Electron Beam Curing Demonstration with Automobile Structures

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Abstract

Continuous carbon fiber/epoxy automobile hoods were electron beam cured to demonstrate the capability to achieve curing throughput rates needed on automotive production lines. The project team demonstrated curing speed of 180 hoods/day. This demonstration extrapolates to 1,600 hoods/day curing throughput using a more powerful electron accelerator, and much higher throughputs may be achievable with innovative design and materials development. Single-pass curing was shown to be feasible. The curing costs are potentially attractive, especially at high production volumes

Test laminate properties considerably exceeded those of the finished hoods. Hood thermo-mechanical properties and surface finish need improvement. This is not surprising since this was the team's first attempt to manufacture electron beam cured automobile structures. Several technical barriers were identified that need further attention.

Introduction

US energy security is at risk, partly because of the high fuel demand attributable to tens of millions of automobiles. Reducing automobile weight by the use of lightweight structural materials, such as polymer matrix composites (PMCs), can substantially reduce our national dependence on foreign energy sources. Hence the US Department of Energy invests toward developing economical lightweight materials and processing technologies to reduce automobile weight. New technology implementation in automobile structures demands manufacturability at high production volumes. Thermal resin curing is often a rate-limiting step in manufacturing polymer composite structures, but electron beam curing can potentially cure polymer composites at automotive production rates. Electron beam curing is a nonthermal curing method that uses the kinetic energy of energetic electrons to effect polymerization and crosslinking reactions in radiation sensitive resins. Advantages over conventional thermal curing methods can include significantly shorter and simpler cure cycles; reduced energy consumption; lower residual thermal stresses; reduced volatile toxic by-products; simpler, less expensive tooling; and improved resin stability.

General Motors (GM) introduced a carbon fiber reinforced composite hood on its 2004 Commemorative Edition Z06 Corvette. The hood inner and outer panels were fabricated by hand lay-up using prepreg, and autoclave cured with the cure cycle being approximately two hours [a]. Upon completion of the hood development program, a team including GM, Oak Ridge National Laboratory (ORNL), UCB Chemicals, Fortafil Fibers, Kent State University, and the Michigan Energy Office used the development tooling to manufacture electron beam cured inner and outer Corvette hood panels. The principal project goal was to demonstrate that electron beam curing can potentially deliver high throughput while satisfying technical performance and cost requirements.

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[a] D. Brosius, "Corvette Gets Leaner with Carbon Fiber", High Performance Composites magazine, March 2004

Irradiation Primer

In electron beam curing, the kinetic energy of energetic electrons is transferred to a radiation sensitive resin to effect curing. The part is normally irradiated to achieve a specified minimum absorbed dose, defined as energy absorbed per unit mass. The SI unit of dose is the Gray, which is equal to one joule/kg and is abbreviated kGy. The most important accelerator parameters are beam energy and beam current. Beam energy is usually expressed in MeV (1 MeV = 1.6E-13 joule) and determines the maximum composite thickness that can be cured. Beam current is usually expressed in microAmps (µA) or milliamps (mA), and determines the dose rate delivered to the product. Therefore at a specified dose, projected area throughput is proportional to beam current.

The accelerator, and therefore radiation, can be turned on and off at will. The product is normally irradiated inside a shielded enclosure that is equipped with various interlocks to prevent personnel exposure to radiation or generated ozone. Common structural materials do not become radioactive as long as the beam energy is limited to about 10 MeV.

Material and Process Design

Most electron beam curing research to date has been conducted using either glass fibers or aerospace grade carbon fibers. Commercial grade fiber in a large tow format offers cost advantages for production automotive applications. Therefore a Fortafil large tow fiber was chosen for this project. Fiber-matrix adhesion is a critical parameter that affects the composite's mechanical properties, and is very dependent on the interaction between the sizing and resin. Electron beam cured resins are known to interact differently with sizings than do their thermally cured analogs [b], therefore it was necessary to characterize the material properties of electron beam cured, carbon fiber reinforced epoxies utilizing Fortafil fiber and sizing. Furthermore, since there is limited previous experience with electron beam curing in automotive applications and the requirements are quite different from typical aerospace requirements, multiple resins were screened to select the resin that best satisfied the technical requirements. Finally, in previous aerospace applications it has been common to cure parts in several passes through the beam, e.g. six passes at 25 kGy per pass to achieve a 150 kGy total dose. At automotive production volumes, a single-pass cure will be preferred (possibly required) to reduce logistical complexity and capital investment. Therefore, the researchers conducted screening trials to assess the viability of single-pass curing, and cure dose therefor.

