# Electron Beam Processing for Aerospace Composites

By Morris A. Johnson

Electron beam-cured composites for aerospace vehicles have been the subject of extensive research over the past decade and more. Aerospace is only one of many transportation modes that can benefit from composite structures, but the advantages of electron beam (EB) curing over conventional thermal cure for this end-use is considerable. A number of investigators have evaluated this technology for both manufacture and repair of military—fixed- and rotary-wing—and civilian aircraft, as well as spacecraft. Increased usage of composite structures on aircraft has introduced new requirements for repair of these structures. Many challenges in the manufacture of composite aircraft are still to be overcome.

## The Need

### *EB Processing for Commercial Composite Aircraft Repair*

Composite usage on commercial aircraft has increased nearly seven-fold in the 30 years between 1965 and 1995.[1] Composite structures vs. metal on aircraft reduce structural weight (high strength/weight ratio), lower initial cost in some cases, improve durability and fatigue life, and improve resistance to corrosion and chemicals. These features all add up to reduced operational cost over the airframe lifetime. Of particular interest is that a lighter airframe affords lower fuel costs and higher passenger yields.

Unfortunately new technologies rarely come without some disadvantages, which may partially or wholly offset the advantages. In the case of composite aircraft structures, thermal cycling with high loads and/or vibration may lead to damage (e.g., disbonds and delamination). In particular, sandwich structures take on fluids, which may lead to damage and certainly increase weight.

Repair of sheet metal is relatively simple, fast and cheap. An aging aircraft fleet with increased composite structural makeup places additional burdens on the aircraft maintenance facility. Facilities that are required to have all relevant composite repair process capability will face high spares inventories, possible dependency on third-party vendors and repair stations, and long processing time for repairs. As downtime for aircraft is extremely expensive, the maintenance burdens described erode the lowered operating costs.

To reduce the negative impact of current composite structures repair, Acsion and Air Canada have undertaken to incorporate the latest beneficial technologies represented by EB cure into the repair process. Vince Lopata and Ernie Fidgeon, formerly of Acsion and Air Canada, respectively, have actively pursued the challenge of EB processing for repair of composite commercial aircraft and have widely discussed the issues in various forums.[2]

### *Background*

EB curing of fiber-reinforced composites was explored more than 30 years ago.[3] European researchers, most notably in Aerospatiale,[4] have devoted considerable effort since the early 1950s.[5] But modern developments in accelerator technology, materials handling and raw materials for use as matrix binders have stimulated the most recent progress. In a Cooperative Research and Development program (CRADA),[6] which ran from 1994 to 1997, two Department of Energy (DOE) national laboratories and 10 industrial participants, including four major aircraft and aerospace companies, three advanced materials companies and three EB processing organizations,[7] joined forces to better understand and utilize EB-curing technology. Chris Janke, Oak Ridge National Laboratory, and Vince Lopata, then of Atomic Energy of Canada Ltd., were key participants in this first large CRADA.

Subsequent work[8] addressed the serious obstacles of relatively poor interfacial properties and resin toughness in EB-cured composites. The composite shear strengths of EB-cured carbon fiber-reinforced epoxy composites were about 25% lower than corresponding thermally cured systems, and resin toughness was about 50% lower. Again, this research was a multi-partner project with DOE as the principal sponsor. It consisted of four government sponsors from three federal agencies, 11 partners from private industry, and two subcontractors[9].

It was after the first two DOE CRADAs that Air Canada, with support from Acsion and Lockheed Martin Skunkworks, undertook a series of type-trials to study the benefits of EB processing for routine on- and off-aircraft repair. Another key player, Don Sidwell, Lockheed Martin Skunkworks, was involved in the effort, which demonstrated that commercial aircraft composite repair could be accomplished in minutes vs. hours for conventional cure. Completion of a permanent repair was done in the same or less time than a traditional temporary repair. This work validated the benefit of reduced turn-around time of a repair and maintenance visit, and further demonstrated the ease of EB-material handling. For example, in a process requiring wet lay-up there were virtually no pot-life constraints, and for pre-preg or resin film, no thawing was required.

***Benefits of EB Processing for Composites in Aerospace Vehicles***

The standard thermal-cure process is a major cost driver in producing polymer matrix composite structures (PMC), and this method of cure also is one of the greatest factors in parts quality and performance.[10] Reduced manufacturing costs and cure times, improved part quality/performance, reduced environmental safety and health concerns, and improved material handling are all demonstrated advantages of the electron-beam or X-ray cure process.[11] In addition to reductions in curing time, a reduction in tooling costs and improved resin shelf life—which may result in less scrap and inventory control costs—as well as easier routine cleaning of resin application equipment have all been seen. This was broadly demonstrated in the first CRADA study coordinated by Oak Ridge National Laboratory. The formal CRADA economic study concurred with other contemporary studies suggesting that significant cost savings of 25% or more could be realized using this technology.[12] To date, a total of six independent economic studies have estimated cost savings of 25-65% for EB over thermal cure.

