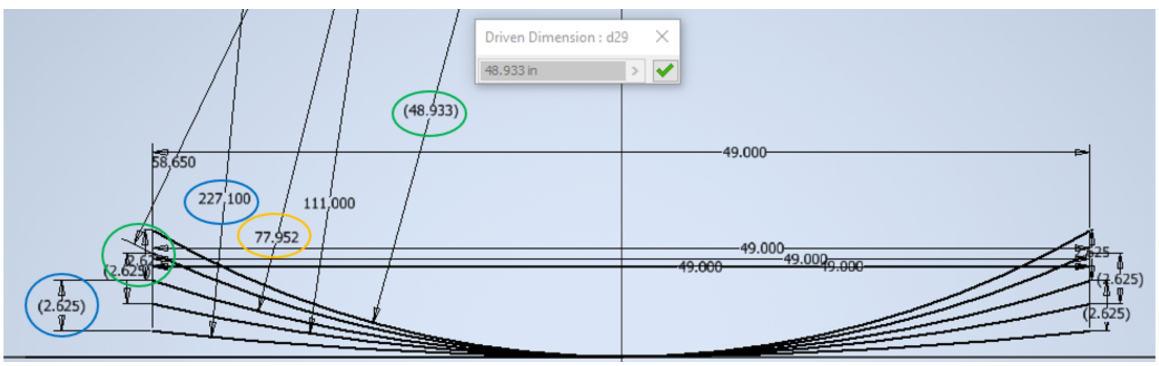


Figure 2. Estimating needed radius of layup surface

This exercise resulted in a tool with two layup surfaces "Zone A" and "Zone B". The features of the tool are shown in Figure 3. Referring back to Figure 1, the Demonstrator skin is 50 plies thick at the aft and ramps down to 18 plies after the aft frame bay. The forward area of the demo skin narrows creating compound contour. The warp compensation tool reproduces these features. Four different parts were made on the warp compensation FPM, their description is in Table 1.

Table 1. Test parts run on Warp Compensation tool

Zone	**Ply Count**	**Features**	**Ran on Zone A or Zone B Side of Tool**
A	24	Constant curvature, thin skin	A
B	60→48→24	Ply ramps, thick skin, compound contour	B
C	32	Constant curvature, moderate thickness skin	A
D	48	Constant curvature, thick skin	B

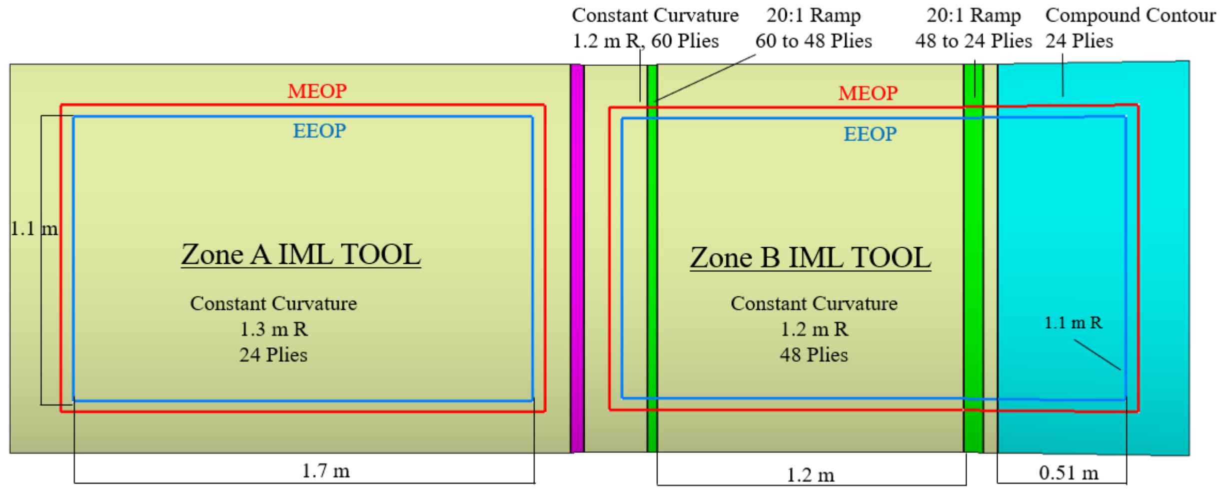
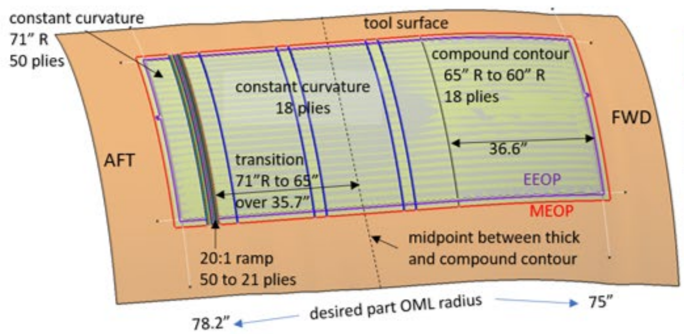


Figure 3. Warp Compensation FPM. Two different layup zones are needed to encompass the complexity to be tested

Parts A-D were scanned from the IML with a Faro® Quantum S Max 7-Axis Arm equipped with a xP Laser Line Probe (LLP), and a Faro® VantageE6 Max Laser Tracker. In Polyworks measurement software, cylinders were created at three points along the length of the panel. The radius of the cylinder was determined by a best fit between the cylinder and the surface of the test parts as determined by the scan data. The radius of the cylinder was considered the radius of the part and used to plan the FPM shape compensation for the Demo skin FPM.

