AUTOMATED FABRICATION PROCESSES FOR LARGE COMPOSITE AEROSPACE STRUCTURES: A TRADE STUDY

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ABSTRACT

A Phase I SBIR program called "Low Cost Processing of Large Composite Structures (1)" reviewed autoclave and candidate out-of-autoclave processes for fabricating very large composite parts like the RLV liquid hydrogen tanks. These highly loaded structures require very high quality microstructure to yield the ultimate in mechanical properties. Autoclave processing yields ultimate properties but carries large capital and operating expenses. Thermoset "all-at-once" E-Beam curing, thermoset/oven curing, Cure On The Fly (COTF™), and Vacuum Assisted Resin Transfer Molding (VARTM) were all considered and discarded because none provided sufficient normal compaction force to the laminate during curing. This high compaction force is considered essential for creating adequate microstructure. Thermoplastic in situ fiber placement and the more embryonic layer-by-layer E-Beam fiber placement process were down-selected because of both their promise in fabricating parts and the high normal force available to compact the microstructure as an integral step in consolidating or curing. Even these processes will not be effective without a proven conformable compaction system to allow complex geometry shapes to be placed. The phase II program will fabricate, assemble, develop, and prove out a number of innovative conformable compactors, then assemble them into deposition heads.

KEY WORDS: Automated Fiber Placement, In Situ Consolidation, Electron Beam Curing

1. INTRODUCTION

The current cost to launch the US Space Shuttle into orbit ranges from $2,300 to $6,800/kg ($5,000/lb. to $15,000/lb.) on a payload basis. In recent years, NASA has initiated an effort to develop a reusable launch vehicle (RLV) to reduce this cost to $450/kg ($1,000/lb). NASA selected Lockheed Martin (2) for the development phase of a scaled RLV called the X-33.

Reducing the payload launch cost with an RLV challenges the structural weight. Since the RLV design eliminates expendable booster rockets, the X-33 will carry the fuel tanks and rockets to orbit and back. The propellant is 88.2% of the gross liftoff weight, leaving 11.8% for the airframe, engines, electronics, and landing gear (9.1%) and payload (2.7%). The structural vehicle weight must be controlled to retain payload capacity, thus, the best quality minimum weight composite laminates will be required for the spaceframe.

The Lockheed-Martin RLV encloses two main liquid-hydrogen (LH_2) tanks and one large liquid-oxygen (LOX) tank in the nose section. The LOX tank is baselined aluminum-lithium; composites are being considered for the LH_2 tanks. The LH_2 tanks are large, made from four 19.3m (760.86-in) long quarter-lobes fitting inside a 4.8m by 3.7m (189.5-in by 145.2-in) cross-section. The tank skins have polymer composite face sheets over honeycomb core. The tank internal complexity rivals that of a commercial wing structure, with a multitude of internal ribs and bulkheads (2). The tanks must withstand primary vehicle loads including landing gear loads. They are subject to extreme temperatures: -253°C when filled with liquid hydrogen, and then alternate high and low temperatures in orbit. Finally, the LH_2 tank walls must be impermeable to the liquid hydrogen inside.

2. AUTOCLAVE FABRICATION PROCESS FOR CRYOGENIC TANKS

The baseline autoclave fabrication process provides a standard of quality and cost for which the out-of-autoclave fabrication processes must aim. In this process, RLV tanks would be fabricated by joining smaller autoclave-consolidated panels. In fact, Lockheed-Martin and Alliant Techsystems recently demonstrated the state of the art for large composite tank fabrication (2). They manufactured an LH_2 test tank from approximately 200 laminates fabricated using conventional thermoset fiber placement or hand lay-up processing followed by autoclave curing. Following assembly, the tank was tested with disappointing results.

2.1 Autoclave Fabrication Features Autoclave fabrication can make several impressive claims:

- Autoclaving is a mature technology for fabricating laminates.
- Substantial NDI techniques and experience exist to verify laminate high quality.
- Commercial composite materials are available for use with thermoset fiber placement machines and autoclave curing to routinely produce well consolidated laminates.
- Good part dimensional control can be achieved with appropriate tooling to control thermal expansion or accommodate thermal mismatch.
- Highly productive, efficient fiber placement machines and tape layers are commercially available from Ingersol and Cincinnati Machine to effectively deposit thermoset composite tows and tapes onto tools with high throughput and repeatability.
- Conventional debulking and autoclave curing technology is available at many airframers and suppliers. For moderately sized autoclaves, substantial US capacity exists.
- For moderate size, autoclave fabrication can prove to be the cost-effective solution.

