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Electron Beam Curing of Composites Overview

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ABSTRACT

Electron beam curing is a very fast, non-thermal curing method that uses high energy electrons and/or X-rays as ionizing radiation at controlled rates to cure polymer matrix composites, making them more affordable. A number of programs and initiatives are now actively evaluating the materials and processes for applications as varied as next generation aircraft, space transportation, military ground vehicles, and others. This technology offers a variety of potential benefits to the transportation industry.

INTRODUCTION

The federal government and the U.S. automotive industry have joined in a historic partnership to establish global technical leadership in the development and production of affordable, fuel efficient, low-emissions vehicles that meet today's performance standards. The Partnership for a New Generation of Vehicles (PNGV) program has three separate but interrelated goals:

- Significantly improve national competitiveness in manufacturing by exploring technologies that reduce the time and cost to design and manufacture vehicles;
- Apply innovations, when they are commercially viable, to conventional vehicles, and;
- Develop a vehicle with up to three times the fuel economy of today's conventional, mid- sized sedans, while achieving improved recyclability and maintaining comparable performance, utility, safety, and cost of ownership.

Candidate technologies are being explored in such areas as power generation, energy storage, electronics, materials, manufacturing and systems analysis. Ultimately the achievement of the PNGV goals should make all American industry more competitive. It should help reduce dependence on imported petroleum, lead to a stronger economy, preserve jobs, produce a cleaner environment, make business more globally competitive, and ensure technical leadership in critical fields[2].

Polymer composites have been used for many years by the aerospace and aircraft industries because of their very high strength-to-weight ratio. They also generally exhibit excellent damage tolerance, corrosion resistance, vibrational characteristics, and dimensional stability. In carbon fiber reinforced composites, the stiffness-to-weight ratio can be a major asset as probably most design is stiffness driven. These attributes are very attractive in automotive applications if the life-cycle costs are competitive. Because the automotive market is a consumer-driven, high volume market, the design philosophy is very different than that in the aerospace industry and composites must "sell" their way into these applications more from a cost standpoint than from performance benefits. One technology that has the potential to drive composites manufacturing costs downward is electron beam curing.

Electron beam curing is a non-thermal method that uses ionizing radiation to cure polymer matrix composites very rapidly, making them more affordable. A number of programs and initiatives are now actively evaluating the materials and processes for applications as varied as next generation aircraft, space transportation, military ground vehicles, and others. This technology offers a variety of potential benefits to the transportation industry:

- reduced energy consumption
- less costly tooling
- faster fabrication
- simplified material handling
- reduced costs related to environmental, safety, and health compliance
- capability to cure through thick sections
- opportunity to create unique parts through novel processes.

All of these attributes can contribute to more affordable manufacturing operations.

Electron beam cured composite materials are currently available with properties comparable in many cases with state-of-the-art thermally cured materials. Also, a number of new facilities are now being developed for contract processing services and the accelerator manufacturers are continuing to advance the technology in ways that would benefit the composites market. These developments can be leveraged for automotive and other industrial applications.

DISCUSSION

TECHNOLOGY OVERVIEW

In traditional thermal curing of a two-part resin system, a hardener or catalyst is combined with the primary resin to induce cross-linking or curing. Although the curing process itself is exothermic, elevated temperatures are employed to speed the process and drive the degree of cross-linking to the desired level to produce acceptable thermo-mechanical properties. Typically, the curing temperature level is directly proportional to the temperature at which the cured system shows significant degradation of thermo-mechanical properties. These relationships are very different for electron beam curing.

Electron beam curing is a very fast, non-thermal curing method that uses high-energy electrons and/or X-rays as ionizing radiation at controlled rates to cure radiation sensitive resins such as those used in adhesives and polymer matrix composites. Elimination of the hardener removes what is typically the most toxic portion of the material system and volatile emissions are much less than for thermal curing. Subject to the well-understood physical relationships governing radiation penetration through materials, this curing takes place throughout the entire volume of the exposed material versus thermal curing in which the heat energy diffuses through the material from the part surface. In electron beam curing, the cross-linking reactions take place very rapidly and the degree of cure is more closely related to the absorbed radiation than to the temperature achieved in the process, as in thermal curing. Without exposure to high temperatures, radiation, or excessive light, the electron beam curable materials do not appreciably autocure; this makes storage, cleanup of excess materials, and other handling practices simpler. Figure 1

As mentioned previously, electron beam curing requires the use of radiation sensitive resin systems. Some systems, including a number of acrylates and esters, are naturally radiation sensitive and typically cure to some degree with radiation exposure. These systems are thought of as at the lower end of the performance spectrum for advanced composites, but due to their generally lower costs, those systems are normally among the materials of choice for automotive applications. A number of the higher performance and higher cost systems including epoxies are not naturally radiation-curable. Epoxies have been modified to make them cure with radiation exposure in research conducted under a Cooperative Research and Development Agreement (CRADA) sponsored by the Department of Energy and 10 industrial partners. The Oak Ridge National Laboratory has patented this technology and granted industrial licenses. The materials breakthroughs established by this team have made radiation curable epoxies comparable in many cases to state-of-the-art thermal cure systems; the CRADA achievements offer optimism for achieving satisfactory properties with electron beam cured automotive materials.

