Radiation Curing of Composites for Vehicle Components and Vehicle Manufacture

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Abstract. Some ordinary uses of metals in vehicle components and vehicle manufacture, such as steel (specific gravity 7.8) or aluminum (specific gravity 2.7), can be replaced by carbon fiber composites (specific gravity 1.6) to provide significant weight savings while still maintaining structural integrity. The aircraft and aerospace industries have adopted this concept. The motor vehicle industry is using composite materials for some non-structural components in automobiles, but have been reluctant to widely adopt this technology because of concerns about thermal curing times and other issues in high-volume manufacturing processes. A typical steel auto body weighing ~750 kilograms would weigh only ~155 kilograms if replaced with carbon fiber composites. Structural members, such as the vehicle chassis and body frame, could also be made out of carbon fiber composites. With only 20% of the typical body weight, smaller, lighter, less powerful and more fuel efficient engines could be used in such vehicles. Commercial aircraft manufacturers have adopted large carbon fiber structures in lieu of aluminum for a 40% weight reduction and estimate a 20% savings in fuel costs for large planes. These aircraft still use conventional materials for motors, tires and interior components. The fuel efficiency of an automobile could be doubled with an 80% weight reduction. As with aircraft, conventional motors, tires and interior components could be used in automobiles. Radiation curing can simplify the manufacture of carbon fiber composites. Penetrating X-rays generated with high-energy, high-power electron beam (EB) accelerators can cure structural composites while they are constrained within inexpensive molds; thus reducing cure times, eliminating heat transfer concerns and potentially hazardous volatile emissions during the curing process. Since X-rays can penetrate mold walls, the curing process is quite versatile, enabling diverse components with varying designs to be cured using a common X-ray generator or multiple parts of the same design could be cured at the same time. Since the power output of an EB accelerator can be tightly controlled, EB processing can be used to produce "B" staged, fiber-reinforced composite materials for sheet molding compounds (SMC) and prepregs. Such materials can significantly reduce the time-to-cure should alternative energy sources or subsequent X-ray curing be used. In the EB mode, SMC materials can be made at more than 100 meters per minute. The polymeric matrix systems are proprietary formulations based on common radiation responsive materials which are used in a variety of radiation curing applications.

1. Introduction

Radiation processing is not an entirely new concept for the automobile industry. Several vehicle parts are already being made with radiation processing, such as tires, foam panels and high-performance electrical wires. An automobile tire consists of several different components: an innerliner, several fabric-reinforced body plies, a rubber-encased steel belt, the sidewalls and the tread. Before the tire is assembled, some components are partially cured with an electron beam (EB) to stabilize their thickness and to control the positioning of the steel belts during the thermal curing process. The complete tire is then cured (vulcanized) using crosslinking agents in the rubber compound by heating the tire in a mold. This EB process produces a more uniform and better balanced tire, which allows a reduction in the thickness and weight of the tire. This reduces its production cost by savings on materials [1].

Closed cell polyethylene (PE) foam panels are used inside the passenger compartment for side panels and for the ceiling header. This foam is made by mixing a blowing agent into the PE, extruding the PE into a form, crosslinking it with a medium-energy electron beam and then heating the irradiated PE to convert the blowing agent to a gas and produce a foam. This process produces controlled small closed cells in the PE. The cell size and the stiffness and

cushioning properties of the foamed material can be controlled with the radiation dose, the amount of blowing agent and the grade of material used. The advantage of this method is that the crosslinking and foaming steps are separate processes. The moderate temperature rise during irradiation is not enough to initiate blowing [2, 3].

The insulation on high-performance electrical wire can be crosslinked with a medium-energy electron beam. This allows such wire to be used in high-temperature areas, such as near the engine or exhaust pipe of an automobile. Crosslinked insulation will not melt or flow when heated. Flame retardant compounds can be added to the insulation so that it cannot propagate a fire. Crosslinking also improves the abrasion resistance, toughness and the resistance to oil, gasoline, and other organic solvents [4].

Some ongoing applications for thermally cured composite materials in automobiles are the outer body and leaf springs of the GM Corvette, the subframe of the Porsche Carrera GT, and the entire body of the new electric car being developed by Tesla Motors. High-speed racing cars use composite materials to reduce weight and increase performance. Information about these vehicles can be found on the world-wide-web. The Automotive Composites Consortium (ACC) performed crash tests of an experimental Ford car with a front end section made with composite materials and concluded that it was as safe as a typical all-metal car [5].