The most significant advantage is the 0.69-1.38 MPa (100-200 psi) compaction pressure applied to the laminate during cure. This compaction force follows the principle of force control; regardless of laminate thickness reduction, the high-pressure gas reliably follows the layers, maintaining normal pressure throughout the cure cycle. Due to the excellent compaction, the mechanical properties achieved following autoclave processing generally have 100% property translation from laboratory coupons, thus the genesis of the term *"Autoclave Properties."*

2.2 Autoclave Fabrication Limitations There are detractors to the autoclave fabrication process for an RLV tank, especially when the assembly process involves the joining many smaller laminates:

- The risk in fabricating the PMC honeycomb laminates themselves, including thermoset prepreg out-time stability, autoclave temperature non-uniformity, process-induced residual stresses, and wrinkling of thin sections.
- The performance penalty incurred with joints. Joints in composite parts are complex, heavy, expensive, and risky. They require shims at the interface to accommodate part tolerances. Even with shims, overall shape accuracy with joined parts is inferior to that for larger parts made all-at-once, and buckling sensitivity might increase.
- The large equipment cost (3). The autoclave requires significant capital investment and large operating expenditures, perhaps exceeding $40 million. Above that, additional costs accrue for many autoclave tools and assembly tools. Autoclave tools are required to fabricate approximately 200 panels per tank. Then, each panel joining operation would require templates and assembly jigs and tooling. Together, these tooling costs would exceed that for any out-of-autoclave fabrication process manufacturing full tank lobes and avoiding post consolidation joining tools.

3. COST AND COMMPACTION PRESSURE AVAILABLE BY PROCESS

Six processes being developed for out-of-autoclave fabrication of polymer composite parts can be considered for fabrication of large composite laminates for the RLV LH_2 tanks:

- Automated fiber placement (ATP)/oven cure - a fiber placement machine is used to deposit thermoset tows and a vacuum bag/oven cure completes the laminate.
- Automated fiber placement (ATP)/Electron-beam cure - a fiber placement machine is used to deposit an E-Beam curable tow, and the part is irradiated with a high-power E-Beam to complete the cure inside a protective concrete vault.
- Vacuum Assisted Resin Transfer Molding (VARTM) - a fiber preform is laid into a one-sided hard tool and vacuum bagged, then the subsequent resin transfer is augmented by pulling a vacuum on the preform. Cure is also under vacuum.
- Cure-On-the-Fly™ (COTF) processing - pioneered by Hercules (now Alliant Techsystems) in the late 1980's, a slightly heated ATP head stages thermoset tows as they are placed. The laminate is completed with a freestanding or vacuum bag/oven cure.
- Automated fiber placement (ATP) with thermoplastic in situ consolidation – an ATP machine is outfitted with a heated head that incorporates a polymer process to melt, deposit, and refreeze thermoplastic ribbons, layer-by-layer, onto a tool surface.
- Layer-by-layer Electron-beam placement - a low-power E-Beam is added to an ATP head, and E-Beam curable tows are deposited and irradiated layer-by-layer, onto a tool surface.

Some have been used to fabricate commercialized parts, although none as large as RLV tanks.

3.1 Compaction and Laminate Quality To downselect from this list, the six processes were ranked opposite ATP/autoclaving based upon cost and their ability to create high-strength laminates. For each out-of-autoclave process, the deposition equipment and/or a post cure with perhaps a vacuum bag is directly responsible for the time/temperature/pressure history required for creating quality microstructure. All six processes can provide adequate energy to fully advance or consolidate the resin, but the actual compaction pressure varies widely, as shown in Figure 1. Thermoset ATP/oven, VARTM, COTF™, and all-at-once E-Beam curing apply only vacuum bag pressure during the final cure, and no pressure if using a freestanding cure. The remaining three processes all employ a significant laminate consolidation force. Autoclaves use 0.69-1.38 MPa (100-200 psi). Layer-by-layer E-Beam and thermoplastic in situ consolidation processes apply their compaction pressure by translating a reaction force from the fiber placement machine or stout gantry tape layer through the deposition head. This compaction force is concentrated into a small spot using a roller or shaped compactor. Because the preceding layers had been cured/consolidated, high pressures, 3.4 MPa (500 psi) or above, can be applied during ATP. Note that this is characteristically different from the compaction force available for thermoset fiber placement, which utilizes a modest pressure to assist in deposition, not in ultimate compaction. A high force is detrimental to the unconsolidated laminate and is useless since the cure occurs within the autoclave.

