FEATURE

Electron Beam Processing for Composite Manufacturing and Repair

By V.J. Lopata and D.R. Sidwell

Thermal-cured composites have been around for approximately 40 years. The understanding of the thermal-curing process is now mature enough where applications such as large and complex structures are being manufactured and repaired. However, there still are many restrictions such as resin time-out issues, autoclave size limitations and tooling costs imposed by the process that will limit the application of composites. Electron beam processing is another method of curing composites that would allow composite manufacturing engineers to think outside the traditional thermal-curing methods and apply novel approaches to manufacturing and repairing large, complex structures not yet achievable. This paper will present an overview of the EB-processing technology, its restrictions, benefits and areas that need to be addressed to make this process an industrial method for manufacturing and repairing composites.

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Introduction

Is electron beam (EB) processing for the manufacture and repair of composites fact or fiction? Bringing a new and different technology to a well-established industry such as aerospace is both challenging and frustrating. Many people have trouble understanding and seeing the potential and benefits of something that is radical. Such is the case with EB processing. With the elimination of resin out-time limitations, high temperature cures, autoclave cures and complex metallic tooling, one can have trouble realizing the curing of composites has changed.

The investigation of EB processing for the manufacture and repair of composites, particularly aerospace applications, has been in progress since the mid 1980s. At this time Atomic Energy of Canada (Whiteshell) (AECL) began investigating the process.[1,2] Aerospatiale started about the same time but stopped their program in the early 1990s while Atomic Energy of Canada continued a research program until the late 1990s. During the 1990s, a number of other organizations started to look at the process, namely through two CRADAs.[3,4] In 1994, Lockheed Martin Skunk Works along with AECL started to look at the process for the manufacturing of complex composite structures. In 1996, Air Canada with AECL started to look at the process for repairing commercial aircraft.[5] The late 1990s saw AECL stop any further investigation of the process and transfer the technology to Acsion

Industries. This company was formed from AECL employees working in the process.

This paper will present the EB process—looking at what some of the problems are, what the benefits are and what areas should be addressed to make the manufacture of composite structures using this process an industrial practice. Although there are many ways to approach the manufacture and repair of composite structures, the use of EB opens new avenues that have not been possible with the normal thermal process. Manufacture and repair methodology of composite structures utilizing thermal-cure resin systems is well accepted. However, EB processing arrives with its new set of rules allowing you to rethink the constraints that limit thermal systems for many applications. The EB process allows you to throw-out many of the thermal-curing constraints.

One misconception is that EB-epoxy resins are similar to thermal-cure epoxy resins. Although the base resins are similar, EB materials are stored at room temperature, cure under vacuum pressure only and provide a very unique resistance to micro-cracking and moisture absorption. The EB-curing process can be utilized for the manufacture and repair of composite structures and the bonding of metallic structures. If the EB process is to become a true alternate curing system, then it must receive more exposure in industry for both aerospace and commercial applications.

Development of the EB Process for Composite Structures

During the development of EB processing, it was discovered that some current thermal materials were not adequate for EB processing. For example, sealant tape would become so sticky that it was just about impossible to remove from the tooling after EB cure, bagging film would poison the cure and release film would disintegrate with high EB dose. These kinds of challenges made things very interesting for some of the early development programs. However, over the years, these issues have been addressed with the introduction of new proprietary materials.

Advanced composites have provided the aerospace community with unprecedented opportunities for design freedom and improved structural performance. Because of these opportunities, the current trends are to increase composite structures usage and component size. Figure 1 shows the use of composites on commercial aircraft since 1960. Considering this percentage is the total weight of the vehicle, composites are replacing most of the metal structures on the aircraft. However, this demand is exceeding the capability to process by conventional autoclave means. Although the size of advanced composite structures is continuing to grow, the need for improved structural mechanical properties has not diminished. One of the limiting factors of the conventional thermal system is the inability of extended "out-time" required to complete lay-up of the desired large structure. The cost effectiveness and size limitations of complex structures has proved to be the biggest obstacle to their widespread use.

In the desire to maintain a leading-edge on technology and its application to the aerospace sector, one of the promising new technology developments has been the introduction of EB-curable cationic-initiated epoxy resins.[6,7] Oak Ridge National Laboratory, UCB Chemicals and Acsion Industries have made significant advances in the availability of EB-curable epoxy resins with varying properties suitable for aerospace applications over the past six years.