2. X-Ray Curing versus Thermal Curing

High-energy X-rays can be used to cure a composite part while it is inside an inexpensive mold, which can be made of aluminum, plastic or a cured composite material. In contrast to thermal curing, whereby the mold must have several heaters strategically placed within it to achieve a nearly uniform temperature inside a part with a complex shape, X-ray curing eliminates the need to heat the mold. This simplifies the design of the mold and allows it to be made with cheaper materials. X-ray curing also eliminates the time required to heat and cool the mold and its contents, and it reduces the time to complete matrix curing. High-energy, high-power X-ray generators are now capable of delivering the dose for curing composite parts within a few minutes.

A thermally cured composite material requires the addition of a catalyst that reduces the shelf-life of uncured material. In contrast, the matrix formulations for X-ray cured composites do not require catalysts and are shelf stable. This reduces waste material and provides more latitude for scheduling manufacturing processes. X-ray curing uses less energy than thermal curing. The X-ray curable matrix materials contain near-zero volatile organic compounds (VOCs) and do not pollute the air. Metal parts such as plates for fastening can be embedded within a composite part and become tightly bonded to the cured composite. Internal shear stresses at the interfaces between metal and composite are greatly reduced as well as the stresses between matrix and fibers, that are caused by differences in thermal expansion [6, 7].

3. Physical Properties of High-Energy X-Rays

High-energy X-rays (bremsstrahlung) are emitted by energetic electrons when they strike any material. The efficiency for converting electron beam power to X-ray power increases with the energy of the electrons and the atomic number of the target material. Tantalum, tungsten and gold have properties suitable for X-ray targets, but tantalum is the most convenient and economical material for making high-power, large-area targets. The efficiencies for X-ray emission in the forward direction are about 8% with an electron energy of 5.0 MeV, 12%

with 7.5 MeV and 16% with 10 MeV. The maximum electron energy used for high-power industrial X-ray generators is usually less than 7.5 MeV. This choice avoids inducing nuclear reactions in tantalum targets. The low X-ray conversion efficiencies are overcome by using high-energy, high-power electron beams to obtain the dose rates needed for industrial radiation processing [8].

The broad energy spectrum of the X-ray photons extends from about 30 keV up to the energy of the incident electrons. The average photon energy with 5 MeV electrons is near 1.0 MeV but the peak of the photon spectrum (most probable energy) is about 300 keV. With electron energies above 2.0 MeV, the angular distribution of the emitted radiation is concentrated in the direction of the incident electron beam and the X-ray dispersion decreases as the electron energy increases. The divergent angle at half intensity with a maximum energy of 7.5 MeV is only about 15 degrees. The forward concentration of high-energy X-rays is different from the isotropic emission of gamma rays from large area cobalt-60 sources, that are mainly used to irradiate products which are too thick to be penetrated with primary electron beams. The narrow angular distribution enhances the utilization efficiency of high-energy X-rays and increases their penetration in irradiated materials in comparison to cobalt-60 gamma rays. It also makes it feasible to process single containers of different products which can be rotated in front of the X-ray target to obtain satisfactory dose uniformity [9].

The absorbed doses with high-energy X-rays decrease exponentially with depth in the treated material. The tenth-value layers increase with increasing maximum energy. They are 39, 44 and 49 cm in water for maximum energies of 5.0 MeV, 7.5 MeV and 10 MeV, respectively. The penetration of a broad beam of X-rays with energies above 3.0 MeV is greater than that from a large area source of cobalt-60 gamma rays, which has a tenth value layer of 31 cm in water. Optimum product thicknesses for two-sided treatment with a max/min dose uniformity ratio (DUR) of about 1.5 are 34, 38 and 43 cm in water, or plastic materials with nearly the same density, for maximum energies of 5.0 MeV, 7.5 MeV and 10 MeV, respectively. The optimum thickness for cobalt-60 gamma rays is 28 cm of water. Product thicknesses greater than the optimum values can be irradiated if higher max/min dose ratios are acceptable. The optimum product thickness makes the most efficient use of the emitted X-ray power. The characteristic values listed in Table I have been calculated with Monte Carlo codes [10, 11].