From the radius measurements made on the test panels an engineering estimate was made to determine the shape compensation of the Demo skin FPM. The tool surface and amount of shape compensation used are shown in Figure 4. At a thickness of 24 plies the amount of spring out was considerable with a radius change of 0.7 m (28"). The difference in spring out between the 60 ply region on Part B and Part D with a constant thickness of 48 plies was insignificant; in both cases the spring out was 0.15 m -0.18 m (6" – 7"). Even though the compound contour area of Part B was the same 24 ply thickness as Part A, the combination of compound contour and the stiffening from the 48 ply thick region of Part B resulted in an opening of the radius only in the range of 0.33 m – 0.38 m (13" – 15") as opposed to twice that on Part A. When deciding on the compensation needed for the Demo Skin FPM the compensation for the 50 ply region was taken from the 48 & 60 ply results in Figure 4. Compensation values for the compound contour section of the RL4 demo skin were taken from the compound contour section of Part B. Knowing that the "middle" of the demo skin was constrained by compound contour in the forward section and a very thick region at the aft instead of compensating using results from Part A whose 24 ply thickness matched the 18 of the demo skin most closely, an intermediate value based on the 32 ply thick Part C was used.

In preparation for laying up the Demo skin in contour flat panels with the same skin thicknesses, ramps, and tear straps were built. The first challenge encountered was the roller would not conform to the ramp from the 50 ply to 21 ply tearstrap thickness region. The problem was most exaggerated on 45° and 135° courses. Having a 10 cm wide roller meant the roller was riding high on the ramp and bottoming out on the tear strap region, leaving the area in-between uncompacted (Figure 5).



Skin Comp Study

Ply Count	Opening of Radius
24	28"
32	13"
48, 60	6"-7"
24 compound contour	13"-15" (AFT- FWD)

Demo Skin FPM

Ply Count	Proposed Compensation
50	7"
18	13"
18 compound contour	15"

Figure 4. Shape compensation of RL4 Demo skin FPM

The result is tows not being properly adhered to the ply beneath as shown in Figure 7. To troubleshoot, a softer roller (60 versus 70 shore A hardness) was swapped in. However, the softness of the roller let wrinkles in the kapton wrapping develop, as seen in Figure 6which were having an unacceptable effect on part quality. By changing from a 10 cm wide roller (16 tows) to a 5 cm wide roller (8 tows) the conformity concerns were overcome.

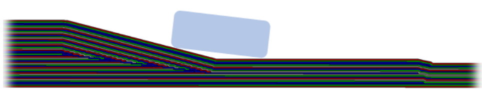


Figure 5. AFP roller bridging

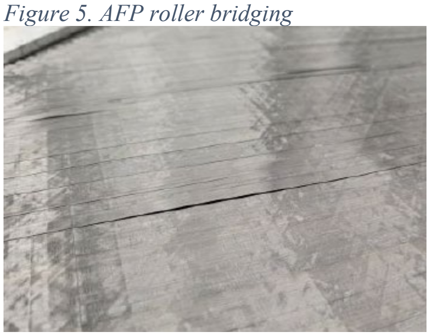


Figure 7. Tows not sticking because of roller bridging

Figure 6. 60 shore A hardness 5 cm compaction roller

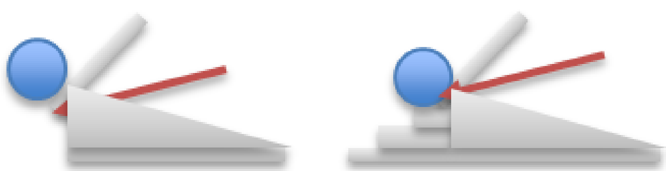


Figure 8. Laser shadowing on thick laminates

The additional difficulty discovered form the flat panel work was getting tows to stick to the 50 ply region when traveling from aft to forward. Spirit's hypothesis was the tows were not receiving enough heat from the laser. The reason for this is purely geometric as illustrated in Figure 8. The left side of Figure 8 shows the AFP head needing to suddenly climb up the tall side-wall of the laminate. The angle of incidence of the laser with respect to the nip point resulted in the laser being blocked from reaching the nip point. In contrast, on the right side of Figure 8 the AFP head has less of a vertical height it needs to suddenly climb so the laser is not blocked by the already laid up plies.