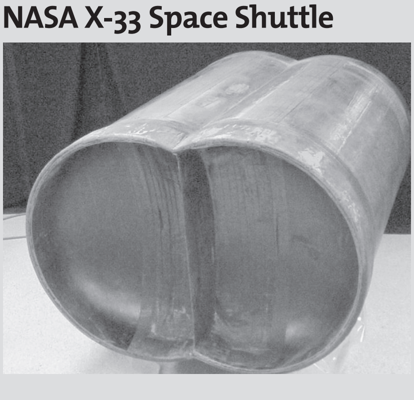
Lopata extensively discusses the benefits of electron beam curing for the manufacture and repair of high-performance composites.[13] The six independent economic studies mentioned above are listed. Additionally, the benefits of reduced curing time, reduced tooling costs, ambient temperature curing and resin stability, minimum production of volatiles, elimination of chemical crosslinking agents for thermosetting resins, and greater process control are all discussed briefly.

EB cure has particular advantages in the manufacture of aerospace components, which are too big to fit into available autoclaves (out-of-autoclave processing). This was demonstrated in the manufacture of a scale model hydrogen fuel tank (Figure 1) for the since-cancelled NASA X-33 space shuttle.[14] Costs are also favorably impacted by the very long pot life for EB adhesives and extremely robust shelf life of prepreg materials containing EB-curable pre-polymer vs. conventional thermally cured resins. In a complex fabrication, the advantage of long pot life may make the difference between feasibility and non-feasibility.

In the first CRADA, it was demonstrated that some manufacturing processes are possible with EB that are otherwise not feasible with conventional thermal cure. For example, EB-cured parts requiring extremely good

**Figure 1**

**Manufactured scale model of hydrogen fuel tank for the NASA X-33 Space Shuttle**



dimensional stability (e.g., with thin radiation reflector bodies or non-symmetrical thicker structures) is possible because of the lower internal stresses of a part cured at ambient temperature via EB. The ability to use lower cost tooling, even cheap tooling such as Styrofoam for internal mandrels allow for a form of the "lost wax process."

The advantages of EB processing become increasingly apparent in the emerging challenge of composite aircraft repair. Sandwich structures in aircraft are, in the simplest form, a rigid honeycomb with carbon fiber "skin" bonded to the outside for maximum rigidity with minimum weight. Whenever the skin is perforated moisture can enter the honeycomb structure. As the aircraft ascends on takeoff and descends on landing (cycles), the effect is that of "pumping water" into the honeycomb. Moisture enters in the form of water vapor, but cannot escape in the condensed-water form, thus adding over time considerable weight to a structure, which was designed for low weight.

If damaged honeycomb structure is to be repaired and resealed, autoclave or heat-blanket curing poses particular problems. Removal of the moisture is very difficult and time-consuming if not impossible. During the heat cycle of the thermal repair process, expansion of the condensed moisture can cause problems, in the worst case delamination of the skin from the honeycomb and even rupture causing catastrophic damage to the part being repaired.

Rapid turnaround time is extremely important in the case of aircraft repair, where downtime is very expensive, thus the high speed of the EB-cure process is most attractive. The longer shelf-life for repair materials and robust process capabilities may be even more important in the repair process than in the original manufacturing process. To reiterate, the benefits of electron beam processing in aircraft repair are many:

**Direct Benefits**

- Rapid cure-minutes vs. hours
- Completion of a permanent repair in the same or less time than a traditional temporary repair
- Reduced turnaround time of repair and maintenance visit
- Ease of material handling

**Indirect Benefits**

- Improved process control
- Reduced scrap due to material out-time limitation
- Reduced inventory of various repair materials
- Reduced space inventory
- Reduced tooling costs
- Improved repair reliability (superior properties)
- Increased repair facility utilization and productivity
- Possibility for certain repairs, which are currently impossible with existing thermal cure methods

***EB Adhesives for Aerospace***

More recently work has been reported on the development of EB-curable adhesives[15] for manufacture and repair of composite structures for aerospace. Given the benefits of EB processing to aircraft repair, it is easy to see where the availability of high-performance EB adhesives would be desirable. The Canadian government sponsored the formal activity in the form of an Industrial Research Assistance Program.[16] The goal was to take advantage of the benefits of curing at room temperature, reduced thermal stresses, shorter cure times and improved process control afforded by EB processing.[17]