POTENTIAL AUTOMOTIVE APPLICATIONS

For automotive applications, it is envisioned that a major advantage would be the speed of curing possible for both adhesives and composites. Processing equipment can be added within the automaker's or supplier's factory. For most parts, the curing operation would be in a totally enclosed station, similar to an automated paint booth, but with walls designed to provide appropriate radiation shielding.

Aside from overall speed improvements, several other advantages are possible. Because the E-Beam curing process does not require high temperatures, multiple materials can be cured concurrently with minimal mismatches in thermal expansions and much lower residual stresses than would be encountered in thermal curing. The composite part shown in Figure 3 is made with glass, aramid, polyethylene, and carbon fiber reinforcements that are co-cured in one cycle with electron beam. The resin has been fully cured at temperatures slightly above ambient, but is comparable to resins cured at 250-350°F, temperatures higher than recommended for the polyethylene (Spectra™).

RTM and vacuum assisted resin transfer molding (VARTM) are cost effective processes for making composite parts where dry preforms are placed in a mold and then the preform infiltrated with resin. Since VARTM is accomplished at low pressures and frequently at low temperatures, low cost tooling can often be employed. One of the key issues is then to balance the low temperature sensitivity of these resins with the need for adequate time to fully infiltrate the preform before initiating curing. Because E-Beam curable resins will begin curing only when exposed to radiation, temperature sensitivity and pot life are not an issue and curing can be performed very rapidly when the part is fully infiltrated. The part shown in Figure 4 was fabricated using the Seeman Composite Resin Infusion Molding Process (SCRIMP), which is a form of VARTM. It demonstrates the use of low cost tooling (also shown) and Spectra fiber to make a simple curved shape.

A difficult problem is to fabricate essentially closed parts that are supported internally during cure and before tooling removal (the "lost core process"). Wax is a common, inexpensive material that can be easily cast. Because it melts at relatively low temperatures, it is also an excellent candidate for single use applications where destruction of the mandrel during part removal is not a problem or where an encapsulated tool must be removed. Figure 5 demonstrates use of wax to make a geometrically simple part. Note that the part surfaces in each chamber replicated the shape of the virgin wax bar very well (flat on one side and concave on the other). The irregular surface on the interior would have prevented tool removal without destruction of the tool. The wax was very easy to melt out and can be recast through at least several cycles. Similarly, styrofoam is a common, inexpensive material that can be easily cast or cut to shape. It is also subject to attack and relatively rapid dissolution by common solvents such as acetone. These characteristics make styrofoam a good candidate for single use applications where destruction of the mandrel during part removal is not a problem. In the case of lost core manufacturing processes where an encapsulated tool must be removed, styrofoam is an excellent candidate. Figure 6 demonstrates use of styrofoam to make a geometrically simple part for eventual tool removal. It also demonstrates how sensitive the styrofoam is to elevated temperatures in that the curing exotherm from one part actually melted the styrofoam. With E-beam curing, the cure rate and associated exotherm can be controlled as demonstrated in the other part that was successfully cured to the desired shape.

Another possible use for electron beam curing in the automotive industry is in applications where enhanced cross-linking provides benefits such as improved chemical resistance and greater stability at higher temperatures. This capability is already being exploited for thermoplastics such as the insulation on spark plug wires and in some plastic tanks. Extent of potential benefits to other materials of interest to the automotive industry need to be quantified.

WHAT NEEDS TO BE DONE

The previously referenced CRADA and a number of other studies have evaluated the economics of electron beam curing. These studies have demonstrated estimated 10-60% cost reduction compared to thermal processing. However, these studies have almost exclusively involved aerospace parts, materials, and processes. Because the design philosophies are so vastly different, similar studies need to be conducted based on automotive needs. As with the aerospace industry, the equipment requirements and overall approaches are enough different that widespread interest and multiple applications would likely need to be developed in order to implement the technology. The automotive industry can build on the knowledge base being assembled by the growing interest in the aerospace industry. Maybe the best lesson to be learned from the current efforts in the aerospace industry is that teaming on precompetitive technology development shortens this curve, brings in a larger resource base, and certainly reduces the costs and risks to any one organization.