Full size demonstrator skins were laid up at 0.5 m/s (1200 ipm) using only five of the planned eight tows. The additional complexity moving from a flat to a contoured layup tool meant there was not enough roller compliance for an eight tow wide course. Only the first ply was tried with eight tows before reverting all plies to a five tow lay down. Spirit believes six tows is possible and that eight tows after the first four plies are down should also be possible. Figure 9 shows the skins fit relatively well in the Co-Fusion tool. They lift off the tool surface about 0.9 cm at the aft end and 1.9 cm at the forward end. This amount of distortion can be pulled down by the vacuum bag, based on trials done with parts A, B, and C. Part D was too thick for the bag to pull it into shape. A laydown rate of 2 kg/hr was achieved. Ply by ply inspection, a standard production practice, accounted for 44% of the run time. Technology advancement of AFP rollers to allow all 16 tows to run and assuming a production representative inspection time of four minute per ply increases the lay down rate to approximately 3.6 kg /hr. Cost modeling assumed 10.4 kg/hr. Additional opportunities to increase the laydown rate would be using 12 mm wide tows, development of a higher areal weight uni-tape product, increasing run speeds to 0.8 m/s, and using automated inspection technologies to reduce inspection time by around 50%.

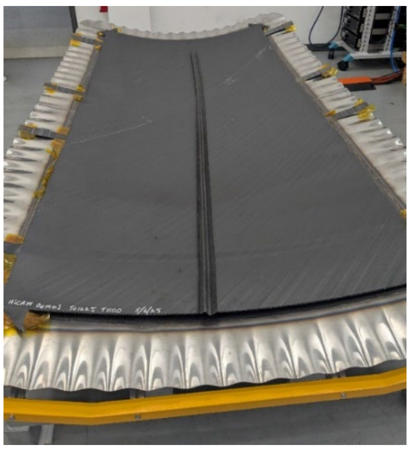


Figure 9. Skin for RL4 article resting in Co-Fusion tooling

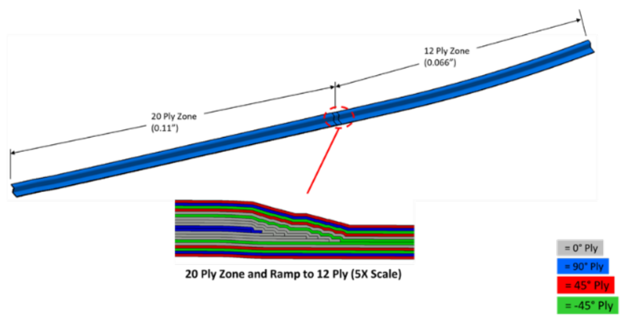


Figure 10. Stringer design

2.3 Stringer Manufacturing

Stringers were not made by Spirit. There are two types of stringers on the Demo Article. One type is made from Stamp Forming with AFP making the blank. The second type is made from the Northrop Gruman Automated Stiffener Forming (ASF) process. ASF stringers are on the order of 2.4 m long and have a thickness change from 20 to 12 plies as shown in Figure 10. ASF stringers are made from Toray T800/TC1225. The stamped stringers share the same outer profile as the stamped form stringer but do not extend into the compound curvature section of the skin. These stringers are made from Syensqo IM8/PEKK-FC. Spirit receives the stringers fully consolidated, trimmed, and inspected and used Co-Fusion to weld them to the skin.

2.4 Frame Manufacturing

Frames are the hoop stiffening elements in the structure of an aircraft. Frames on the demo article represent about a 30° arc segment of a complete frame for a single aisle aircraft. Features of the frame include a one-piece design and the tailoring of ply thickness as seen in Figure 11. The variable thickness of the frame adds considerable complexity to the stamp forming process as the ply drops need to be located perfectly in the stamp die [8]. This requires a high degree of repeatability and accuracy on the AFP machine to put the ply drops in the correct place (the right distance between the top flange and skin flange ply drops) and the same place every time. The blank also needs to be accurately placed or indexed into a shuttle tray that carries the blank from the oven to the press. The shuttle tray positioning is accurate and repeatable, but the manual operation of placing the fame blank in the shuttle tray relies on index features on the blank that can coordinate to hard tooling points in the shuttle tray.