TABLE I. PHYSICAL PROPERTIES OF HIGH-ENERGY X-RAYS

Electron Energy	Mean Energy	Emission Efficiency	Tenth Value Layer (cm) Present Work			Optimum Thickness Double Sided	
(MeV)	(MeV)	(%)	Calculated	Measured	Previous	(g/cm2)	Max/Min
10	1.56	16.2	49.0	47.9	49.0	43	1.54
7.5	1.38	13.3	44.3	N/A	N/A	38	1.54
5.0	1.19	8.2	39.0	39.5	38.0	34	1.54
Co-60	1.25				31.0	28	1.75

4. High-Energy, High-Power X-Ray Generators

Several industrial irradiation facilities can now provide electron beam and X-ray processing for a variety of applications. There are three such facilities in Japan. One of these is equipped with a 5.0 MeV, 150 kW Cockcroft Walton accelerator [12]. Another has a 5.0 MeV, 200 kW Dynamitron® accelerator [13], and the third facility has a Rhodotron® accelerator with two beam lines rated for 135 kW at 5.0 MeV and 200 kW at 10 MeV [14]. There are two facilities

in the United States, which can also provide both electron beam and X-ray processing. One of these has an L-band microwave linac rated for 150 kW at 5.0 MeV [15]. The other one has a Rhodotron accelerator with three beam lines rated for 135 kW at 5.0 MeV, 190 kW at 7.0 MeV and 200 kW at 10 MeV [16]. In addition, there is a facility in France, which has an S-band microwave linac rated for 20 kW at 10 MeV [17]. These facilities use removable X-ray targets and can irradiate products with either electrons or X-rays.

Recent developments have increased the beam power ratings of high energy electron accelerators in order to get higher throughput rates for X-ray processing. The Dynamitron accelerator, made by IBA Industrial, Inc. (formerly Radiation Dynamics, Inc.) in the USA, has been upgraded from 200 to 300 kW at 5.0 MeV [18]. With 8% power conversion efficiency, the emitted X-ray power would be 24 kW. This is nearly equivalent in processing capacity to the gamma-ray power emitted by 2 MCi of cobalt-60. At a typical price of $2.25 per curie, the user's cost of the cobalt-60 sources at this capacity would be substantially more than the cost of a 300 kW Dynamitron. The Rhodotron accelerator, made by IBA in Belgium, has been upgraded from 200 to 500 kW at 5.0 MeV and to 700 kW at 7.0 MeV [19]. The emitted X-ray power at 5.0 MeV and 500 kW with 8% conversion efficiency would be 40 kW. This would be equivalent to the gamma-ray power emitted by about 3 MCi of cobalt-60. The emitted X-ray power from the same accelerator operated at 7.0 MeV and 700 kW with 12% conversion efficiency would be 84 kW. This would be equivalent to the gamma ray power emitted by about 6 MCi of cobalt-60, which just for the cobalt-60 sources would be substantially more the user's cost of a 700 kW Rhodotron.

A new Rhodotron facility will soon be completed in Switzerland. It will be used to sterilize medical products exclusively with X-rays. Continuous operation of this facility will show that X-ray processing is a practical alternative to gamma-ray processing. More information about this project can be found on the IBA website: http://www.iba-worldwide.com.

5. Vehicle Components Cured with X-Rays

Several experiments have been done with the 3.0 MeV, 90 kW Dynamitron accelerator in the facility of IBA Industrial, Inc., which is located in Edgewood, Long Island, New York, to demonstrate the feasibility of curing carbon fiber reinforced composite materials with X-rays. These included evaluating several shelf-stable matrix formulations, showing that the liquid, uncured matrix material can be drawn into an evacuated mold and wet several layers of woven, carbon fiber twill, and determining the X-ray dose needed to cure the composites.

Several parts with different shapes were cured with X-rays while in simple molds. These included flat panels, small cups, a motorcycle fender and an automobile fender. See Figures 1, 2, 3, 4 and 5. They were fully cured and had smooth, Class A, surfaces when removed from their molds. Materials impacted with a round tipped steel rod, a falling tup, have shown that carbon fiber reinforced composite panels have more impact resistance than aluminum panels with the same thickness [20]. The next step will be to produce structural pieces that could be used to make the chassis or the body frame of an automobile.

6. Conclusions

Modern, high-energy, high-power X-ray generators can cure fiber reinforced composite parts while still in the mold in less time than is needed for thermal curing. Inexpensive molds made of aluminum, plastic or composite materials can be used because they need not be heated to

affect a cure. Common radiation curable polymeric materials can be used in formulating matrix systems suitable for X-ray curing.

