Process Technology for Radiation Curable Composites

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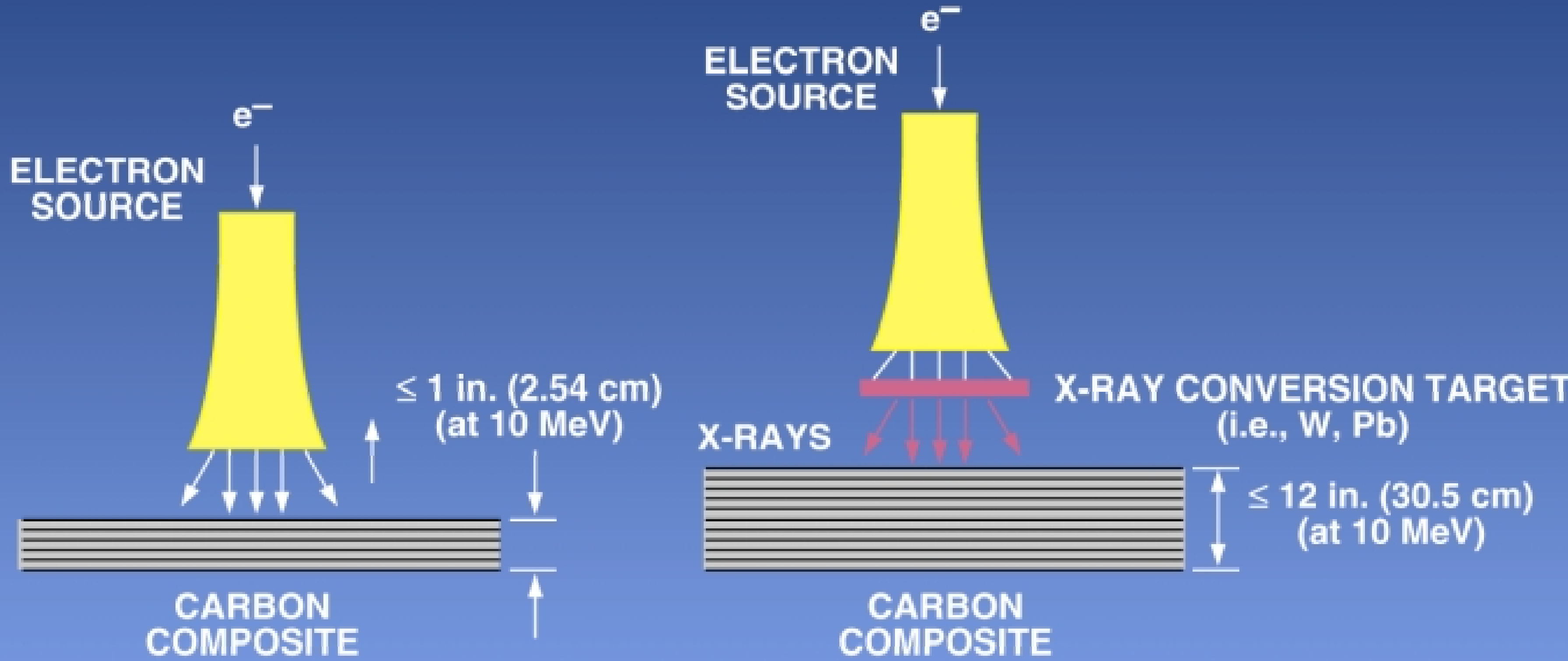
Radiation Curing of Composites

- Visible and ultraviolet light curable resins can be cured by electron beams or X-rays.
- Usually, the thermal and mechanical properties of these resins are not suitable for high-performance applications (e.g., aerospace).
- The ionizing radiation initiates reactions in the resin that cause molecules to crosslink.
- Radiation-cured cationic photoinitiator epoxy resins have thermal and mechanical properties that meet most requirements for high-performance applications.

The Penetration Depth of E-Beam Curing Is Inversely Proportional to the (Density of the Part) x (Part Thickness)