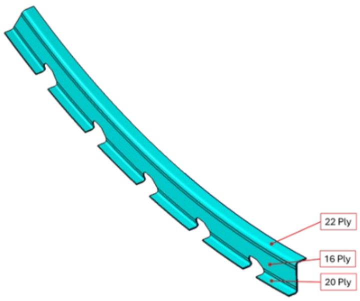


Figure 11. Frame design

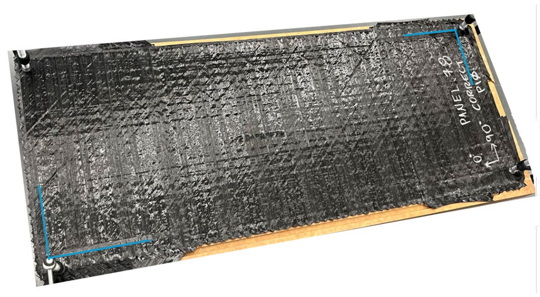


Figure 12. Example of cross hairs for index location

An indexing feature was created by having the AFP place two tows at a right angle to each other to form a corner marking on the top ply of the frame blank. This was done at two locations. An example of this is given in Figure 12 with the cross hairs exaggerated by blue lines. After AFP the next step is trim. A laser pointer is put into the chuck of the trim machine and the location at which the laser pointer aligns with the indexing mark is stored. Holes are drilled in those two points and become the locating features that coincide with hard points (circled in yellow in Figure 13) on the shuttle tray. Two more important aspects of the shuttle tray are how it holds the blank and how it accommodates the large Z-axis travel of the stamp die. For repeatability and ease of loading, the frame blank is held by tabs which fit into slots put into the blank during trim. Compared to the wire and hole method seen in Figure 14; this way of holding is more robust and less likely to induce severe wrinkling. The inner portions of the shuttle tray start attached but then as the stamp die starts to fold the flanges of the Zee the inner portion breaks away to minimize the pulling / wrinkling forces along the sides of the blank.

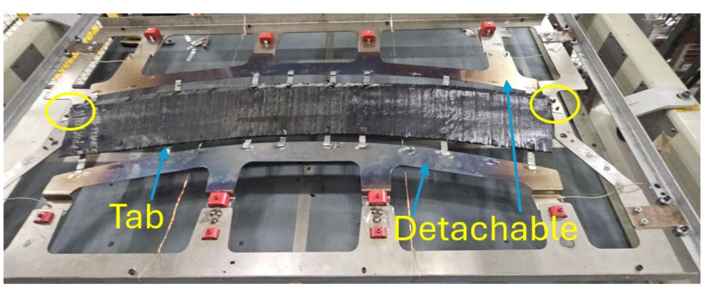


Figure 13. Frame blank loaded in shuttle tray

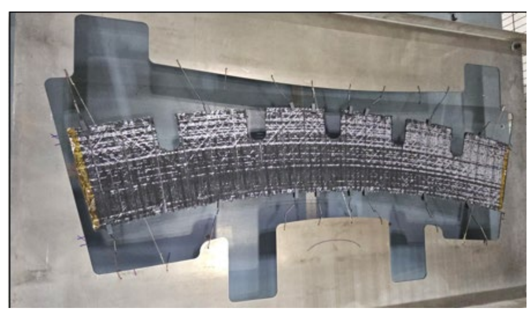


Figure 14. Old style shuttle tray

2.5 Co-Fusion

Co-Fusion is the welding technology Spirt chose to join stringers to the skin. Advancements to the Co-Fusion process included induction heated facesheer made from a low Coefficient of Thermal Expansion (CTE) alloy, unheated substructure with differential expansion guide stems, stringer support fixture, bagging procedures for pressure uniformity and process modeling.

Heated tooling allows for rapid heating and cooling compared to an oven cycle. Spirit chose induction heating over joule heating (used for their ASPERA article) for increased temperature uniformity and still further reduced cycle times. An infrared image of a temperature uniformity check of the Co-Fusion tool is reproduced below as Figure 15. The pattern of the induction coils can be clearly seen. The hottest spots on the tool are outside of the edge of part. Also evident in the thermal image are the patent pending expansion stems that isolate the heated face sheet from the cold substructure of the tool. The expansion stems are each uniquely oriented such that they allow undistorted expansion of the compound contour tooling facesheet.

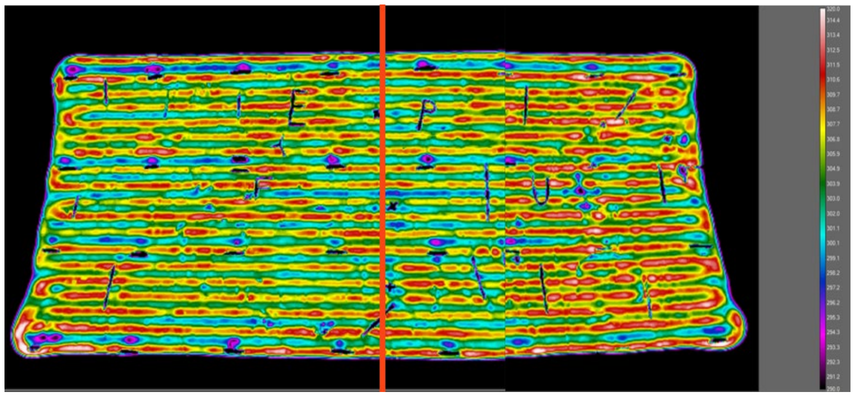


Figure 15. Tool temperature survey

Figure 16 shows Co-Fusion bagging in practice. There is a risk the bag will want to grab the upstanding leg of the L-stiffener causing it to lean. In this example three angles support per stringer are used. Supports generally need to be longer than they are tall otherwise they will tend to lean. Additional best practices around the angle supports include rounding corners to not puncture the bag, reducing friction between the angle supports and the stringer, and having an even surfaces for the angle support to rest on.