EB curing uses high-energy electrons, rather than heat, to initiate polymerization and cross-linking reactions in composites. Many benefits have been identified for EB-curing fiber-reinforced composites, including reduced residual stresses that result

FIGURE 1

Composite usage on commercial aircraft

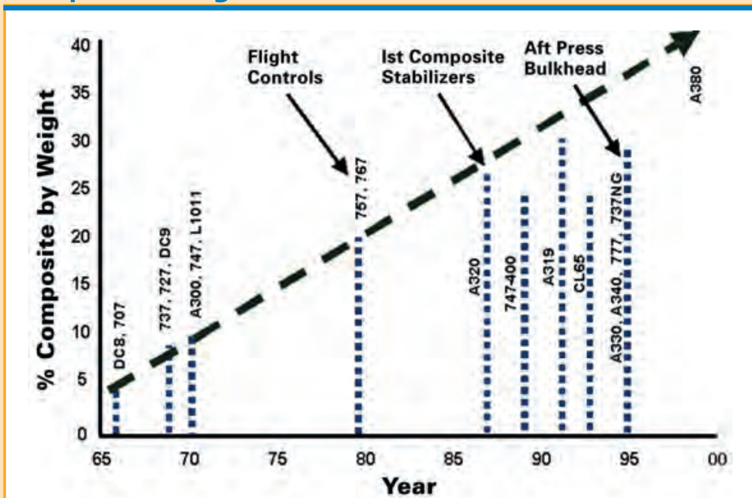

TABLE 1

Comparison of attributes for EB- and thermal-curing manufacturing methods

	Tool Cost	Equip. Cost	Aero. Perf.	L.T. Cure	C.Cure M.M.	S.A. Cure	Large Struct.	Void Control	Fib Vol Control	Out Time	Mature
E-Beam Hand Layup	E	V	V	G	E	E	E	V	V	E	Med
E-Beam VARTM	E	G	V	E	E	E	E	G	V	E	Med
E-Beam Fiber Placement	E	V	G	E	E	E	E	G	G	E	Med
Cure Form	G	V	E	V	G	G	V	G	E	V	Med
Low Temp. Vacuum Bag	E	E	P	G	A	P	A	A	A	P	Med
RTM	P	G	G	V	P	P	A	V	A	G	Med
VARTM Thermoset	G	E	V	V	P	P	E	V	A	G	Med
Fiber Placement Thermoset	A	A	E	A	V	P	E	G	E	V	Med
Autoclave Thermoset	A	P	E	A	A	P	A	E	G	V	High

Excellent
Very Good
Good
Acceptable
Poor

Aero. Perf. - Aerospace Performance
L.T. Cure - Low Temperature Cure
C. Cure - Co-Cure
S.A. Cure - Small Area Cure
M.M. - Multi-Material
Fib. Vol. - Fiber Volume

from curing at ambient or sub-ambient temperatures, shorter curing times for individual components (minutes vs. hours), improved material handling (unlimited room temperature storage), and process automation (fiber placement). This all translates into improved product quality, and lower production and facility costs. Current EB-curable epoxy resin formulations are meeting the strength requirements of those for 977-2 and 977-3 epoxy resin systems, which meet the demanding requirements of high-performance composite structures.

Table 1[8] shows a comparison of manufacturing methods to various attributes for EB and thermal-curing methods. The table shows that for all manufacturing methods EB processing has significant benefits when compared to the same method for the thermal-curing method. The resin-transfer-molding (RTM) process for the thermal-curing method has significant advantages over the EB process. This is primarily because the electron beam cannot penetrate the thick metal tooling required to produce the composite parts.

Materials

Many people in the aerospace industry say that the EB process is not understood enough to be considered seriously for manufacturing or repairing aerospace composite components. The primary reasons are a lack of information on material properties of some of resin systems that have been developed over the years and a lack of understanding of the curing mechanisms. DOE Oak Ridge National Laboratories (ORNL), AECL and Applied Poleramics (API) initially developed the EB-curable epoxy resin systems for aerospace applications.[6,7] Recently, there has been considerable work on development of EB-curable epoxy adhesives for aluminum-to-aluminum, graphite-to-aluminum and graphite-to-graphite bonding. Acsion Industries and UCB carried out this work [9,10] over the last three years. Acsion Industries along with Acetek Composites[11] carried out an extensive certification program for repair of fiberglass fairings for commercial aircraft. Transport Canada awarded a Repair Design Certificate (RDC) for the process in May 2003. In this section, a brief summary will be presented on EB-curable materials,

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some advantages and disadvantages, material properties for some resin systems including adhesives. A more descriptive listing will be provided in the Specific Projects section.