Based on performance specifications supplied by GM, three uni-directional prepreg materials were selected for initial evaluation. These prepreg materials each contained a different electron beam curable cationic epoxy resin system and included either Uvecryl® AD 1798 (ORNL 798), Uvecryl® CP3000 (ORNL 3K), or Experimental Product RX05207 (ORNL 800E). In addition Fortafil's 80K, 510 carbon fiber was selected as the reinforcement fiber for the project.

Due to the sensitivity of the electron beam curable resins to short wavelength light, resin filming and prepregging must be conducted in a wavelength-controlled environment to prevent partial resin curing. All non-fluorescent lighting was turned off during filming and prepregging, and fluorescent lights were covered with special UV resistant, flexible plastic film sleeves that shielded radiation with wavelength below 500 nm. The filming and prepregging operations proceeded smoothly after a quick adjustment of the process conditions, yielding excellent

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[b] C. J. Janke, et. al., Report ORNL/TM-2003/130, *Interfacial Properties of Electron Beam Cured Composites*, to be published in 2004

quality prepreg material. The final 12” wide prepregs had a fiber areal weight of approximately 190 g/m^2 with 40% by weight resin content.

Irradiation Trials

The authors believe this was the fastest cure cycle that has been attempted in composites curing. Although electron beam curing occurs by nonthermal mechanisms, the resin exotherm and beam heating raise the material's temperature. A faster cure cycle generates higher resin temperatures, which may increase the reaction rate and reduce the required dose to cure, thereby increasing throughput. In addition, as material temperature and cure rate increase, the initiator required in concentration, hence resin cost, may also be reduced. Because there was no prior experience with such fast cure cycles, irradiation trials and materials testing were conducted to characterize the resin temperatures and resultant material properties. Parametric variations studied include laminate thickness, tool thermal inertia, dose rate, and total dose. Table 1 describes the specifics of these experiments and their results. All curing was performed at Kent State University’s NeoBeam facility, using a 5 MeV, direct current electron beam.

Material Testing and Selection

To determine the mechanical properties of the three selected prepreg materials, a series of laminates sized 12” x 12” x 6 plies thick were fabricated from unidirectional prepreg. After lay-up, the laminates were debulked for one hour at 100°C, sandwiched between 1/16” aluminum plates, and shipped to the irradiator. The aluminum-laminate sandwiches were conveyed through the beam on a ¼” thick aluminum tray and cured under vacuum bag pressure, with wooden blocks positioned around the sandwich edges to prevent undue pressure on the laminate edges. The electron beam curing was conducted using either (1) 6 passes at 25 kGy/pass using 16 mA, 5 MeV with a conveyor speed of 18.8 ft./min. or (2) 1 pass at 100 kGy using 4 mA, 5 MeV with a conveyor speed of 1.2 ft./min.

Prior to testing, the laminates were thermally post-cured at 150°C for 1 hour to simulate the processing conditions in a paint booth. A summary of the mechanical property test results and the specific testing conditions are shown in Tables 2 and 3, respectively.

Based on the near equivalency of the mechanical property results for the three prepreg materials and on the handleability of the various prepregs, the project team selected the 510/798 prepreg as the material of choice for fabricating the hood panels.

BODY PANEL FABRICATION AND CURING

The Corvette hood consists of two pieces, a "hood inner" and "hood outer", that are bonded into an integrated structure. Five each of the hood inner and hood outer panels were fabricated and cured. The hood panels were fabricated by prepreg hand lay-up on the tools that had been used in the thermally cured carbon fiber hood development program. Panel lay-up, debulking, and curing were conducted at the NEO Beam irradiator in Middlefield, Ohio. Lay-up was performed in a room that was shielded from light below 500 nm wavelength. Figure 1 shows the composite technicians forming a hood inner. After forming, the parts were debulked at about 93°C for about one hour in an insulated plywood box with a piping manifold that distributed hot air relatively uniformly.

Table 1. Irradiation Trials

Panel ID	Configuration	Nominal Dose (kGy)	Actual Dose (kGy)	Method	Speed (ft/min)	Irradiation Duration (sec)	Beam Current (mA)	Beam Energy (MeV)	Max. TC Temp. (°C)
1	Standard	25	31	Single Pass	18.8	1.6	16	5	48, 43
2	Standard	50	64	Single Pass	9.4	3.2	16	5	98, 60
3	Standard	75	95	Single Pass	6.3	4.8	16	5	145, 75
4	Standard	100	127	Single Pass	4.7	6.4	16	5	156, 89 (repeat 174, 90)
5	Massive Tool	75	95	Single Pass	6.3	4.8	16	5	149, 74
6	Insulated Upper Surface	75		Single Pass	6.3	4.8	16	5	
7	Standard	75	95	Single Pass	1.6	18.8	4	5	122, 63
8	Standard	75	95	Single Pass	11.8	2.5	30	5	148, 82
9	Insulated Upper Surface	25		Single Pass	35.3	0.8	30	5	
10	Thin Lam. (4 plies)	75	95	Single Pass	6.3	4.8	16	5	118, 79
11	Thicker Lam. (16 plies)	75	95	Single Pass	6.3	4.8	16	5	165, 77