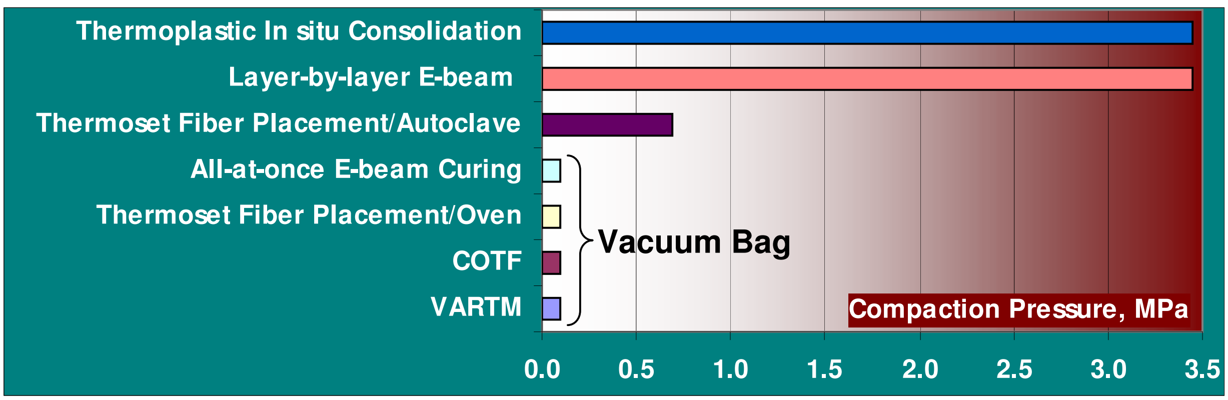

Figure 1 Four processes provide only provide vacuum bag pressure, but thermoset fiber placement/autoclave curing, layer-by-layer E-Beam, and thermoplastic in situ consolidation can provide as much as 3.4 MPa (500 psi) compaction pressure.

3.2 Equipment and Material Acquisition Cost The study then compared the acquisition cost to obtain the materials and equipment for fabricating an LH_2 tank (amortized for four vehicles plus two test tanks) using the seven processes outlined above. The study accounted for the materials, the fiber deployment equipment, and the consolidation equipment costs. The material cost for all the processes is similar except for VARTM, which requires no prepreg. The deposition equipment would be a custom fiber placement machine, with a simpler device adequate for VARTM. The ATP equipment expenses increased for thermoplastic in situ consolidation and were highest for layer-by-layer E-Beam. The consolidation cost for an LH_2 tank utilizing the VARTM, COTF™, or thermoset ATP/oven processes would require only vacuum bag debulking and oven curing. It would be more expensive to complete the all-at-once E-Beam curing process by virtue of the concrete vault and the large accelerator that would be required. An autoclave cure would be the most expensive. E-Beam layer-by-layer curing and thermoplastic in situ consolidation have no consolidation cost, as that is accommodated during ATP.

Figure 2 shows that VARTM has the lowest cost equipment acquisition cost for fabricating a tank at \$0.6 million. COTF™ and thermoset ATP/oven curing are next at \$1.2 million. The projected acquisition costs for "all-at-once" E-Beam curing, layer-by-layer E-Beam curing, or thermoplastic in situ consolidation range between $1.4 and 1.6 million. All are far lower than the acquisition cost for thermoset ATP followed by autoclave curing, where the total placement and autoclave equipment acquisition cost exceeds $6 million/tank.

Noting the extreme complexity and performance requirements of a composite cryotank to minimize RLV weight, the quality reproduced by any out-of-autoclave fabrication process would have to be exceedingly high. This rules out the four fabrication processes from Figure 1 not capable of at least what the autoclave provides: 0.69 MPa (100 psi) of radial compaction pressure during cure (those using a vacuum bag). ATP/autoclave, layer-by-layer E-Beam, and thermoplastic in situ consolidation remain, with the later two being the low cost processes. It is the conclusion of this section that the two out-of-autoclave processes that should be developed are thermoplastic in situ consolidation and layer-by-layer E-Beam curing.

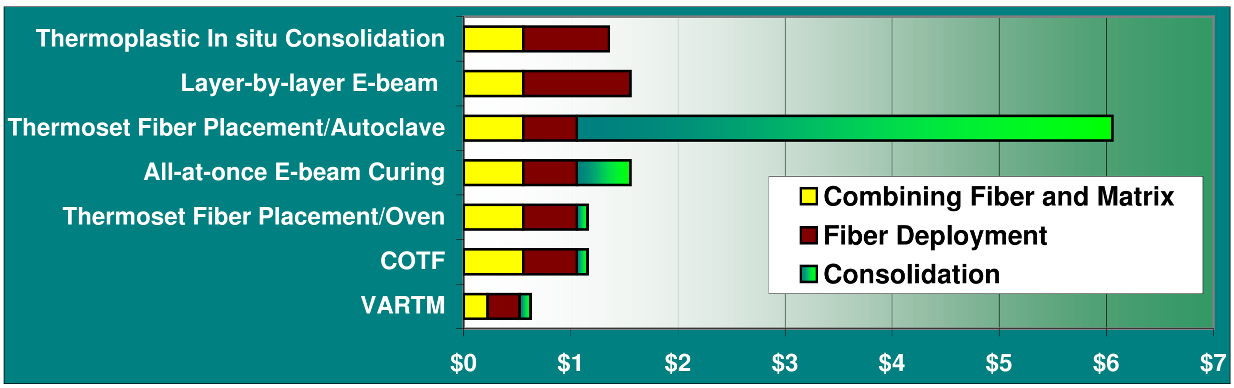

Figure 2 Comparison of the cost of material and equipment acquisition amortized for ten Reusable Launch Vehicle LH_2 tanks *(millions of dollars)*