Advantages and Constraints of EB Systems

Over the years, there have been many papers that have expounded the advantages and constraints of the EB-curable resin systems. In the past, many of these attributes had only been surmised. However, with many of the projects those have been recently carried out by various organizations many of these attributes have been verified or discounted. These attributes will be discussed in the following sections. However, there are some constraints that are common to all EB-curable epoxy systems. These are:

- **Availability of qualified EB-curable epoxy resins.** To date there are no certified EB-curable epoxy resins for industrial use. Traditional thermal-cured systems still dominate the marketplace. Lockheed Martin and Acsion Industries have performed extensive mechanical property testing on one or two resins. In Acsion's case, they have obtained Transport Canada approval for repair of commercial aircraft fiberglass fairings. However, obtaining industry acceptance and certifying new EB-curable epoxy resins will be challenging and costly. A typical certification program can cost between $2 to 5 million.
- **Light sensitivity.** Many EB-curable epoxy systems are sensitive to ultraviolet and near-ultraviolet light (up to wavelengths approaching 450 nm). All handling must take place under filtered light conditions.
- **Chemical incompatibility issues.** EB-curable epoxy systems are sensitive to certain chemical species. Chemical species that act as Brønsted bases (proton acceptors) have been found to interfere with the curing mechanisms of EB-curable epoxies.[12]
- **Lack of optimized primer systems and fiber sizings.** All primers, fiber sizings and surface preparation methods, currently in industrial use, are optimized for thermal-curable epoxy and acrylate-based systems. There has been limited work done on sizings and primers for EB-curable epoxy resins. Acsion, as part of its adhesive development program, looked at various primers for aluminum as well as composites. They were able to see significant improvement in the adhesion properties of joints. The Interface CRADA also looked at sizings primarily for graphite fibers with mixed success.[3]
- **High Viscosity.** Toughened EB-curable epoxy adhesive systems tend to be very viscous at room temperature. Steps must be taken to ensure that the EB-curable resin properly wets the substrate surface to maximize adhesion. This usually involves applying heat to reduce the adhesive viscosity and allow wet-out prior to EB curing.

Some of the striking advantages for EB-curable epoxy systems are:

- **Material Storage.** EB-curable epoxy resins can be stored at room temperature in UV-protected sealed bags. The current EB-curable epoxy resins have a storage shelf life in excess of 24 months and still retain the same mechanical, chemical and physical properties when first made. If the EB-curable resin is exposed to UV light for a short period of time, then a partial cure will exist and thus become temperature sensitive. Some properly stored EB-curable epoxy resins can reach temperatures in excess of 170°C before auto-curing. Materials that have been stored outside the UV-protective sealed bags and under UV-protective lighting have been successfully worked with even after 15 months of storage. Acsion Industries carried out a preliminary certification program using EB-curable epoxy prepreg that was stored at room temperature for over 24 months achieving mechanical properties that were the same as the newly produced prepreg.

  Today, there are several types of EB-curable epoxy resins being supplied and each have some special requirements for UV protection. Before use, these requirements should be discussed with the resin manufacturers.

  It can become very interesting when fabricating a part and it starts to color. Color change is an indicator that the material is starting to cure when subjected to EB, γ-rays, X-rays or UV exposure. As a matter of fact, the initial test to ensure a resin is EB-curable, is to dip a wooden tongue depressor stick in the resin and take it out in the sun. If the resin changes color, usually the resin is deemed EB-curable.
- **Layup.** When working with EB-curable resins, because there is no heat used during the cure process, one must devise a methodology to achieve the desired consolidation of the laminate. This can be achieved using hot or cold debulks to obtain the correct resin flow for fiber content and removal of any air entrapped. With adequate UV protection, debulking of the uncured stack can be accomplished at temperatures between 90-150°C for extended amounts of time. Laminates with complex shapes up to 2 cm thickness have been fabricated and still achieved less than 1% void content with only

vacuum pressure. As with most composite structures, there is a substantial benefit to fabricating the component the same each time, utilizing the same lay-up techniques, debulk cycles and vacuum bagging procedures.