Standard Configuration =

6"x6"x1/16" Al plate covered w/FEP

6"x6"x0.40" Panel (6 plies, except ID 10,11)

12"x12"x1/16" Al plate covered w/FEP

48"x72"x1/4" Aluminum Tray

Effect of Thermal Environment - ID 3 = 145°C, ID 5 = 149°C, ID 6 not measured

Effect of Dose Rate - ID 7 = 122°C, ID 3 = 145°C, ID 8 = 148°C

Effect of Total Dose - ID 1 = 48°C, ID 2 = 98°C, ID 3 = 145°C, ID 4 = 156°C or 174°C

Effect of Panel Thickness - ID 10 = 118°C, ID 3 = 145°C, ID 11 = 165°C

Notes: 1. 1 Thermocouple was centered in laminate thickness and length, and approx. 1" from its edge. 2. 2nd Thermocouple was taped on the FEP covered 12"x12"x1/16" Al plate ~ 1 inch away from laminate (Note: No vacuum bag was used with the 6"x6" panels). The Al tray was grounded to avoid shorting the thermocouples. 3. Thermocouple data was recorded until sufficient evidence of the reaction was observed (~ twice the time from start to the peak temperature). 4. Panel distance from the scan horn (2'), scan width (48"), pulse width (DC), current, scan rate (100 Hz). 5. Laminate was centered across 48" width of tray and approx. 10" from front end of tray Fresh room temp. Al trays and Al plates were used on each run. The entire tray was irradiated on each pass. 6. Omega instrument (OM-3000 Series), thermocouple wire - (fast response) Part #GG-E-24-SLE, + purple chromega, - red constantan. 7. Material - Fortafil 510, 80K fiber/798 resin, 190 FAW, 40% resin content. 8. Massive Tool = 12"x12"x0.25" Al tool, which was placed on top of Al tray and directly below the FEP covered Al plate. 9. Insulated Upper Surface = Additional minimum 4 plies of glass above breather. 10. Used average of 3 FWT dosimeters for nominal 25 and 50 kGy runs.

Table 2. Laminate Mechanical Properties

Material System ---->	Thermally Cured Toray T600S/Epoxy QuickCure[1]	Thermally Cured Toray T600S/121°C Conventional Epoxy[2]	Thermally Cured Fortafil 510/121°C Epoxy[2]	Electron Beam Cured Fortafil 510/3K (31 kGy x 6)	Electron Beam Cured Fortafil 510/3K (130 kGy)	Electron Beam Cured Fortafil 510/798 (31 kGy x 6)[3]	Electron Beam Cured Fortafil 510/798 (130 kGy)	Electron Beam Cured Fortafil 510/800E (31 kGy x 6)[3]	Electron Beam Cured Fortafil 510/800E (130 kGy)[3]
Laminate Mech. Props. (Norm. to 60% fiber vol.)[4]									
RT O° Flex. Str. (ksi)	215 (184)	245	310	294	270	235	245	285	283
RT O° Flex. Secant Mod. at 0.5 mm deflec. (Msi)	17.5 (15.0)	17.5 (Note: may not be Secant Mod.)	18.0 (Note: may not be Secant Mod.)	17.2	16.4	16.9	15.5	16.8	15.7
RT O° Flex. Secant Mod. at 2.5 mm deflec. (Msi)	n/a			17.6	16.2	n/a	15.3	16.8	15.8
150°C O° Flex. Str. (ksi)	26.6 (22.8)			54.9	53.8	47.4	50.9	55.4	52.9
150°C O° Flex. Secant Mod. at 0.5 mm deflec. (Msi)	5.3 (4.5)			7.9	7.8	7.0	7.6	8.4	8.0
RT O° Tensile Str. (ksi)	347 (297)	330	280	274	249	253	276	260	n/a
RT O° Tensile Mod. (ksi)	20.3 (17.4)	20.0	19.0	20.2	18.5	19.3	19.7	19.7	n/a
RT O° Tensile Strain at max. stress (%)	1.64			1.3	1.4	1.4	1.4	1.3	n/a
RT 90° Tensile Str. (ksi)	8.0	10.0		3.4	4.2	3.6	3.2	6.7	5.1
RT 90°Tensile Strain at max. stress (%)	n/a			0.54	0.64	0.56	0.40	1.00	1.08

1 - Average data at 51.4% fiber volume appears in parentheses

2 - From Toray and Fortafil data sheets using thermally cured, conventional epoxy resins

3 - Values for Fortafil 510/798 31 kGy x 6, Fortafil 510/800E 31 kGy x 6, and Fortafil 510/800E 100 kGy should be considered conservative since there were fiber alignment problems with these sets of samples.