4.0 THERMOPLASTIC IN SITU CONSOLIDATION

Thermoplastic in situ consolidation has been developed and demonstrated by a number of companies over the past 15 years. This section will remark on its claims and technology gaps.

4.1 Thermoplastic ATP Features First, thermoplastic materials have infinite material shelf life. In an RLV tank, this may provide a significant advantage over a catalyzed thermoset material, because it may not be possible to fabricate a thermoset tank within the time bracketed by the material out-time stability of any thermoset. Second, thermoplastic in situ consolidation has demonstrated 100% translation of autoclave properties from thermoplastic cylinders (4). DuPont, Cincinnati Milacron, and Boeing teamed to demonstrate fiber placing thermoplastic ribbons and tapes on flat structures using a gantry style tape layer. Testing revealed that 85% to 100% of autoclave properties were achieved (5).

4.2 Thermoplastic ATP Limitations There are several detractors with respect to thermoplastic fiber placement of generally shaped parts that must be remedied for process commercialization:

- Thermoplastic in situ ATP falls short (~15%) of reliably translating autoclave properties.
- Technology is not available or demonstrated for fiber placement of non-uniform shapes.

- No commercial equipment is available for articulate fiber and tape placement.
- No conformable compaction system or conformable control systems have been attempted or demonstrated on the prototype thermoplastic heads. This prevents the in situ consolidation of generally shaped parts.
- Thermoplastics are placed and consolidated at elevated temperatures, approximately 400°C, adding process-induced thermal residual stresses to those resulting from cooling from room temperature to LH_2 temperature or orbital temperatures.
- There are no currently (2000/2001) funded development efforts in the United States supporting this technology.

This section will concentrate on the difficulty in achieving full properties and show that a conformable compaction system is required. First laminate quality will be discussed. Figure 3 shows the before and after ultrasonic C-scans made of a poorly consolidated laminate (left) and a very nicely consolidated laminate (right) after autoclaving that laminate for one hour at 400°C at 1.38 MPa (200 psi). Both resulted in the upper right C-scans and lower right photomicrographs, respectively. Autoclave curing improved both poorly consolidated and well-consolidated thermoplastic laminates, although both lacked full autoclave properties.

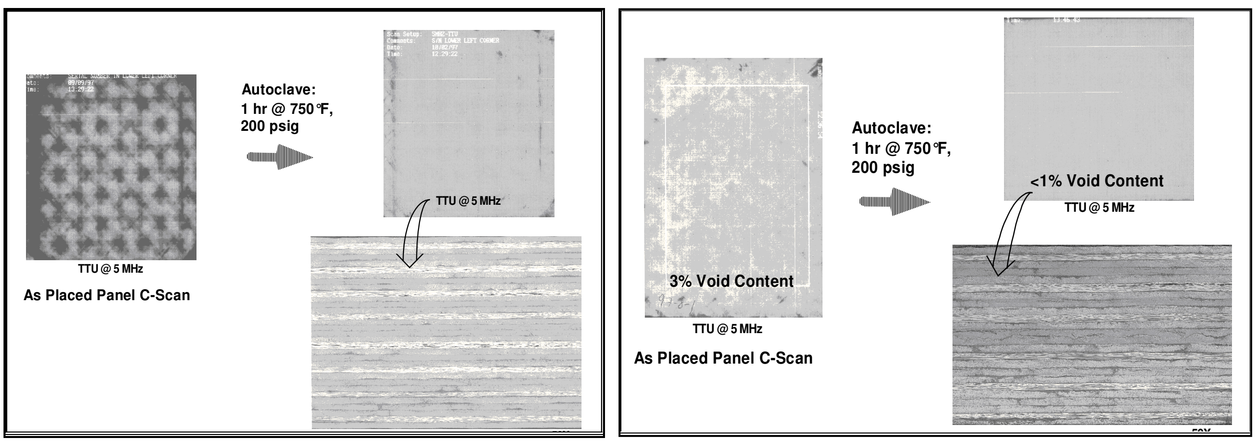

Figure 3 Ultrasonic C-scan and photomicrographs of thermoplastic in situ consolidated laminates made via placing three-inch tape. The autoclave consolidation process significantly improved the laminate.