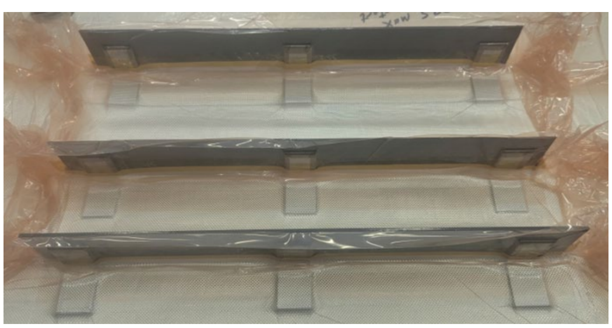


Figure 16. Co-Fusion process development showing stringer angle supports

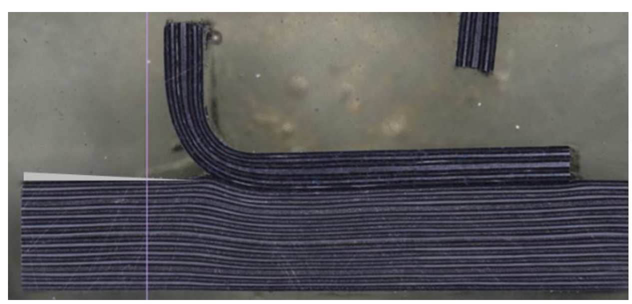


Figure 17. Co-Fusion pressure defects

Once vacuum is applied the Co-Fusion insulation reduces in thickness. This causes the angle support to slide against the stiffener and the resulting friction counters the bag pressure, reducing the pressure applied for consolidation under the support. Teflon tape is applied to the angle supports to reduce friction. Any time a reduction in consolidation pressure occurs there are corresponding indications on the OML that show as flaws during inspection. Figure 17 helps to illustrate two possible process insufficiencies. The first is the stringer getting pushed down into the skin by the bag; this is assumed to be from friction on the upstanding leg. When this occurs, the skin undulates before and after the stiffener. A second challenge is getting pressure under the upstanding leg, into the gap left by the radius of the stringer. Cauls (represented as the gray triangle in Figure 17) are used to cantilever the pressure from the unobstructed space to under the upstanding leg.

Process modeling of Co-Fusion has been focused on heat transfer rather than the prediction of weld strength. Temperature predictions of the skin and stringer helped to inform process decisions on heat loss through the angle supports, the amount of Co-Fusion insulation needed to achieve uniform skin temperature, the feedback thermocouple location, and the location of the melt front as a function of feedback temperature. The melt temperature of PEKK-FC is 337ºC (639ºF); Spirit preferred to see the back of the welded flange temperature reach a temperature in excess of that to ensure a low enough viscosity for polymer chain reptation. However, the temperature at the weld line could not be measured without contaminating the weld with a thermocouple. Therefore, the goal was to let the skin flange of the stringer reach a cut off temperature above melt temperature before turning off the heat during Co-Fusion. As demonstrated in Figure 18 there are four combinations of skin and stringer thickness that must be welded together. Spirit chose not to make the Co-Fusion tool zoned to cater to these changes in thickness. To weld the stringers at the aft end of the panel enough energy must be put into the assembly to bring a 70 ply stack-up to temperature. On the forward end the stack-up is only 30 plies. Also in Figure 18, simulation shows about a 20ºC temperature delta between the thickest and thinnest combined skin plus stringer thickness using the same amount of insulation over all surfaces. The 20ºC delta risked either overheating the thin stringer region allowing the radius of the stringer to melt or not getting the thick stringer hot enough to ensure a strong weld. Simulation results shown in Figure 19 indicate adding 6 mm more of insulation over the thick skin-stringer weld will produce a very similar temperature distribution to the thin skin.