4 - Toray 600S fiber tensile strength, modulus and % elongation = **600 ksi, 33.4 msi, 1.8%** vs. Fortafil 80K 510 fiber = **550 ksi, 33.5, and 1.64%,** respectively. All electron beam cured materials were thermally postcured at 150°C for 1 hour (simulates paint booth) before mechanical testing.

Table 3. Laminate Lay-up, Cure, and Test Conditions

Test	**Material**	**Crosshead speed**	**Sample dimensions**	**Span**	**Span:Depth**	**Notes**
RT, O° Tensile - ASTM D3039	Thermally cured - Toray T600S fiber/Quick cure epoxy resin	**0.197"/min.**	**Type IB specimen** - 0.5" x 0.047"			Note: Different fibers, resins, crosshead speeds, and sample types were used with Toray thermally cured and electron beam cured materials
	Electron beam cured, Fortafil 510, 80K fiber with 3K, 798, or 800E cat. epoxy resins, thermally post-cured in 150°C oven for 1 hr.	**0.05"/min.**	8" x 0.5" x 0.040" w/ approx. 4" gage length			Electron beam cured samples were tested with tabs and without tabs using wedge grips w/10,000 lbs. load cell
RT and 150°C Flexure - ASTM D790 - 3 pt. Bend	Thermally cured - Toray T600S fiber/Quick cure epoxy resin	**0.079"/min.**	3.15" x 0.984" x 0.098"	1.575"	**16:1**	Different fibers, resins, crosshead speeds, support spans, and span:depth ratios were used with Toray thermally cured and electron beam cured materials
	Electron beam cured, Fortafil 510, 80K fiber with 3K, 798, or 800E cat. epoxy resins, thermally postcured at 150°C for 1 hr.	**0.063"/min.**	3.5" x 0.50" x 0.040"	1.187"	**32 to 1**	150°C testing - samples were placed in 150°C chamber and allowed to dwell for 35-50 min. at143 – 150°C, then tested in flexure w/1000 lbs. load cell.
RT, 90° Transverse Tension - ASTM D3039	Thermally cured - Toray T600S fiber/Quick cure epoxy resin					
	Electron beam cured, Fortafil 510, 80K fiber with 3K, 798, or 800E cat. epoxy resins, thermally postcured at 150°C for 1 hr.	**0.05"/min.**	5-6" x 1.0" x 0.040" w/ 3-4" gage length			Samples were tested without tabs using wedge grips and 1000 lbs. load cell

Note: All electron beam cured laminates (12"x12"x 6 plies) were composed of unidirectional prepreg (resin content before bleed = nominal 40 wt%) and were fabricated using ORNL's #4 lay-up scheme and hot debulked w/ bleed once at 100°C for 1 hr. and electron beam cured at Kent State either at: 1). 6 passes at 25 kGy/pass using 80 kW, 16 mA, 5 Mev (conveyor speed = 18.8 ft./min, approx. 3.2 sec/pass, maximum composite temperature during cure = 43° - 74°C); or 2). 1 pass at 100 kGy using 20 kW, 4 mA, 5 MeV (conveyor speed = 1.2 ft./min, approx. 50 sec/pass, maximum composite temperature during cure = 107° - 109°C).

Figure 1. Hood inner fabrication

Production was limited to serial part flow, since there was only one debulking box, one tool each for hood inner and outer panels, and two fabrication technicians. Although electron beam curable prepreg is not substantially different from conventional prepreg, there was enough difference in stiffness and tack to require some acclimation by the technicians. The hood outer panel was a relatively simple part, being nearly flat with no sharp breaks in geometry. Conversely, the hood inner featured several sharp breaks or deep draws that complicated its forming. The first part formed was a hood outer, and almost one entire day was spent in its forming. Forming time was quickly reduced, with most parts formed in less than four hours.

Curing

After fabrication, the parts were instrumented with thermocouples, vacuum bagged, debulked, loaded onto a wheeled cart-type conveyor, instrumented with dosimeters, then electron beam cured at ~130 kGy dose. Five each hood inners and hood outers were cured. Figure 2 shows a hood outer in the vault, positioned to begin its pass through the beam.

Figure 2. Hood outer ready for irradiation

The curing demonstration verified that very short curing cycle times are achievable. The parts were irradiated at 5 MeV and 20 mA delivered beam energy and current. The hood outer was fully cured in a single pass requiring two minutes. The hood inner, with its more complex geometry, required 3 passes lasting two minutes each. Electron beam curing trials therefore demonstrated a *curing* throughput of about 180 hoods per day. To achieve this throughput would require dramatic improvement in the fabrication and logistics, as discussed below; furthermore, it is projected that with those improvements, 1,600 hoods per day could be readily cured on a more powerful accelerator.