Dosage and Dose Rate

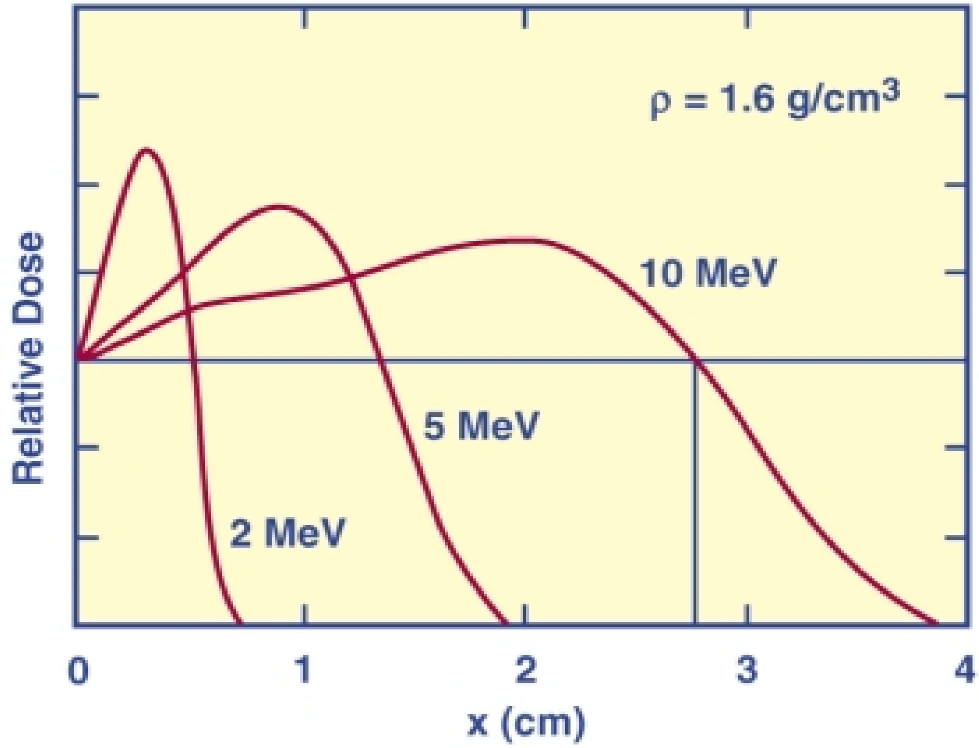
- **Radiation curable carbon/epoxy laminates can typically be cured with a dose of 100-200 kGy**

- **Dose rate must also be considered for process tooling to control temperature rise**

$$T_{max} = D/C_p$$

T_{max} = temperature rise (°C)
D = exposure dosage (kGy)
C_p = material specific heat (J/g•° C)

Electron Beam Curing



Power level = throughput
Energy level = depth of penetration

Conversion of High-Energy Electrons To X-Rays

- **Greater Penetration**
  - **approximately 10X greater**

- **Reduced Dose Rate**
  - **approximately 10X slower**

- **Lower Temperature Rise**
  - **based on slower dose rate**

Radiation Curing Vs. Thermal Curing

RADIATION CURING
IS AFFORDABLE, FAST,
AND SAFE

- **Reduced manufacturing costs and energy requirements**
- **Reduced tooling costs**
- **Generally at least ten times faster**
- **Simplified processing and material handling**
- **Reduced costs related to environmental, safety and health compliance**

Energy Requirements
Thermal Curing Vs Radiation Curing

Product Description	*Size (cm)*	*Mass (kg)*	*Thermal Cure Energy (kWh/part)*	*Radiation Cure Energy (kWh/part)*
Hatch Cover (1)	122 cm x 244 cm x 3.3 mm	15.8	35	4.12
Sports Equipment (1)	Cylinder wall 1.5 mm thick	0.3	0.24 **(3)**	0.02
Filament Wound Tube (2)	Cylinder wall 5.1 mm thick	2.0	13.5	1.73

(1) Graphite/Epoxy (2) Glass/Epoxy (3) Post Cure Only

Data provided by Acsion, Inc.

Unique Capabilities

- Selectable cure temperatures
- Improved part performance and quality
- Ability to cure thick parts in one cycle
- Part thickness limited to 1-2” (electron) or 12” (X-ray)
- Material integration flexibility
  - different resin systems and fibers
  - metal fasteners
  - low temperature materials
- Tight tolerances from minimal thermal mismatch
- Removes need to “balance” fiber architectures
- Curing may be interrupted and restarted

Typical Composite Fabrication Methods

Open Tool Processes

- **Hand Lay Up**
- **Filament Winding**
- **Spray Lay Up**

Closed Tool Processes

- **Pultrusion**
- **Injection Molding**
- **Resin Transfer Molding (RTM)**
- **Structural Reaction Injection Molding (SRIM)**

Prepregging

- **tapes and tows**
- **used for hand lay up or fiber placement**

Radiation Processing Opportunities And Issues

<u>Open Tool Processes</u>

- **Lightweight, low cost tooling**
- **Embedded metal fasteners**
- **Multiple resins used in same part**
- **Thick part capability**

<u>Closed Tool Processes</u>

- **Lightweight, low cost tooling**
- **Cure dose must account for external tool**

Tooling Flexibility

- Electron beam curing opens the door for alternative tooling materials and cost effective solutions
  - foams, plasters, woods, plastics, metals

- Tooling should be optimized for:
  - weight, cost, temperature rise
  - ability to pass energy through for a closed mold

- Cure possibilities
  - total cure on tool, partial cure in mold, cure in-situ

Design Factors for Tooling

- Fabrication process, itself
- Mold fabrication process
- Maintenance and repair
- Handling
- Venting
- Part curing pressure
- Temperature level
- Need for resin flow
- Dimensional stability and achievable tolerances
- Required thermal expansion