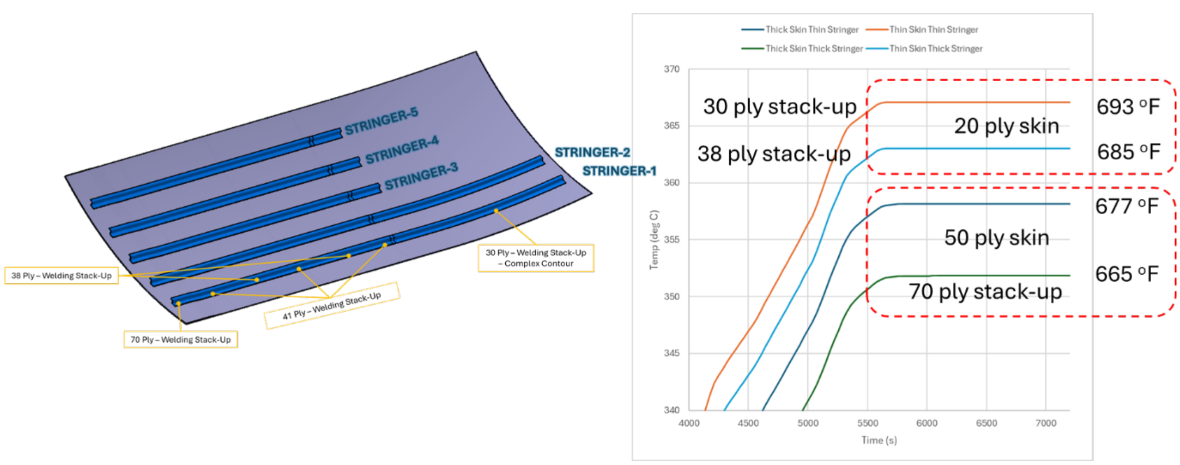


Figure 18. Surface temperature for different welding stack-up thicknesses

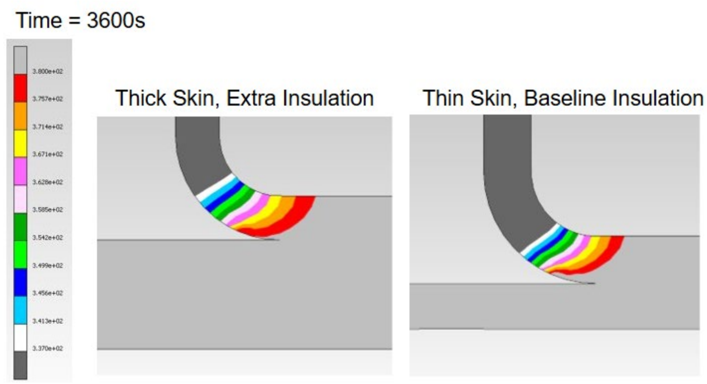


Figure 19. Stringer radius temperature with varying weld thickness and insulation

Vacuum Bag Only (VBO) consolidation of thermoplastics commonly used a process temperature dwell of 60 - 90 minutes, whereas dwell times considered for Co-Fusion as a welding process were 5 – 10 minutes. Simulation was used to judge if adding additional dwell time during Co-Fusion risked melting the stringer radius. Figure 20 shows the temperature distribution in the skin and stringer with and without an additional five minute dwell. While the temperature bands of 364ºC and 370ºC widen ever so slightly with the five minute dwell, the temperatures in and near the radius do not change.

Peeling the stringer off the skin by hand was a qualitative way to judge the progress of Spirit's Co-Fusion process development. Spirit found that the portion of the skin flange closest to the radius was the easiest to peel off the skin, suggesting a weak weld. Spirit hypothesized the weld was forming from the free edge and progressing towards the web of the stringer where the heat losses would be greatest. As described earlier, once the thermocouple on the stringer skin flange reached a cut off temperature in excess of melt heat was turned off to keep the stringer radius from melting. The top image in Figure 21 is a simulation where the thermocouple is on the free edge of the stringer skin flange melts before the rest of the stringer. By moving the thermocouple location closer to the radius, the entire faying surface of the stringer gets hotter without melting the radius leading to a stronger weld. The qualitative test of peeling the stringer off the skin was repeated and the fiber pull out in the fracture surface reached all the way to the stringer radius.

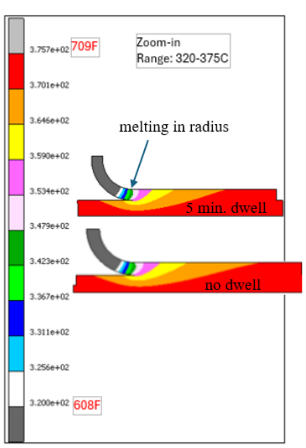


Figure 20. Effect of dwell

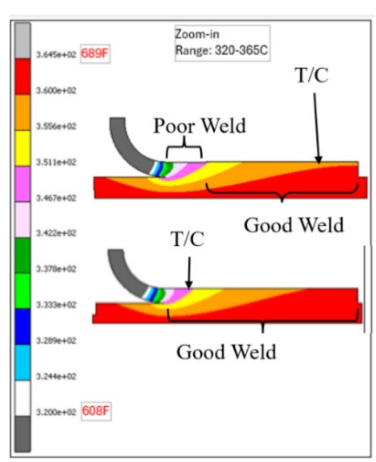


Figure 21. Effect of thermocouple placement

2.6 Induction Welding

Spirit's induction welding process followed a stepwise approach where the coil was integrated into an end-effector that clamps the parts to be welded and keeps them under pressure throughout the welding cycle prior to moving to the next station. Spirit's step wise induction process was originally developed as a universal welding solution applying it to frame to skin welds is fortuitous since they are discontinuous welds but helps establish the uniqueness of Spirit's technology. Figure 22 shows an example of how the frame welding process works.