One of the sometimes challenging requirements of electron beam curing is that all cured material must be exposed to a specified minimum dose. Electrons deposit their energy non-uniformly through the material depth, with the dose at first increasing, peaking, then rapidly decreasing with material depth as shown in Figure 3. The equal entrance-exit dose criterion, which states that maximum allowable part thickness is chosen such that the dose is the same at the entrant and exit surfaces, is normally applied. By this criterion, Figure 3 shows that maximum allowable part thickness is about 1.5 cm for 5 MeV beam energy. Both the hood inner and outer are less than 2 mm thick, but complex geometry can complicate curing. The allowable part thickness is measured along the beam "line of sight", so deep draws or other complex geometry can make the part "look thick". The hood outer does have some minor geometry breaks, but nothing that presents a problem to a 5 MeV beam. The hood inner, shown in Figure 4, features several deep draws, some as deep as four inches. The deepest draws are also "wide", so they could be resolved by tipping the part so that the beam line of sight passed through the draw at an oblique angle. The deep draws featured enough draft that it was feasible to fully cure the hood inner in the flat position, and that was the chosen orientation.

To confirm that adequate dose could be delivered to all material in the hood inner, dosimetry film was attached to the "exit side" of a hood inner, and attenuated dose was measured. A section of the dosimetry trace is shown in Figure 5. From this trace, it was determined that the minimum single-pass dose in the hood inner was 41 kGy, so three passes were required to fully cure the hood inners, delivering a 123 kGy minimum dose, which is sufficiently close to the nominal 130 kGy dose target. This irradiation protocol could not utilize the equal entrance-exit dose criterion, and much of the hood inner received 3X required dose. The challenges associated with irradiating the hood inner could be at least partially mitigated by redesigning the hood panels with curing process considerations, and designing an irradiator facility to better accommodate composites curing.

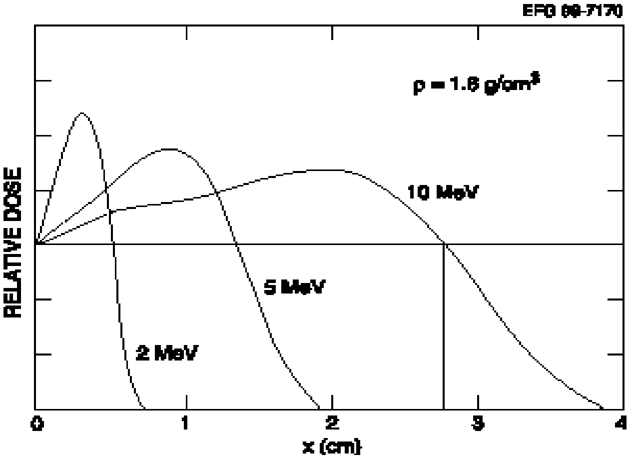

Figure 3. Depth-dose profile in composite

Figure 4. Finished hood inner

After an initial calibration pass, the hood parts were irradiated using 20 mA beam current, 5 MeV beam energy, 3.2 feet/minute conveyor speed, and maximum scan width to irradiate to 130 kGy nominal dose. The parts were thermally postcured at 150°C for one hour, to simulate conditions in the paint booth, followed by shipment to GM for structural rigidity testing. The finished electron beam cured Corvette hood outer is shown in Figure 6.

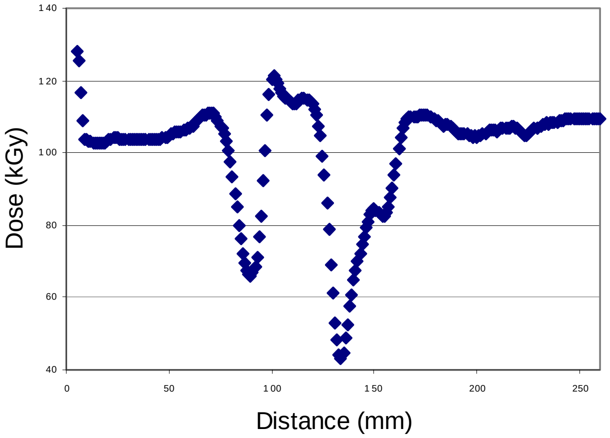

Figure 5. Worst case "back side" dose measurements across a deep draw section in

Figure 6. Electron beam cured corvette hood outer

Structural rigidity tests were conducted on two of the electron beam cured hoods, and the results compared to the reference thermally cured hood. The results of these comparison tests are shown in Figure 7.