More extensive applications of carbon fiber reinforced composite materials in automobiles would substantially reduce their weight and increase their fuel efficiency. Replacing most of the steel parts, including the chassis and frame, with composites could reduce the weight by 80%, which would double the fuel efficiency. In contrast to steel, composite structures would not need corrosion protection coatings, being inherently corrosion resistant. This would reduce the total production costs of vehicle manufacture by eliminating an entire process operation.

Automobile owners would benefit from greater use of composites through greater fuel efficiency. Societies would benefit from the decreased dependence on fossil fuels and from the reduction of environmental emissions.

7. References

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FIG. 1. Tup impacted at the same force: a four-ply X-ray cured carbon-fiber composite panel and aluminum plate of the same thickness. Carbon-fiber was indented; aluminum plate was fractured.

FIG 2. Carbon-fiber composite cups X-ray cured in a thin steel mold beneath a 2 centimeter thick aluminum plate to simulate a thick walled metal mold.

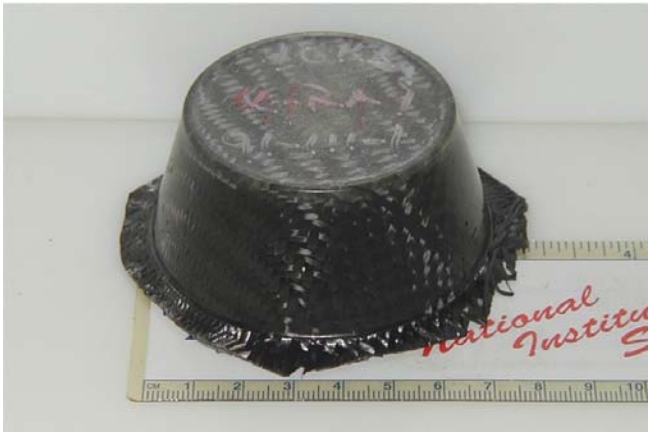

FIG 3. Six-ply carbon fiber cup X-ray cured in a thin steel mold beneath the 2 centimeter aluminum plate.

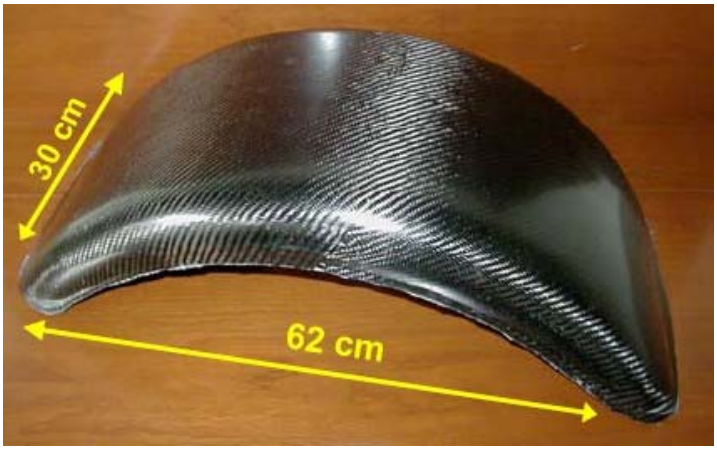

FIG 4. X-ray cured six-ply carbon fiber composite motorcycle fender.

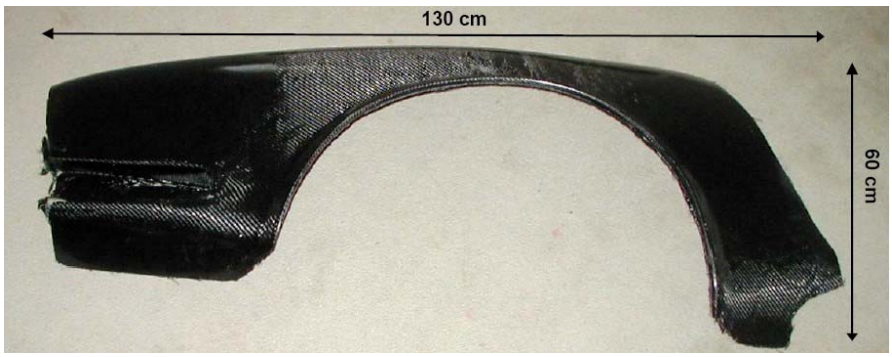

FIG 5. X-ray cured six-ply carbon fiber composite sports car fender.