- **Tooling.** There is still a lot to be learned about tooling—what kind of materials, density, handle ability and shielding. Two main criteria need to be considered when looking at tooling for EB processing, the material's specific heat and its density. The temperature-generated due dose absorption is inversely proportional to the material's specific heat. The ability of the electron beam to penetrate a material is inversely proportional to its density. With these two criteria, one can see that foams such as polyurethane can make excellent tools. They have high specific heats and low densities providing low-tool temperatures and high-penetration capabilities during the manufacturing process.

The ability to cure a composite part by passing the EB through the tool is a little different than for a thermal-cure part. Early in the EB-process development, it was a great idea to utilize foams for tooling; they were cheap, easy to machine and accurate. But like all things that look good, tooling foams work very well for small parts. It becomes more challenging when you start having 100+ kg tools to manhandle as in the case for thermal curing. In this case, foam tools may be a great idea. Composite tooling such as fiber-glass can be very accommodating when some state of production is required. Dependent upon the complexity of the composite part, even prototypes and limited production may benefit from composite tooling.

EB Curing

The total dose, the dose rate, the number of passes and the power of the equipment all have an effect on the final result. The composite structure's end-use determines the degree of cure. You can control the degree of cure with the EB process. This again differs from a thermal-cure system. As with complete composite structures, the total EB dose is an integral part of the composite part design. If you take the complete EB process into account there is leverage because each area will play on the other (i.e. tooling, design, material, and total EB dose).

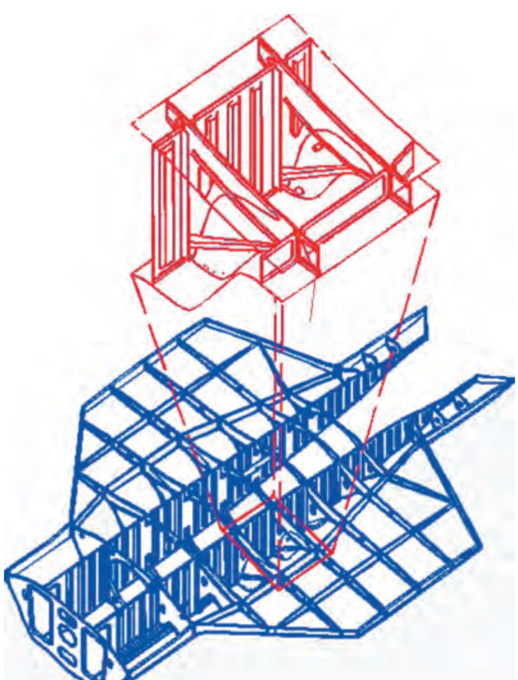
Material and Process Development Programs

A number of programs looked at the manufacturing and materials strategy focus, providing cost effective application of existing and emerging manufacturing technologies, tooling approaches and materials for large complex composite structures, and expanding design options and capabilities. Evaluation of the EB process has been very successful in these programs. These programs were carried out to demonstrate the various manufacturing practices EB processing allows. Many of these manufacturing practices are not achievable by any other means and still provide the material properties aerospace requires. Three projects that demonstrate the manufacturing and repair advantages of EB processing are:

- A full-scale process demonstrator for the Joint Strike Fighter (DARPA IATA).
- A 1/10th scale of the proposed RLV graphite composite liquid hydrogen tank.
- Composite repair of commercial aircraft components.

FIGURE 2

Schematic of EB-processed composite part and its position on the JSF aircraft structure



Integrated Airframe Technology for Affordability Program

The Integrated Airframe Technology for Affordability (IATA) Program attempted to reduce the overall cost for a new start program, in this case the X35 Joint Strike Fighter (JSF). The initial approach was to integrate all disciplines and feed off each expertise to come up with a solution. This was very successful, as part of the program was to build a full-scale demonstration section of the wing area over the main landing gear. The goal was to show what cost-savings could be achieved if design, materials and manufacturing are integrated into a coordinate approach. EB processing was considered as one of the production practices. While this demonstrator was planned to be a sub-scale demonstration, the team decided to do a full-scale demonstration because of the increased fidelity in the cost numbers. The full-scale demonstration left little doubt as to the assembly issues that needed to be resolved. A section of the airframe around the landing gear bay was chosen as this represented the highest loaded region of the structure, as well as the most complex and challenging region for composites. The sub-assembly was fabricated using 80% EB-cured structure and 20% resin transfer molded (RTM). Figure 2 shows a schematic of the part that was built and its position within the JSF aircraft.