What are the causes of the shadows in the C-scan of the as-placed laminates? One is the inability to achieve adequate width tolerance in tapes or ribbons (tows) used for thermoplastic in situ consolidation. Figure 4 shows four very nice quality individual thermoplastic ribbon cross-sections. The ribbon edges are not perfectly square. With the thermoplastic's high viscosity, ribbons and tapes do not flow together achieving the same quality at their edges as in the centers. Exacerbating the edge problem is the width variation. Thermoplastic ribbons and tapes are commonly fabricated to a width tolerance of ±254μm (±10-mils), yet fiber placement machines and tape layers have machine tool accuracies of ±25μm (±1-mil). Thus, material imperfections are reprinted onto the laminate and result in either laps or gaps. Figure 5 shows a photomicrograph of a laminate made with tape having excessive width variation. The laminate quality is excellent away from the tape edges. However, seven large voids are left from tapes edges that did not flow together. In one case, the gap was as wide as the thickness of two tows.

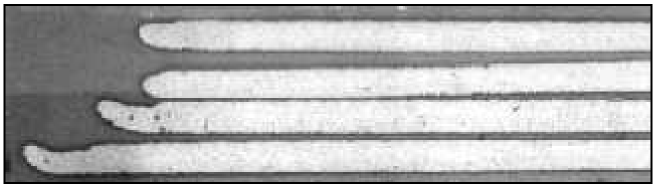

Figure 4 Photomicrograph cross-section showing four very nice quality thermoplastic ribbons

Figure 5 Photomicrograph of well-consolidated laminate with tape-to-tape width defects.

Figure 6 shows a laminate fabricated over a missing thermoplastic ribbon. The layers placed on top could not fill the space left. This shows what happens when a rigid compactor is employed and there are thickness variations in the incoming ribbons or tapes, or there is a tape overlap or ply add. A rigid compactor concentrates force on high spots, but low spots are not substantially compacted, leading to a significant loss of quality.

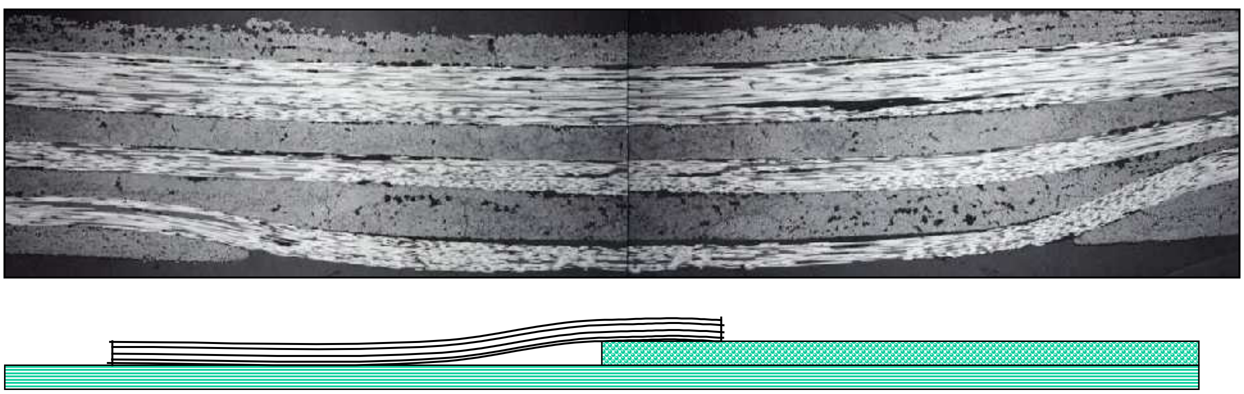

Figure 6 Photomicrograph of a laminate made with a missing ribbon illustrates the likely quality that would be achieved should an overlap be consolidated with a rigid compactor.

Figure 7 shows two layers placed over each other in the very first ply next to the tool. If a thickness defect begins in a laminate and a rigid rather than a conformable compactor is employed, that defect will reproduce itself throughout much of the laminate thickness.

It can be seen from the preceding photomicrographs and C-scans that the intimate contact was not achieved, yielding shadows in many of the actual C-scan plots. A deposition head built around a rigid compactor preserves problems with intimate contact throughout the laminate. If intimate contact cannot be achieved, neither can healing and full stiffness and strength. It is postulated that this is the primary reason why thermoplastic laminates have not achieved full translation of autoclave properties for the various material systems evaluated.