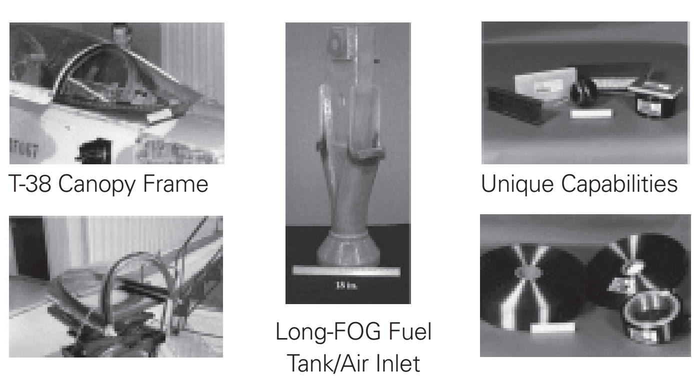
## The Solutions

***EB Cure of PMC CRADA* (CRADA I)**

A family of high-performance, EB-curable cationic epoxy resins was developed in the first CRADA. Several hundred formulations using these cationic epoxy resins were tested and most resulted in test specimens with physical and mechanical properties equal to or better than the analogous thermally cured epoxies. A number of demonstration objects were produced. See Figure 2. Industrial licenses have been granted to two polymer resin manufacturers[18] for this patented technology.[19, 20] A 1997 research and development 100 award was granted in recognition of these significant technological innovations.[21]

**FIGURE 2**

**EB-cured evaluation/demonstration parts**




* *Figure 2 courtesy of Oak Ridge National Laboratory. The T-38 canopy frame was constructed of EB-cured composite in a previous project.*

## Table 1

### EB repair type-trials Airbus A320 aircraft

| Part | Repair Size | Flight Hours | Flight Cycles | Months in Services |
|---|---|---|---|---|
| WB fairing | 25 X 30 cm | 18,000 | 9,200 | 48 |
| WB fairing* | 75cm$^2$ | 4,615 | 1,774 | 19 |
| Fan Cowl | 75cm$^2$ | 7,031 | 2,963 | 17 |
| Fwd LH WB fairing | — | 655 | 280 | 2 |
| Fwd RH WB fairing | — | 655 | 280 | 2 |

*** Removed for analysis**

*The above table provides information on all type trial repairs done on Air Canada A320 aircraft.*

***Interfacial Properties of EB-Cured Composites CRADA* (CRADA II)**

Important discoveries from the second CRADA included fiber coatings or treatments, which improved fiber-matrix adhesion by 40% or more according to microdebond testing.[22] Sue Williamson, Cytec (formerly UCB Chemicals Corporation), devised and demonstrated one such treatment during this period which showed 50% adhesion improvement. Thermal post cure treatment substantially improved fiber-matrix adhesion. Up to 80% increase in EB-resin toughness was obtained with the best (798 resin) candidate. Approximately 25% improvement in ultimate tensile strength and 50% improvement in ultimate tensile strain were obtained vs. earlier generations of EB-curable resins. Another best candidate (800E resin) showed generally good properties and 120% improvement in composite transverse tensile strength vs. earlier generation resins.[23] Chemical kinetics studies showed that reaction pathways can be affected by the irradiation parameters.

***Air Canada Commercial Aircraft Composite Repair***

The Air Canada type-trials were conducted on Airbus A320 aircraft. Five repairs were performed, four wing-to-body fairings and a fan cowl. Surface areas of the repair patches ranged from 75-750 cm$^2$. The repaired aircraft were flown in excess of 4,000, 7,000, and 18,000 hours, respectively. Flight cycles (take-offs and landings) for the same repairs were from more than 1,000 to 9,000 cycles respectively over periods of time ranging from 17-48 months in service. See Table 1.[24] Transport Canada has issued a Repair Design Certificate for electron beam repair of fiberglass wing to body fairing panels.[25]

***Industrial Research Assistance Program* (EB Adhesives)**

Approximately 235 adhesives were screened using, as appropriate, gamma calorimetry, DMA analysis, fluid uptake (water), and lap shear testing to determine tensile mechanical strength of the adhesives.

Twelve adhesives provided single lap shear values on aluminum adherends of 35 MPa (ca. 5,000 psi) or higher. Table 2 summarizes a preliminary report[26] of these results. Values as high as 52 MPa were found. Lap shears found on carbon substrate, however, were significantly lower with none greater than 15 MPa. Of those adhesives,