The process demonstrator evaluated, in a limited production atmosphere, some of the key design, process, materials and tooling approaches developed. Components fabricated were upper and lower skins, bulkheads 506 and 539.6, keelson, and hand lay-up, outboard rib closure. This full-scale structure was approximately five feet on each side. The processes and materials selected were based on the down-selected design features and preferences for large integrated (fastenerless) structure, continuous load paths, and structural continuity through multiple-service temperature zones.

Lower Wing Skin Assembly. The full-scale process demonstrator lower wing skin assembly utilized fiber-placed skin laminates with EB-curable epoxy resin tow preg. The honeycomb structure, which utilized large cell HRP core due to budget constraints, was originally designed for large cell graphite core. Internal build-ups for spar caps and localized reinforcements utilized EB-compatible materials. The process demonstrators, completed prior to start of the full-scale process demonstrator, provided the bases for the fabrication procedure utilized. The top picture in Figure 3 shows tow-placement of graphite fiber at the main landing gear section of the lower skin assembly. The bottom picture shows the final structure with the foam that the part was assembled and cured on.

Upper wing skin assembly. The upper wing skin assembly was fabricated utilizing the same methodology as the lower wing skin. Figure 4 shows the fabrication and final structure for the upper wing assembly.

FIGURE 3

Lower wing skin assembly

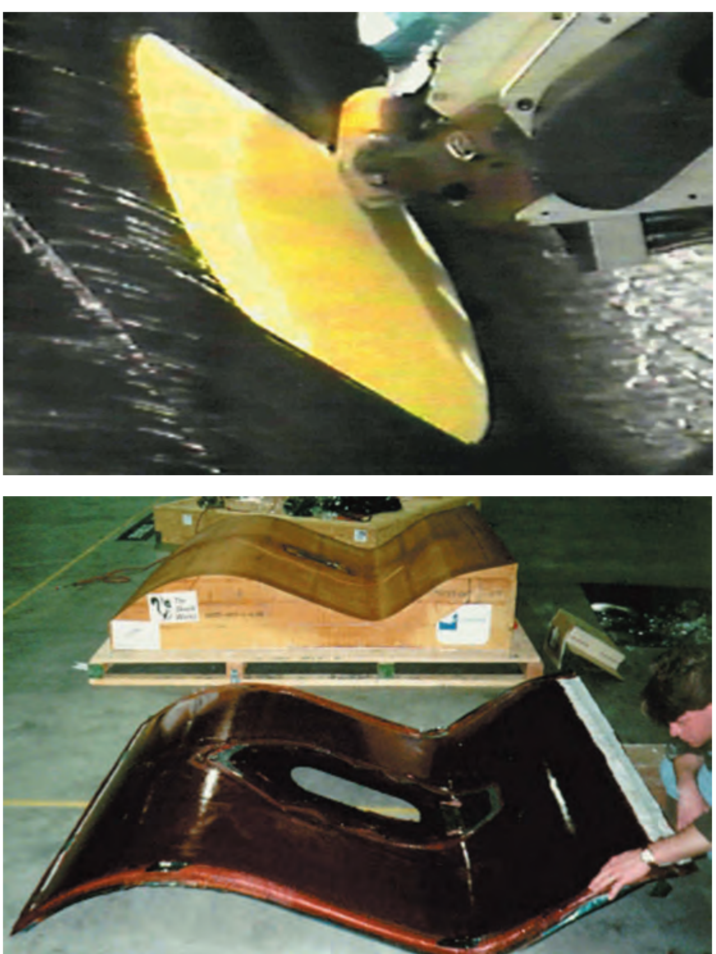
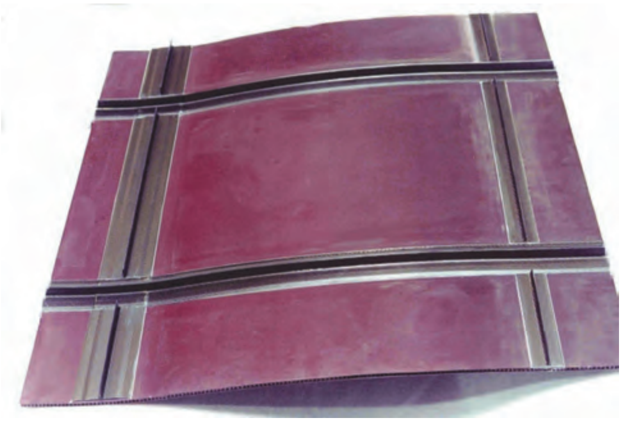