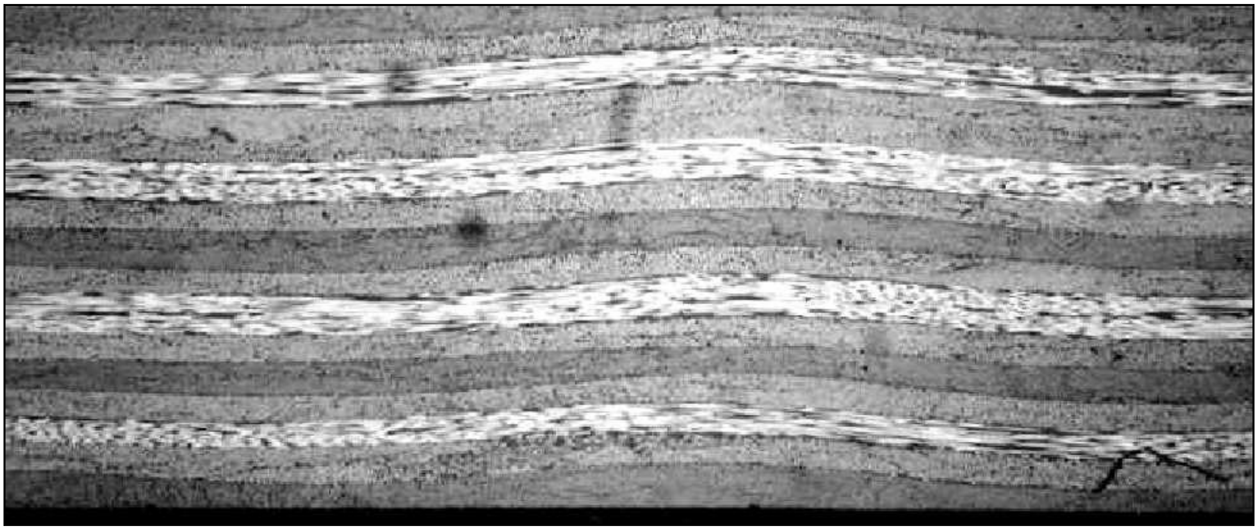

Figure 7 Photomicrograph of laminate with two tows placed directly over one another in the base ply. The ply undulation is reproduced throughout the laminate thickness.

In conclusion, the thermoplastic fiber placement process has much to offer because the thermoplastic in situ consolidation process has achieved good properties in thermoplastic filament winding (4). The basic process physics is sound. However, filament winding does not equal fiber placement, which must be used for RLV cryotank open-section laminates. From photomicrographs and C-scans, thermoplastic ATP requires improved intimate contact to be viable. This intimate contact will only be created once a working conformable compaction system is developed, even for flat laminates (1). Then thermoplastic ATP can be extended to curved laminates or other complicated shaped structures. A conformable compaction system is thus the next logical step in the development of thermoplastic in situ consolidation as an out-of-autoclave process viable for RLV tank fabrication.

5.0 E-BEAM CURING

E-Beam curing uses an electron beam source to irradiate a part to cure the matrix resin. The two sub-process categories are "all-at-once" E-Beam curing in reference to full part irradiation that follows the composite material system deposition, and "layer-by-layer" E-Beam curing, where each layer is cured after deposition and there is no final post cure after the deposition/cure of the surface layer.

5.1 E-Beam claims Although E-Beam process development is embryonic compared to other processes, E-Beam process developers make several impressive claims. First is that low or room temperature curing can be accomplished, avoiding elevated temperature curing. This, of course, would greatly reduce the magnitude of the process-induced residual stress, a significant advantage in the fabrication of RLV cryogenic tanks. This promise alone makes E-Beam worth developing, but it must be demonstrated, especially with the layer-by-layer process where the residual stresses can be truly minimized. Further it is claimed that since there is low residual stress and heat is not built into the part, fiber architecture need not be balanced. It would be interesting to know if any designer would make use of this feature.

It is claimed that the E-Beam cure process will lead to a reduced manufacturing cost and energy requirements, and reduced tooling costs by virtue of not needing to accommodate thermal expansion mismatch. This claim is significant but must be demonstrated. E-Beam researchers are currently not fiber-placing complex geometry parts, so the dimensional accuracy of relevant parts is unknown. Further, it is claimed that E-Beam curing is generally ten times faster than autoclave curing, and results in simplified processing and material handling. A convincing demonstration of both features would be a side-by-side comparison with a double curvature open-section skin made by E-Beam and by thermoset fiber-placement/autoclave curing.

E-Beam advocates state that curing can be interrupted and restarted. A convincing demonstration to prove this as a process feature would be to fabricate a part from beginning to end without stopping, and a part with process breaks in between. Geometric shape and mechanical properties could then be quantified to see if the E-Beam process delivered on this feature.