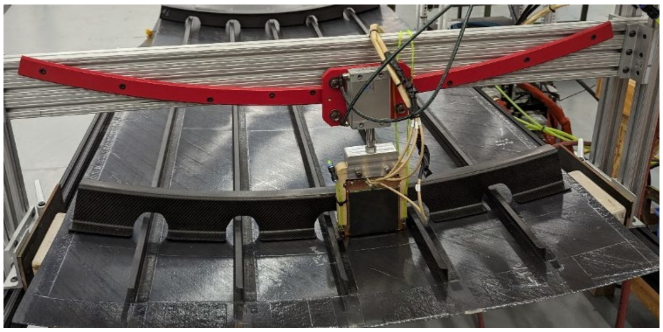


Figure 22. Induction welding of frames

Figure 23. Induction welding pressure bladder

A challenge with using the coil to also apply weld pressure accommodating non flat surfaces like curved skins or joggles. This was previously achieved using molded shoes that fit the coil on the inside and the outer surface is molded to match the surface of the part being welded. Spirit's patent pending solution implemented on the RL4 demo article was to use a bladder as seen in Figure 23. For maximum effect the bladder is pressurized with coolant to minimize surface melting and bladder durability. The reaction force on the gantry assembly is not insignificant and the gantry pictured in Figure 22 is being replaced with a stiffer one.

For Co-Fusion it was very common to use thermocouples to measure temperature at or near the weld line; for induction welding the thermocouples influence the electric field and do not allow for a truly representative weld profile. None the less thermocouples were used to find the amperage and time settings as part of recipe development. Some temperature setpoint features of the welding power supply were also used. This required the use of a thermocouple in the weld line so would not be a production viable solution but was found to be helpful during the recipe development portion of the project. A desired temperature setpoint and amperage limit were set in the power supply, and the power supply would attempt to ramp to the temperature setpoint by modulating the applied power. The first attempts at using this feature either resulted in the amperage limit being hit without achieving the desired temperature setpoint or making smoke by overheating the top adherend. A more gradual heating of the weld achieved melt at the weld line without detrimental heating to the top adherend, although there were still edge effects and partial width welds. Critical to the success of the final welding recipe was increasing the pressure of the bladder from at 0.207 MPa to 0.34 MPa. The added pressure kept the heat affected zone on the skin and top adherend from deconsolidating allowing for a more complete weld without quality concerns on the top surface.

For purposes of developing a welding rate metric, all HiCAM partners, including Spirit collected temperature data along a 25 cm long L-stiffener welded to a skin. For Spirit, the data is shown in Figure 24. Five thermocouples are placed along the length of a L-stiffener so that at each step two or three thermocouples would be under the coil while the remainder would show how far heat travels away from the coil giving insight into the heat affected zone. A 90s weld time per shear tie is claimed for frames on the basis the next shear tie is not at risk of getting heated by the previous step weld as is the case with a continuous stiffener. The large time interval between peaks in Figure 24 is to allow the weld zone to cool to 40-50ºC before initiating the next weld. About 60s of cycle is to get the weld to peak temperature. After 30s of cooling the part is below melt but above its glass transition temperature, *Tg*. An additional 15-20s appears to be sufficient for temperatures to recced to *Tg*. Another strategy to control heat buildup would be to move to non-adjacent locations even for a part that needs a continuous weld.

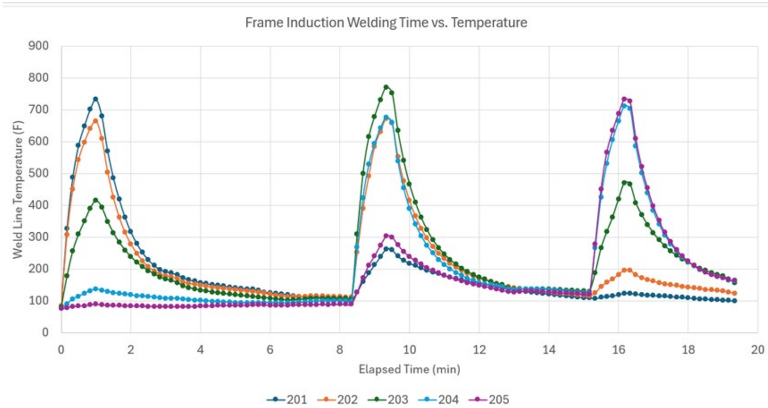


Figure 24 Induction welding time-temperature profile

2.7 Assembly and Inspection Planning

The following is a brief list of the assembly and inspection steps for Spirit's RL4 Demo article.