Design Factors for Tooling

- Part release
- Wear and durability
- Mold fabrication process
- Thermal mass and conductivity
- Cooling
- Undercuts
- Hardware and inserts
- Surface finish
- Ease of mold duplication
- Radiation absorption

Tooling Exposure
Test Results and Observations

Ceramics

- **Cures of 4500-7500 kGy**
- **No failures to date**

Epoxies

- **Six of seven stable past 7000 kGy**
- **One material lost dimensional stability at 4500kGy**

Polycyanate

- **No failure to data at cures of 5625-6750 kGy**

Tooling Exposure
Test Results and Observations

Polyvinyl Chlorinate

- **Dimensional stability and hardness failed at 0-4125 kGy**

Urethanes

- **Eight of 15 stable to 5000-7500 kGy**
- **Seven lost dimensional stability at >750 kGy**

Plasters

- **Dimensional failures at 4125-7125 kGy**

Tooling Exposure
Test Results and Observations

<u>Woods</u>

- **Mahogany lost hardness at 3750kGy**
- **Jelutong lost harness at 750 kGy**

<u>Others</u>

- **Acrylate lost hardness at 6750 kGy**
- **Phenolic lost hardness at 3750kGy**

Tooling and Part Size Limits in Commercial Accelerator Facilities

E-BEAM Services (Cranbury, NJ)

- **3.7 m x 0.8 m x 0.8 m (12 ft x 2.5 ft x 2.5 ft)**

Iotron (Vancouver, BC)

- **2.5 m x 1.1 m x 1.0 m (8 ft x 3.5 ft x 3 ft)**

Aerospatiale (Bordeaux, FR)

- **10.0 m x 4.0 m dia. (32.5 ft x 13 ft)**

Acsion (Pinawa, MB)

- **2.7 m x 1.2 m x 0.6 m (8.5 ft x 3.5 ft x 2 ft)**

New facilities coming online will be discussed in Workshop.

Materials Issues for Radiation Curing of Composites

- **Effect of curing temperature on the performance of composites over the expected use temperature range**
- **Mechanical property requirements**
  - ***material qualification***
- **Curing under pressure is often impractical**
  - **vacuum bagging**
  - **debulking/consolidation under pressure**
  - **voids**
- **Fiber selection**
  - **use of organic fibers (polyethylene, nylon) must be done with caution**

Materials Issues for Radiation Curing of Composites

- **Fiber sizings for e-beam curing**
  - **GP sizing is most compatible so far**
- **Shear properties require improvement**
  - **New DOE CRADA research partnership is addressing the issue. Results to date will be presented at Workshop**
- **Applicability of radiation curing process to wider range of resins**
- **X-ray cured materials need additional characterization**

Processing Issues for Radiation Curing of Composites

- **Traditional fabrication methods for composite materials can be combined with e-beam curing**
  - **filament winding or tape placement**
  - **resin transfer molding (work beginning)**
  - **pultrusion (no work to date)**
  - **hand lay-up, multi-step processes, or repair**
    co-cure materials with dissimilar thermal properties
- **Curing parts “on the fly” is beginning to be investigated**
- **Optimization of radiation parameters (dosage, dose rate, etc.)**
- **Durability of tooling, bagging and other materials**
- **Methods for minimizing voids**

Processing Issues for Radiation Curing of Composites

- **Fixed position of beam output**
- **Process simulation capabilities primitive**
- **Dosimetry measurement devices saturated at low dose**
- **Cure monitoring**
- **Process qualification and procedure documentation**
- **Part handling and tool maintenance in high-volume production (e.g., maintaining seal on vacuum bags, removal of polymer tooling that has also been cured)**

Facility Issues for Radiation Curing of Composites

- **Existing facility infrastructure is limited**
  - size
  - availability
  - accelerator power and energy
  - locations (concentrated on coasts)
- **Dedicated facility costs**
  - Accelerator facility costs are projected to be somewhat less than high volume autoclaves
  - Current estimates are on the order of10 million for multi-purpose, high-throughput facility, more if vault is to be extremely spacious

Facility Issues for Radiation Curing of Composites

<u>ES&H issues associated with ionizing radiation</u>

- **Routine industrial hazards**
  - falls and accidents
  - material handling
  - electrocution
- **Removal of Ozone**
- **Radiation protection**
  - shielding
  - time
  - distance

Electron Beam Curing of Composites Workshop

Tonight at Garden Plaza Hotel

- Registration Desk
  - Open until 7:00 p.m.
- Hospitality Suite
  - 6:00 p.m. to 8:00 p.m.
  - Cash Bar, Room 201

Tomorrow at Pollard Auditorium

- Registration Desk
  - Opens at 7:30 a.m.
- Workshop
  - Begins at 8:30 a.m.