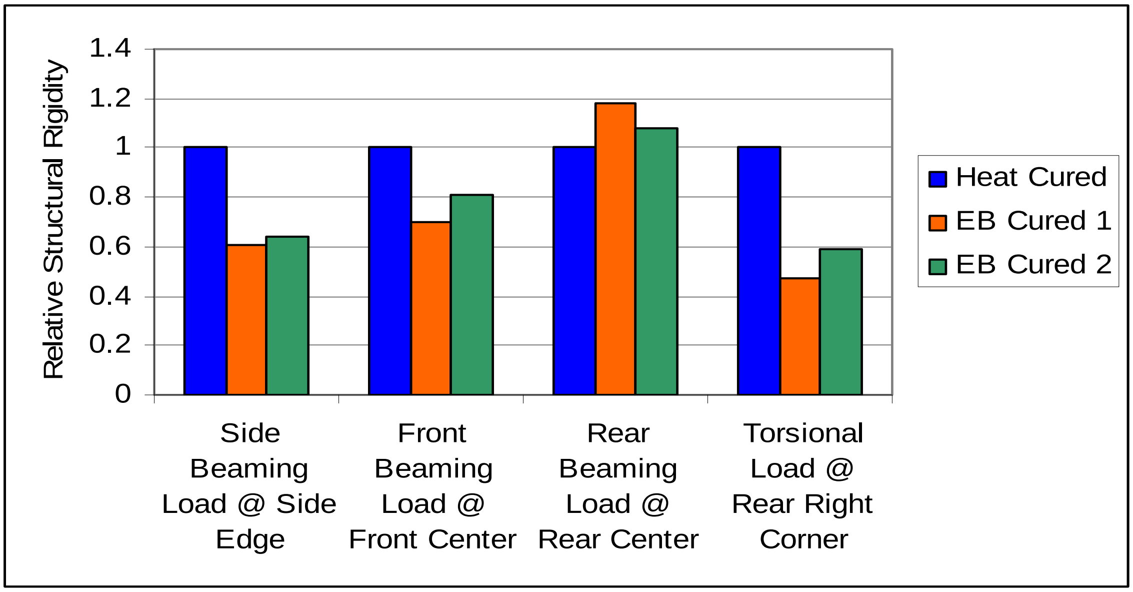

Figure 7. Relative structural rigidity of carbon fiber hoods

The results indicated that, except for rear center, the beaming stiffness and torsional rigidity are lower for the electron beam cured hoods than for the thermally cured reference. Possible explanations for the lower mechanical properties of electron beam cured hoods include:

- Electron beam hoods were not laid-up as well as the heat cured reference, since they were made in a makeshift fabrication room by technicians lacking experience in handling electron beam curable prepreg. Likely consequences include:

  Poor material consolidation, leading to high void content

  Slightly off-axis or misplaced ply orientation (just 5° off-axis can have a large effect)

- Lack of good wet-out/bonding between the resin matrix and fiber. Electron beam cured materials traditionally suffer from poor fiber-matrix adhesion. The relatively low transverse tensile strengths of electron beam cured specimens as tabulated in Table 2 suggest this may be a problem. Recent progress toward improving fiber-matrix adhesion[b] may be applicable.

- Final structures appeared to be resin-starved. Prepreg quality was good, so probably too much resin bleed occurred during debulking.

As expected, the surface finish on the parts did not satisfy automotive body panel finish requirements. The lack of heat to reduce resin viscosity and promote flow, as well as limited consolidation pressure, make it very difficult to achieve Class A surface finish with electron beam curing. The observed resin starvation and difficulty with forming operations further degraded surface finish. The known challenges to achieving satisfactory surface finish with electron beam curing suggest that a structural application, without demanding finish requirements, is a prudent first application of the technology.

Economics

An approximate analysis was conducted to investigate the process economics. Three different facility operations business models are considered. In one case, curing is conducted at a toll irradiation facility on a fee-for-service basis. In the second case, a dedicated irradiation facility is owned by the part manufacturer and operated in-line in the part manufacturing plant. In the third case, denoted as manufacturer owned, toll operated (MOTO), the part manufacturer makes the capital investment and contracts operation by a toll irradiation company. The analysis considers only the curing and associated marginal costs. The detailed economics assumptions are documented in the full project report.[c]

Seven curing scenarios were considered. They are:

1. Curing exactly according to the irradiation protocols demonstrated in this project, on an identical accelerator: 20 mA, 5 MeV, 130 kGy dose, single pass for hood inner, three passes for hood outer, curing throughput 7.7 hoods per hour.
2. Curing at 30 mA, 5 MeV, 100 kGy dose, single pass for hood inner, two passes for hood outer, curing throughput 20 hoods per hour. This requires modest design changes to the hood inner to soften the draws.
3. Curing at 60 mA, 5 MeV, 100 kGy dose, single pass for hood inner, two passes for hood outer, curing throughput 40 hoods per hour. This requires modest hood inner redesign and a 300 kW Dynamitron accelerator.
4. Curing at 100 mA, 7 MeV, 100 kGy dose, single pass for hood inner, two passes for hood outer, curing throughput 67 hoods per hour. This requires a 700 kW Rhodotron accelerator. The 7 MeV beam energy may eliminate the need for hood inner redesign.
5. Curing at 100 mA, 7 MeV, 50 kGy dose, single pass for hood inner, two passes for hood outer, curing throughput 133 hoods per hour. This requires a 700 kW Rhodotron accelerator and technical advancements in resin chemistry.
6. Curing at 100 mA, 7 MeV, 50 kGy dose, single pass for hood inner, single pass for hood outer, curing throughput 200 hoods per hour. This requires a 700 kW Rhodotron accelerator,