In order to evaluate the potential benefits in automotive applications, it is recommended that an industry or government/industry group:

- Select one or more target applications and lay out a conceptual design of an integrated manufacturing process and/or facility. The application may be a particular part up to a full assembly, and may involve a single electron beam cured material up to multiple materials bonded together using an electron beam curing process.

- Analyze part requirements and select appropriate materials. Materials selection will likely require some optimization and/or formulation development. Limited equipment and process development may also be required.

- Design and fabricate appropriate tooling. This may also require some process development and materials testing.

- Perform a manufacturing demonstration of a small production run and evaluate mechanical properties of representative sections.

- Evaluate full economics of the manufacturing process, including materials, labor, equipment, etc., to compare with existing processes, keeping in mind that there may be some unique advantages that are difficult to quantify.

This process will help to establish if and where electron beam curing may offer significant advantages to the automotive industry.

CONCLUSION

The electron beam curing technology offers the transportation industry the potential to more cost-effectively utilize composite materials. The following general advantages have been shown for this technology in aerospace applications:

- shorter cure times - the cure itself is many times faster than thermal curing;

- simplified processing, material handling - improved resin stability at room temperature, indefinite shelf life, less waste;

- reduced costs related to environmental, safety, and health compliance - reduction of volatiles, no catalysts or hardeners required;

- reduced tooling costs -

4. R. E. Norris and M. D. Shulz, “Selection of Materials to be Utilized in Fabrication Tooling for Electron-Beam Curing of Composites,” SAMPE Technical Conference, November 1996.

	Traditional Thermal Curing	E-Beam Curing
Resin System	**Resin and Hardner**	**Radiation-Sensitive Resin No Hardener Required**
Cure Temperature	**High**	**User Selectable**
Cure Speed	**Slow**	**Fast**

Figure 1. Differences Between Thermal Curing and Electron Beam Curing

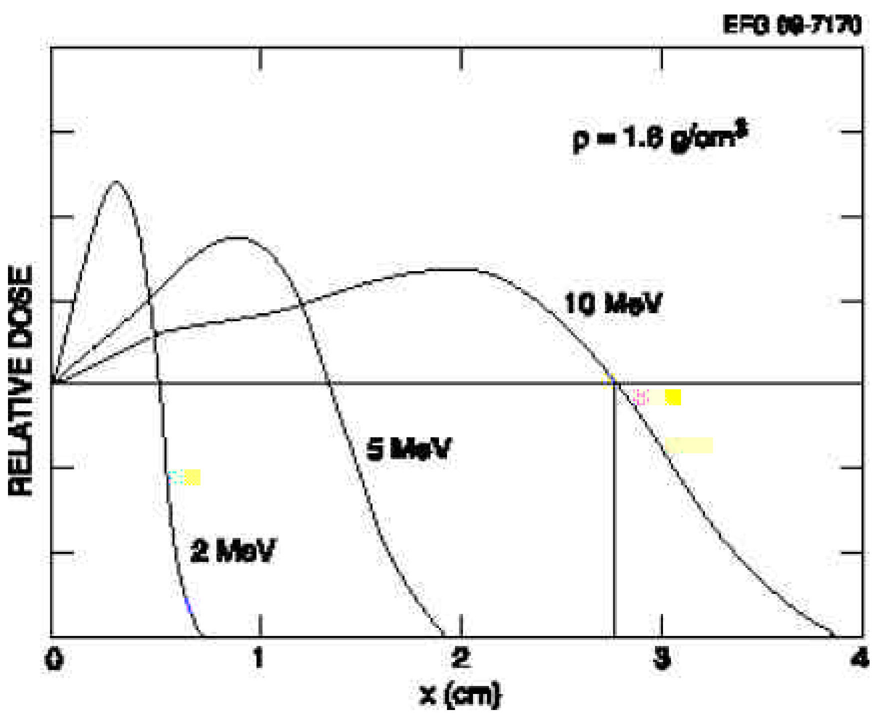

Figure 2. Penetration Dosages Versus Beam Energy

Figure 3. Multiple Materials Cured Concurrently

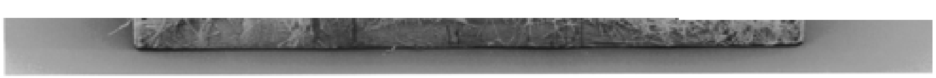

Figure 4. Part Fabricated Using Seeman Composites Resin Infusion Molding Process (SCRIMP)

Figure 5. Wax Forms Used As Tooling

Figure 6. Styrofoam Used as Tooling