Perhaps the most significant advantage enjoyed by E-Beam curing is the current substantially funded efforts at a number of research groups in the country.

5.2 Layer-by-layer E-Beam Processing A few labs (9) are moving to layer-by-layer E-Beam processing. This process mounts a low power E-Beam source with a fiber placement machine. Beam penetration is limited to one or a few layers. The layer-by-layer process has a chance at using an external compactor to provide a compaction force during the consolidation of individual layers, so quality will be far higher than with all-at-once E-Beam processing. However, those experienced with the development of composite in situ consolidation processes can cite a number of detractors that need to be considered in the development of E-Beam curing:

1. There are no high performance resins or tough resins currently available. Current materials under development are often brittle. Material qualification must be completed for a fiber-resin system that meets the physical, mechanical, environmental, and durability property requirements relevant to a flying RLV tank.
2. There is no commercial equipment available - current E-Beam heads are custom-made for each application (6-7), which is impressive, laudable, and in context with the current state of the art in E-Beam process development, but that equipment is nothing like the type of automated fiber placement equipment supplied by Cincinnati Machine and Ingersol.
3. There are no conformable compactors available. Today's conformable compactors used on thermoset fiber placement machines are not adequate for three reasons. First, they contain plastic parts that will not survive E-Beam exposure. A conformable compaction system is needed that employs metal parts. Second, the compactors used on fiber placement machines and tape layers do not have large force capability. Third, today's compactors are conformable enough to assist deposition, but not enough for point-of-application consolidation.
4. The placement of the accelerator and E-Beam gun on the placement machine could limit the ability to articulate the head motions to place very complicated shapes.
5. The heavy radiation from the E-Beam gun has two consequences. First is radiation protection, usually achieved by a concrete vault, wall, or heavy shielding. A formidable byproduct of a vault is the inability to directly witness the process. This should not be underestimated based on the authors' ATP experience.

6. There has been little experience in the fabrication of open-section skins using all-at-once E-Beam curing. Technical papers (9-11) show a number of structures E-Beam fabricated using filament winding. Open-section skin fabrication is far harder than filament winding cylinders because the cylindrical geometry cannot be taken advantage of to translate material tension into radial compaction force. Even large diameter cylindrical closed-section parts preserve tow tension and hold plies closely to the previously deposited plies. Tension is not preserved with open-section skins, which have released in-plane loads at boundaries. For E-Beam processing to prove itself, open-section skins must be demonstrated.
7. Current parts are often made with fabric plies and low fiber volume fraction materials. Open-section parts made with unidirectional high (60%) fiber volume fraction plies must be tested, as those will be attributes of laminates used on the RLV tanks.
8. The literature lacks relevant compression-after-impact (CAI) and open-hole-compression (OHC) properties for open section skins made from E-Beam curing. Some research groups have measured short beam shear strength properties (9) but those properties are not going to be usable for the design of primary aircraft structure like that used on the RLV cryotank.
9. The existing E-Beam facility infrastructure in the US is limited. Even with new machines being developed, only NASA - Marshal Space Flight Center has a full-fledged gantry tape layer capable of placing an aerospace part. E-Beam curing facilities are expensive. A multipurpose high throughput E-Beam curing facility is estimated to cost ~$10 million.
10. The tenth problem will be the toughest to solve. Head and process developers will have to develop a control system that synchronizes the curing with the head motions. This problem is discussed in section 5.3.

5.3 Layer-By-Layer E-Beam Process Control The most severe challenge to layer-by-layer E-Beam processing of generally shaped parts will be process control. To understand this, it is important to realize that the deposition head <u>must</u> speed up and slow down during placement – it is not possible to fabricate a complex geometry part with constant placement speed. In the two figures below, specific deposition requirements for real complex-geometry heavily loaded parts are shown.

Figure 8 shows tow cut and add ply detailing used for quasi-isotropic placement around a cut out