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[c] C. J. Janke, et. al., Report ORNL TM-2003/129, *Efficient, High Volume Production of Ultra-Light Auto Body Panels,* August 2003

advanced resin chemistry, and aggressive hood inner redesign.

7. Curing at 100 mA, 7 MeV, 50 kGy dose, with hood inner and outer unitized and cured in a single pass, curing throughput 400 hoods per hour. This requires a 700 kW Rhodotron accelerator, advanced resin chemistry, and very aggressive hood system redesign.

Estimated per-hood unit curing costs and energy requirements are tabulated in Table 4. The MOTO business model delivers the lowest unit curing cost because it combines the longest capital amortization periods with the highest annual throughput (due to more annual operating hours). Irradiation at 7 MeV (scenarios 4 - 7) sacrifices some energy efficiency to gain throughput and hence unit cost reductions. More sophisticated irradiation protocols, e.g. irradiating the hood outer at lower energy, can potentially improve energy efficiency and unit cost, but for simplicity are not considered here. Technology development costs are not included in these estimates.

Table 4. Estimated Part Manufacturer's Unit Cost and Energy for Electron Beam Curing Hoods

Scenario	**Throughput**	**Toll Irradiator**		**Manufacturer Irradiator***		**MOTO****	
		Cost	Energy	Cost	Energy	Cost	Energy
1	7.7 hoods/hr	$70.60	164 MJ	$64.50	171 MJ	$51.30	164 MJ
2	20 hoods/hr	$27.90	77 MJ	$25.70	80 MJ	$20.50	77 MJ
3	40 hoods/hr	$15.80	70 MJ	$14.50	71 MJ	$11.70	70 MJ
4	67 hoods/hr	$12.20	86 MJ	$11.40	87 MJ	$9.40	86 MJ
5	133 hoods/hr	$6.90	43 MJ	$6.80	43 MJ	$5.60	43 MJ
6	200 hoods/hr	$5.20	29 MJ	$5.30	29 MJ	$4.40	29 MJ
7	400 hoods/hr	$3.50	14 MJ	$3.90	14 MJ	$3.20	14 MJ

*Cost excluding profit or mark-up

**Includes 20% profit margin for facility operator

The estimated unit costs shown in Table 4 are based on historical data and/or standard pricing from the electron beam processing industry, with uncertainty in the 20% range, except for tool set cost. The tooling design depends on the fabrication process, which is expected to differ substantially from that used in this demonstration project. Furthermore, required tool life ranges from approximately 20,000 to 150,000 curing cycles, depending on throughput and based on five year tool amortization. This will require more robust tool sets than the ones used in this project. These limitations make tool set cost highly uncertain. Tooling contributions to unit curing cost can be significant, with tool set

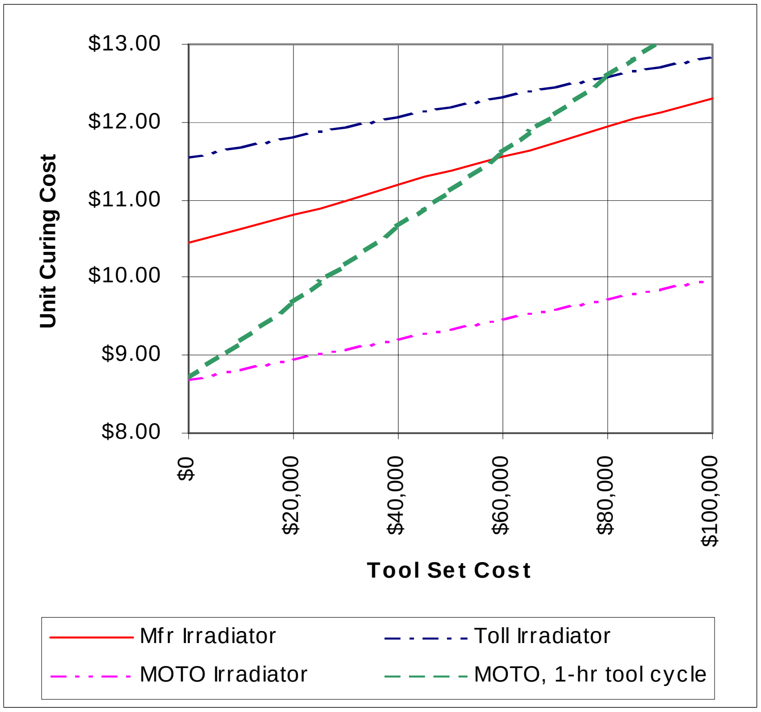

Figure 8. Effect of tool set cost on unit curing cost, with 10-minute tool cycle unless noted otherwise