FIGURE 4

Upper wing skin assembly



The upper picture shows the tow-placement of the graphite prepreg on the foam tool. The lower picture shows the final cured structure from the under side. The X and Y lines on the structure are part of the clevis joint used to bond the structures together.

One interesting fact was it cost more to do the RTM components, bulkheads 506 and 539.6, than all the EB-cured structures combined. A cost analysis was carried to the same level detail as a full start-up program such as F-22 or JSF. Depending on the part being manufactured, the analysis showed that costing savings between 25-70% could be achieved using EB processing. Prototype development savings using EB processing showed cost saving could be as high as 95%. Program comparisons prepared during the IATA program showed that the average $/lb for F18E was approximately $950/lb, the proposed initial 140 design for the JSF was approximately $900/lb, and the proposed cost derived from the IATA program was $480/lb.

EB-Cured Composite Liquid Hydrogen Tank

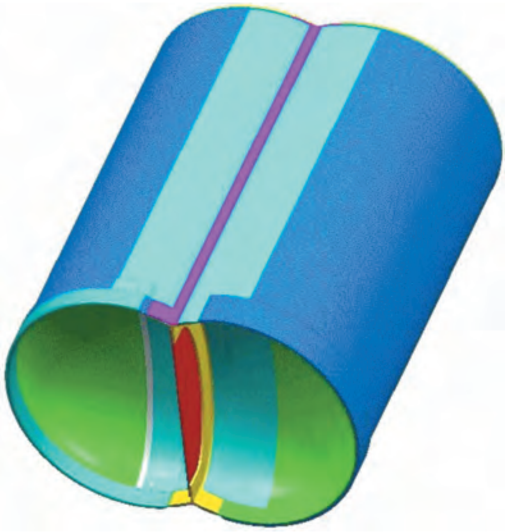
The challenge for this program was how to build a very large liquid hydrogen (LH_2)composite tank, 40-feet in diameter and 90-feet long, economically with all the material properties required. By far, this was the most challenging project utilizing EB processing to date.

Progress has been made in the development of Out-Of-Autoclave (OOA) processing of advanced composite materials and related manufacturing technologies. However, the capability to take advantage of these technologies and to determine the long-term effects on these materials under adverse conditions has not followed a parallel evolution. Investigation of these approaches provides the opportunity for a break-through in OOA advanced composite structures, irrespective of quantity produced. As structures continue to grow in overall size, one of the limiting factors is the inability of extended “out-time” required for the prepreg before its starts to cure to complete lay-up of the desired structure. The emergence of EB processing provides the opportunity for a breakthrough in affordable large complex composite structures.

An integral part of the LH_2 EB tank program was the manufacturing and materials strategy focus, providing cost effective application of existing and emerging manufacturing technologies, tooling approaches and materials for large complex composite structures, which expands design options and capabilities. The NASA LH_2 EB tank program was designed to evaluate the possibility of utilizing EB processing for the fabrication of LH_2 tank structures for the X-33 & RLV related programs. It was an effort to use the technical approaches developed in the IATA program and internal IRAD efforts at Lockheed Martin Aeronautics-Palmdale, to demonstrate that a very complex LH_2 tank structure could be manufactured using the EB process. Although this was achieved with reasonable success, it was the capabilities of the EB process to selectively pre-cure distinct areas of the structure that was the highlight of the program.