## Table 2

### Aluminum and graphite substrate

| Aluminum Substrate | | | Graphite Substrate | | |
|---|---|---|---|---|---|
| Adhesive Designation | Lap Shear Strength MPA | Morphology | Adhesive Designation | Lap Shear Strength MPA | Morphology |
| 69-10 | 52(5) | Mixed | 3-2 | 13(3) | Mixed |
| 69-11 | 51(3) | Mixed | 3-3 | 12(3) | Cohesive |
| 69-12 | 48(5) | Mixed | 132-C | 12(1) | Adhesive |
| 105-6 | 44(3) | Mixed | 35-1 | 11(2) | Mixed |
| 69-14 | 43(2) | Mixed | 40-1 | 11(1) | Mixed |
| 105-10 | 42(3) | Mixed | 43-2 | 11(1) | Adhesive |
| 105-5 | 38(11) | Mixed | 69-2 | 11(2) | Adhesive |
| 69-13 | 36(2) | Adhesive | 132-B | 11(2) | Adhesive |
| 105-4 | 33(9) | Mixed | 132-E | 11(1) | Adhesive |
| 105-8 | 33(9) | Mixed | 8-2 | 10(1) | Mixed |
| 105-9 | 32(2) | Mixed | 44-3 | 10(2) | Adhesive |
| 105-2 | 31(5) | Mixed | 46-AEBA | 10(2) | Adhesive |
| 8-1 | 30(5) | Cohesive | 57-6 | 10(2) | Adhesive |
| 105-1 | 29(3) | Adhesive | 105-9 | 10(1) | Adhesive |
| 105-3 | 28(3) | Mixed | 105-11 | 10(2) | Mixed |

*For each substrate, data was in descending order based on lap shear strength. Standard deviations are in parenthesis.*

19 gave lap shear strengths >10 MPa. Only one adhesive was "best" on both aluminum and carbon substrate. Modes of failure gave no clear correlation with lap shear values. Selected adhesives were tested for water and solvent resistance. Selected candidates were tested (lap shear) at -55˚C, ambient temperature, 80˚C (dry state), 80˚C (wet state), and 120˚C (dry state). Excellent retention of mechanical strength was found at high temperatures in both the dry and wet state, with some adhesives showing increases in mechanical properties at these elevated temperatures.[27]

## The Challenges

I continue to be surprised at and impatient with the slow progress toward commercial EB-cured composite manufacture and/or repair in aerospace. Aircraft manufacture is a complex, multifaceted endeavor. EB processing adds, in some ways, to that complexity. For each different type of fabrication (e.g., filament winding, hand lay-up, automated tape placement,[28] film infusion, etc.), EB-curable systems may require different techniques from the conventional. For example, room temperature processing by EB may present several advantages: longer "shelf life," lower cost tooling, lower energy costs, greater dimensional stability of cured parts. On the other hand, composite structures often achieve better consolidation from the high temperatures and pressures afforded during the autoclave process. If thermal consolidation of EB lay-ups is required to achieve optimum part fabrication, the advantage of RT processing is eroded.

There are huge economic barriers to greatly increasing the size of autoclaves for curing large parts, but the size of a shielded EB-processing blockhouse is also limited. Will it be possible to e-beam cure via robot in a hole in the desert?

While (meth)acrylate chemistry is cheaper for EB-curable PMC, the work described in this paper deals almost exclusively with epoxy chemistry initiated by cationic mechanisms. One advantage of this chemistry to the aerospace industry is the extensive history of successful use of epoxy resins for aerospace composites. On the negative side, commercial fiber sizings have been developed for the thermal cure systems. Some are not suitable for EB processing as they have not been designed with EB processing in mind, and none has been optimized.

Just a few of the more obvious challenges to be overcome in commercializing EB composites for aerospace have been listed. A successful commercial application must have an economic advantage. Simply stated, for a new technology to supplant an old one, it must be better *and* cheaper, or it must accomplish a necessary task that can't be otherwise done. New technologies are brought on line by the vision and enthusiasm of one or more champions who are in decision-making positions. These champions must see an exploitable competitive advantage. Few have yet begun to exploit the advantages.

An excellent case for the benefits of electron beam processing for space structures was submitted to Phillips Laboratory in 1997 by AECL Technologies Inc.[29] These authors state that in the short term the true value of EB curing will be in making unique products to meet the ever-increasing demands of the aerospace industry. Nearly ten years have passed since that publication with very limited production of EB-cured parts.

A comprehensive discussion of the challenges of developing and transitioning this new technology into production was presented this year at the Society for the Advancement of Material and Process Engineering (SAMPE)[30] by Mark Wilenski, James Sands, Cliff Eberle and Jay Batten. These researchers list numerous encouraging implementations, accomplishments and a 13-point matrix of prerequisites for commercial success. Electron beam curing reached implementation on the U.S. Army RAH-66 Comanche helicopter (Figure 3) prior to its cancellation in 2004. This work is probably the best evidence to date as to why I still believe the time will come when all necessary pieces will fall into place and that the future of this technology for use in aerospace is bright.

FIGURE 3

**U.S. Army RAH-66 Comanche helicopter prior to its cancellation in 2004**


## Acknowledgments

I thank the dozens of colleagues with whom I worked for many years on this, my favorite technical challenge. Some are mentioned by name in this article, many aren't. Those were good years! The best years are yet to come.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