cost, tool life, and tool cycle time all being important factors. Figure 8 shows the unit curing cost sensitivity to tool set cost for scenario 4, with 67 hoods/hour throughput. The MOTO curves show the difference in cost for tool cycle times of ten minutes and one hour outside the irradiation vault.

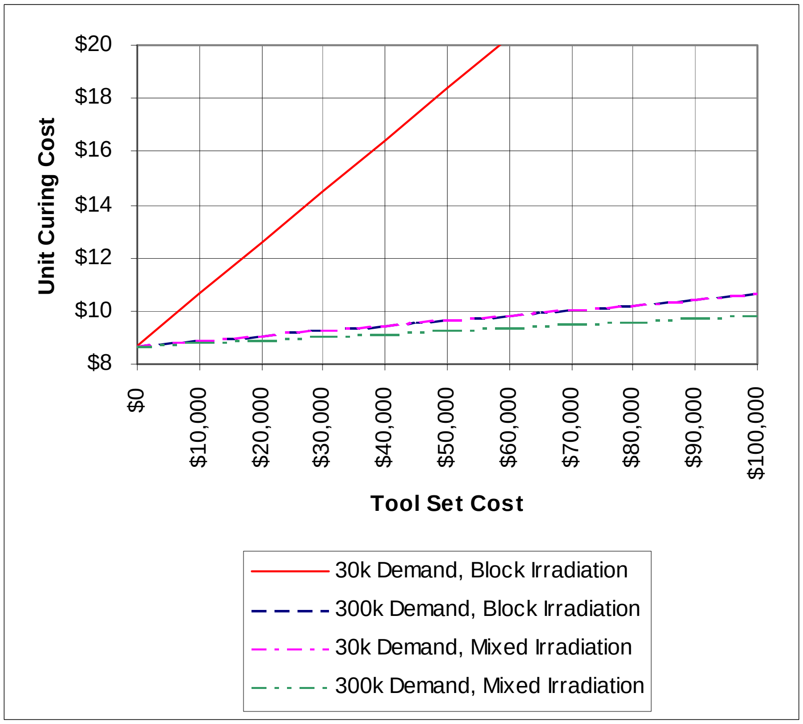

Figure 9. Estimated unit curing cost for 30k and 300k annual demands cured at 500k annual capacity

Table 4 and Figure 8 assume that curing demand approximately matches curing capacity, which is rare. Figure 9 shows unit curing costs, again vs. tool set cost, for 30,000 unit annual demand (Corvette) and 300,000 unit annual demand (family sedan) cured at a facility with 500,000 unit annual capacity (MOTO scenario 4). Estimated unit costs are shown for two logistical strategies. In "block irradiation", the daily throughput is run in a single block of time. This strategy is costly, especially for low production volumes, because it requires the same number of tools that are needed if demand matches curing capacity, yet the tools are amortized over a small number of parts. In "mixed irradiation", the product is uniformly distributed with other products. "Mixed irradiation" reduces the number of tool sets such that the number of parts produced on each tool set, and therefore unit curing cost, is about the same as when demand matches curing capacity. The "block irradiation" and "mixed irradiation" estimates represent the logistics extremes. Hybrids of these two cases may be desirable for various reasons, for example all hoods may be cured in one or two shifts instead of distributing them with other product during all shifts. The unit curing costs shown in Figure 9 were estimated on the basis that there is enough other product irradiation demand to achieve 90 % capacity utilization.

Scenario 4 in Table 4 is considered the best scenario upon which to base economics comparisons and forecasts. It requires no change in hood geometry or materials from those used in this project, and is based upon commercially available equipment. Scenarios 5 and 6 may be readily achievable, but only with significant modifications to the materials or the hood design. Scenario 7 would require significant materials development and extremely innovative engineering.

Conclusions

This experimental study demonstrated the feasibility of curing composite automotive structures at high production volumes using electron beam processing technology. The study suggested that the electron beam curing process may be economically attractive, especially at high production volumes. Judging from the thermo-mechanical properties of the electron beam cured laboratory laminates, it should be possible to increase electron beam cured hood rigidity to satisfy structural requirements. To fully exploit the potential of electron beam curing, advancements in robust, high production volume upstream manufacturing are needed.

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