FIGURE 5

Schematic of the EB-processed composite liquid hydrogen tank

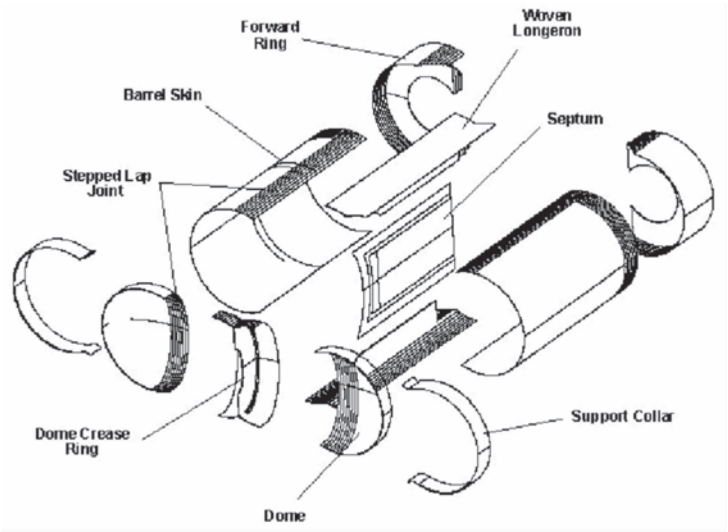


The capability to re-evaluate the direction of the program and to re-manufacture the remaining portions of the LH_2 tank in order to achieve success was a major break-through in composite manufacturing over the thermal-curing processes.

Figure 5 shows a schematic of the EB-processed composite liquid hydrogen tank. The tank measured 180 cm long by 180 cm wide by 90 cm high. Figure 6 shows the various individual components that make up this tank. The shaded areas were left uncured by shielding during initial curing of the components. These areas were consolidated at final assembly and then cured. This ability to cure selective areas of a structure while leaving other areas uncured showed that EB processing could be used to manufacture any size of structure. This ability is not available in traditional composite manufacturing.

FIGURE 6

Schematic showing components of the EB-processed composite liquid hydrogen tank



EB-Cured Repair of Commercial Aircraft Composite Parts

The repair of commercial aircraft composite components using the EB process is the nearest activity to commercialization. Air Canada, first with AECL and then Acsion Industries, have over the past seven years been developing the processes and material databases to obtain certification from Transport Canada and the FAA.

Initially, it was thought that the processes and materials were advanced enough to conduct a series of type-trials on commercial aircraft. The demonstration repairs were conducted such that if they failed they would not affect aircraft air worthiness. The type-trial repairs that have been carried out are detailed in Table 2. The performance of repairs on the components during normal aircraft operations has been excellent. The EB repairs have out-performed similar thermal-cured repairs. This is primarily because EB-cured repairs have the properties of high-service temperature resins while being cured at room temperature. This allows the EB-cured repairs to be used on a wide variety of traditional aircraft components with varying service temperatures while curing at room temperature.

Some details and benefits of the process have been detailed in a

Table 2

EB-processed repairs for Airbus A320 components

Part	Material	Hours	Cycles
Wing-to-Body Aft Fairing	Fiberglass/nomex core	13,225	4,872
Wing-to-Body Aft Fairing	Fiberglass/nomex core	1,800	900
Fan Cowl	Graphite/aluminum core	9,501	3,873
LH Forward Fairing	Fiberglass/Fiberglass core	1,000	425
RH Forward Fairing	Fiberglass/Fiberglass core	1,000	415

Note: All the parts listed in the table above have been removed from service for analysis. The Fan Cowl component is the only part still flying.

number of papers.[5,13,14] Some of the primary benefits of EB processing for repair have been the use of prepreg for all the repairs. This is due primarily to the EB prepreg not having a time-out issue. Another benefit is the speed of repair process. Most repairs are completed in 50-70% of the time of a normal thermal-repair. A further benefit is the use of cheaper or no tooling. This is because the repairs are performed at room temperature. The other benefit is the capability of using prepreg with high-service temperature properties. This has been shown to produce a better all-round repair with a longer service life than the traditional thermal repair.

Recently Acsion received a RDC from Transport Canada for repairs on fiberglass components. Work is continuing on certification of other aircraft components.

Summary

EB processing is revolutionary technology for the manufacturing and repair of composite structures. The process has been investigated for approximately 20 years. Over this time, there have been major advances such as the development of EB-curable epoxy resins and adhesives and a better understanding of processes and material requirements and constraints. Programs such as the integrated airframe technology for affordability and the EB-cured composite liquid hydrogen tank have shown the viability of the process for commercialization. The EB-cured repair of commercial aircraft composite parts program was a major achievement with Transport Canada certifying the process for repair of fiberglass composite components for commercial aircraft. All these activities have shown that the EB process has come of age to consider as a viable process for the manufacture and repair of composites.

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