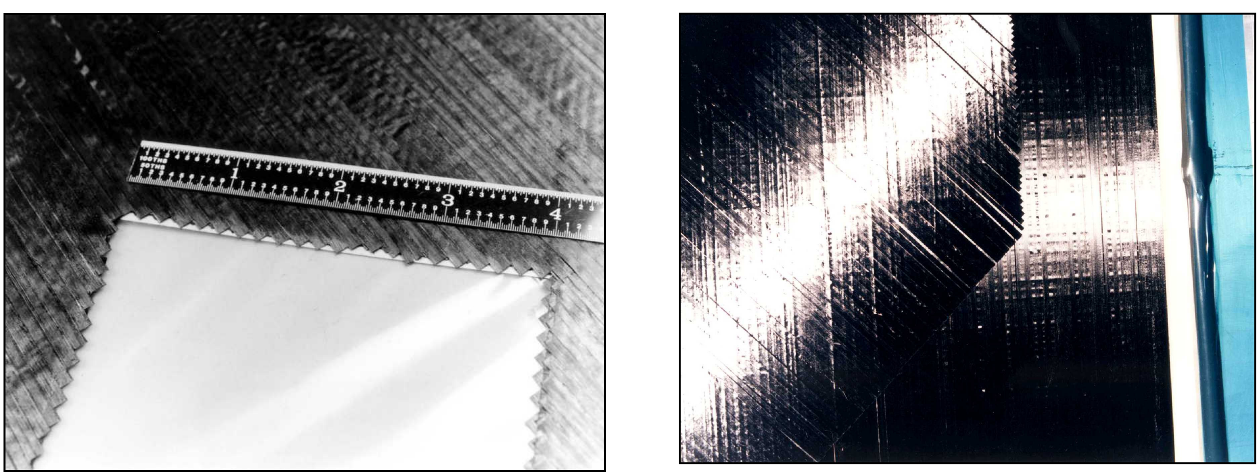

Figure 8 Tow cut and adds around cut outs and ply adds requires ±760μm (±30-mil) accuracy on ends, requiring slow placement velocity.

(left) and for ply additions (right). Tow additions and deletions also occur for ply tapering. The head feeder mechanisms cannot be triggered quickly enough for the tow ends to be added or cut precisely at full placement velocity. Also, when traversing a sharp corner, the placement speed slows substantially as the head steers to place over the severe change in curvature.

The impact of speeding up and slowing down directly impacts the ability to control the curing process. Today's fiber placement machines and tape layers provide for material deposition, usually difficult enough without a consolidation process. Thermoplastic in situ consolidation adds one layer of complexity to deposition, that is the physical processes of melting and refreezing. A layer-by-layer E-Beam process is even more complex, adding chemical kinetics to deposition and processing. Significant challenges will accrue in synchronizing the placement and cure kinetics, which must be accomplished under the head compactor to achieve ultimate properties. This is because the cure kinetics will have to be ramped with the head velocity. However from a controls viewpoint, since the very mechanism of resin curing involves more than a physical change but also a change in the material chemical state, curing is not strictly observable or controllable, and it is unlikely good microstructure can be produced during velocity changes, as required.

6. CONCLUSIONS

This study shows that the RLV tank requires ultimate properties like that available from autoclave properties, but autoclave processing of large tanks is very expensive. Four candidate out-of autoclave processes were discarded due to inadequate normal compaction force during cure. Thermoplastic in situ consolidation and layer-by-layer E-Beam curing were cited as processes deserving development, owing to the use of a compactor to apply a normal force to the laminate during consolidation or cure. E-Beam and TP/ATP fiber placement heads must be developed with conformable compaction systems so that the head force can create the type of laminate consolidation needed to manufacture the ultimate quality required. Without such a compactor, development on both processes for this application will not be successful. Conformable compactor development is the focus of a Phase 2 SBIR.

Both processes face the challenge of demonstrating high properties in complex shapes. The more embryonic layer-by-layer E-Beam process was cited as having a potentially large advantage for low or no residual stress parts. It must be developed for open-section fiber placement. E-Beam curable materials are required that will yield CAI and OHC property results commensurate with flight hardware. E-Beam was cited as the harder process to control.

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BIOGRAPHIES

Mark B. Gruber, MSME, P.E. - Mark has 20 years experience in DuPont and as a principal at Accudyne Systems. He was lead technical for several key thermoplastic in situ consolidation programs including the DARPA Advanced Submarine Technology Program, the DARPA/ARO RAPTECH programs, the NASA HSR program, and the Pratt & Whitney Advanced Composites for Propulsion (ACP) Program. Mark has also been active in thermoplastic ribbon and tape development. He holds eight patents for processing equipment for the manufacture of thermoplastic composite parts and has published 12 papers in the field of composites processing.

Mark Lamontia, MSME - Mark spent 15 years of his 21 years at DuPont developing composite process and equipment and finished parts for the underwater vehicle and aerospace industries, especially using out-of-autoclave processing. He was Program Manager of the DARPA Advanced Submarine Technology Program, the ARPA/ARO RAPTECH program, and the NASA HSR Dry Materials Team to develop non-autoclave processable dry materials for fiber placement and tape laying. Mark has published 48 papers and reports in the field of composite process and equipment development.

Brian J. Waibel, MSME - Brian is a Senior Partner and a co-founder of Accudyne Systems. He developed the process and machine control systems for thermoplastic in situ deposition heads, especially DuPont’s thermoplastic deposition head system developed under the RAPTECH programs and the NASA’s High Speed Research program. Brian focuses on systems requiring the integration of machine control, process control, and process models.