1. Demonstration article skin will be fabricated using AFP. Locating holes will be drilled into tooling tabs of the skin while it is still on the Fiber Placement Mandrel. The holes will coordinate with holes on the Co-Fusion tool to locate the skin longitudinally and to restrain any rotation. (Figure 26)
2. The skin is loaded and pinned to the Co-Fusion tool. Stringers are clamped to hard tooling bars pictured in Figure 27. Once located, the stringers are tacked to the skin to hold them in place. Co-Fusion will weld stringers to the skin at the same time as consolidating the skin.
3. The skin stringer panel will undergo final trim on a 5-axis trim machine using the panel OML and tooling tabs as datums.
4. After trim the skin-stringer panel transferred to the induction welding gantry and located using the same datums as during trim. The induction welding end effector is moved to each frame station. Frame stations are set by indexing holes in gantry side rails.
5. The demo article will go through non-destructive inspection (NDI) after trim and then again after the frames are welded on. During NDI the demo article is held by an inspection fixture.
6. Dimensional inspection of the assembly takes place in two stages. The first after Co-Fusion and has requirements listed in Table 2. After the frames are welded on, an additional set of measurements are taken and assessed against the requirements from Table 3.

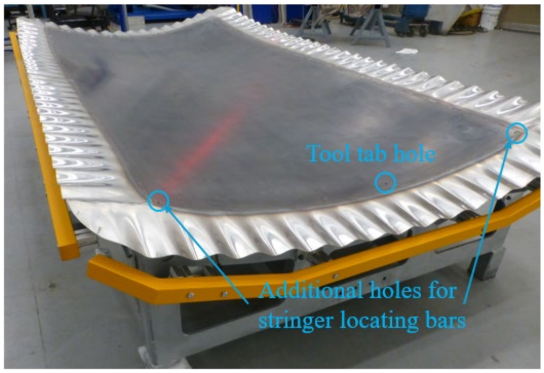


Figure 25. Co-Fusion tooling

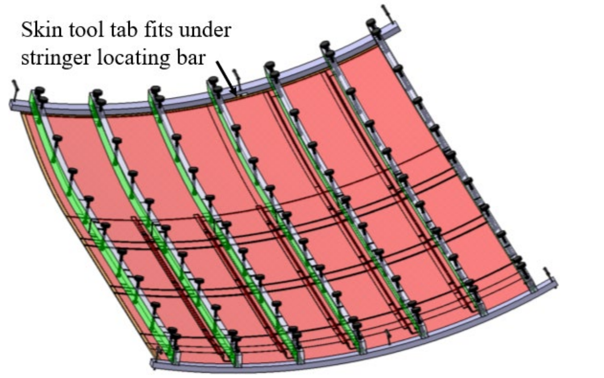


Figure 26. Stringer locating bars that pin onto Co-Fusion tool

Table 2. Co-Fused Skin-Stringer Assembly Inspection Plan

Step	Part	Processing State	Dimensional State	Task	Targeted Requirement	Inspection Fixture
1	Skin-Stringer	CoFusion	Unconstrained IML Up	Profile Check	No Requirement	Cofusion
2			Constrained IML Up	Profile Check	⌓ 0.03 A	
3				Thickness check between assumed OML and IML	± 7%	
4				Determine skin IML profile and thickness rate of change at tear strip locations using 8 points.	⌓ 0.10 A B C ⌓ 0.010 0.004/1.000X6.000	

Table 3. Skin-Stringer-Frame Assembly Inspection Plan

Step	Part	Processing State	Dimensional State	Task	Targeted Requirement	Inspection Fixture
1	Skin-Stringer-Frame	CoFusion Trimmed	Unconstrained IML Up	Profile Check	No Requirement	Trim Fixture
2			Constrained IML Up	Measure trim profile using 24 points along 8' edge	⌓ .060 A B C	
3				Measure trim profile using 12 points along 4' edge		
4				Check C datum hole location with respect to B datum. Check perpindicularity of hole B. Check holes with alignment pins.	⌖ Ø0.014 A B C ⊥ 0.01 A B	
5				Recheck assembly profile now that frames are attached.	⌓ .060 A B C	

3. CONCLUSIONS

Spirit AeroSystems has prepared the largest thermoplastic composite fuselage demonstrator panel made in the United States as part of the HiCAM project. The demonstrator is a RL4 article used to prove out rapid manufacturing technologies. There is significant complexity in the part fabrication alone which is why a successful demonstration article will get aerospace OEM and Tier 1 organizations to believe in these new technologies like laser assisted AFP, stamp forming, and thermoplastic welding. No stamp forming press in the United States had both enough daylight and an efficient transfer system to make the frames; having this equipment domestically will be important for future development. The assembly process is a chance to show off unique capability in thermoplastic composites, specifically fastener-less assembly, and reformability of interfacing parts during welding. AFP of the skin did not meet rate targets however the repairability of the process and no material outlife concerns makes the technology worthwhile. Welding times were significantly faster than the rates used for cost modeling; induction welding ran at two min /weld compared to the expected five minutes and Co-Fusion had a two versus five hour heat-dwell-cool cycle. The GD&T inspections during the assembly process will provide much anticipated for designers on the limits and advantages of thermoplastics. The learnings and demonstration of technology and manufacturing readiness proven by this demonstration article are instrumental for thermoplastics earning their way onto larger and more complex structures within the HiCAM project and eventually a new airplane.

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