

Power Demands for Curing Carbon Fiber Composites for Automotive Components

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ABSTRACT

The power demands in terms of kilowatt-hour electrical use were compared for autoclave curing commercial thermosetting carbon fiber pre-pregs with an innovative alternative of high energy X-ray curing. An automotive component, now made with carbon fiber composites, was selected as an illustrative example, an Aston-Martin hood. Temperature resistant polyester molds for these hoods were used and manufacturer recommended autoclave curing conditions were followed. X-rays, which can penetrate about 15 cm (6 inches) in unit density materials (or less into higher density materials as molds), were used to cure pre-pregs made with a specialty matrix material using the same molds, but doing so without adding any heat for curing. High energy X-ray equipment, generated from a 7 MeV, 700 kW electron beam, is in commercial use for medical device sterilization. This same equipment can also be used for composite curing. Automotive components can be exposed on a continuous basis by passing them in front of the X-ray source. Such electrical sources must be enclosed within thick shielding structures to prevent X-radiation from entering the workplace. Feasibility studies, relying upon vacuum assisted resin transfer molding (VARTM), had shown that select combinations of functional monomers and oligomers can be formulated for the X-ray curing of carbon fiber composites within molds. The viscosity of these epoxy based materials was increased for their use as the matrices in pre-pregs. Dynamic mechanical analyses of cured components were used to assess some performance parameters. The New York State Vehicle Composites Program and the prior feasibility studies on X-ray curing were supported by the New York State Energy Research and Development Authority.

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INTRODUCTION

Fiber reinforced composites have been used in the automotive industry since General Motors production of the Corvette in 1953 with its fiberglass reinforced body trim. Because of its superior strength-to-weight properties, carbon fiber has emerged as a way to lower weight and maintain, if not enhance, strength in a variety of

industries. For example, the aircraft industry has replaced aluminum fuselages and other components with carbon fiber composites as for the Boeing 787 Dreamliner and the Airbus 350.

For vehicles, carbon fiber bodies have been adopted by the racing professionals and are beginning to be used in premium passenger cars, such as the BMWi3 series, Tesla, and other high end vehicles. Here the strength-to-weight benefit of carbon fiber technology

enhances a vehicle's power efficiency, whether in terms of kilometers/liter (mpg) or the ability of an electrically powered car to go farther on a given battery charge.

While the end-user benefits for the adoption of carbon fiber composites for vehicles have been well studied, less is known about the energy demands required to produce such materials and possible alternatives to historic thermal processing. For example, as shown in [Figure 1](#), a 103 kg (227 pound) carbon fiber composite prototype vehicle, Concept Zero, developed by the New York University Department of Engineering and Nordan Composites Technologies, was powered by a 1.1 horsepower engine and attained greater than 60 kilometers/liter (140 miles/gallon) in a Shell Eco-marathon.[1]



Figure 1. NYU-Nordan Composite Technologies carbon fiber concept vehicle.

Matrix Materials

Engineers and chemists are well trained in heat transfer, thermodynamics, and such classic uses of energy deposition. Much less of the education process is devoted to electro-technologies or alternative means of energy transfer. The chemistry upon which many of the composite matrices have been developed follow what has been used in the aircraft industry: the curing of epoxy resins with additives or curatives to crosslink the epoxy into a solid. However, such curatives, whether amines, amides or anhydrides, have been shown to be incompatible with the base epoxy resins themselves. Thus, when used in pre-blended systems, as the matrices for prepreps, cold storage is required to prevent unwanted initiation and a gradual heating is called before reaching cure temperature. The kinetics of most of these reactions follows the general rule that the reaction rate doubles for every 10°C increase in temperature. Cold storage then reduces the reaction rate. If very fast curing epoxy formulations are developed, their viable use, even with cold storage, will be reduced. At the micro-phase level, the epoxy and its curative retain some phase distinction, as shown in [Figure 2](#), a one micron photo-micrograph of a thermally cured amine-epoxy.[2]

The specialty X-ray responsive matrix materials discussed here are also epoxies, but onto which an acrylate group has been added so that free radical polymerization-crosslinking can take place. Such materials have a long history of use in the coatings industry and are well known for the long shelf-stability, being stored at ambient

temperatures for many years without any reaction being initiated nor gel formation. [Figure 3](#) depicts the chemical structure of an epoxyacrylate.[3]

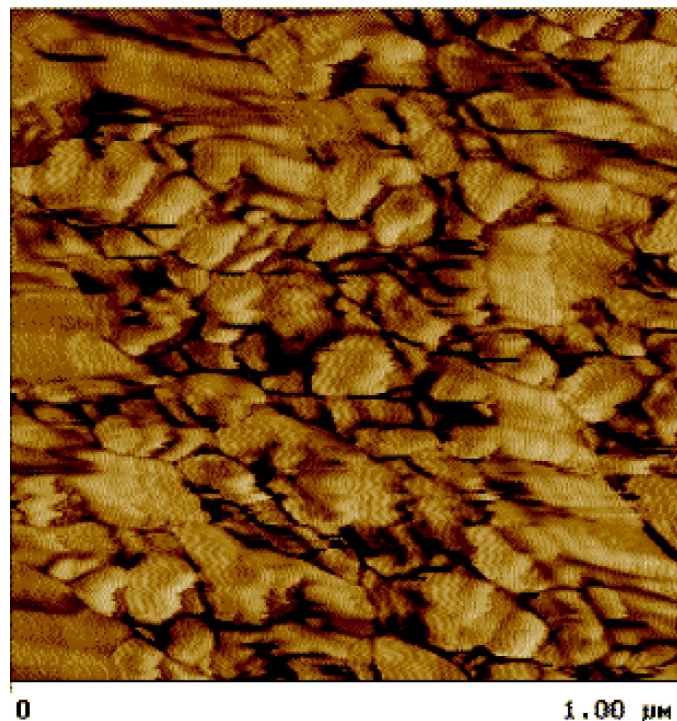


Figure 2. Microphase structure of an amine cured epoxy.

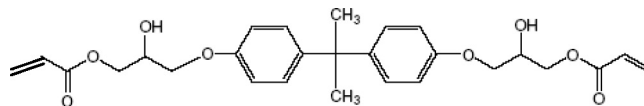


Figure 3. Bis-phenol-A Diacrylate.

The molecular weight of this type of material is controlled by its manufacturer. However, formulators, such as Rapid Cure Technologies, can modify these epoxy-acrylates with other free radical responsive monomers and oligomers to even further adjust viscosity and/or to enhance impact resistance, cure rate response and other factors if so desired. Photo-micrographs of such radiation cured matrix materials have shown their homogeneity reflecting their micro-phase compatibility. [Figure 4](#) is a photo-micrograph of a radiation cured formulated epoxy-acrylate at the same one micron scale as [Figure 2](#). There is a lack of internal phase separation as remains within the thermally cured two component epoxy system.

In order to compare the power demand for curing between the use of heat and pressure when using an autoclave with an out-of-autoclave use of X-rays, pre-preps were obtained based on 3k 2×2 carbon fiber twill. Thermosetting carbon fiber pre-preps were obtained from two companies: Cytec Industries (now part of Solvay) and Renegade Materials. Renegade also produced a radiation curable pre-prep using an epoxy-acrylate formulation provided by Rapid Cure Technologies.

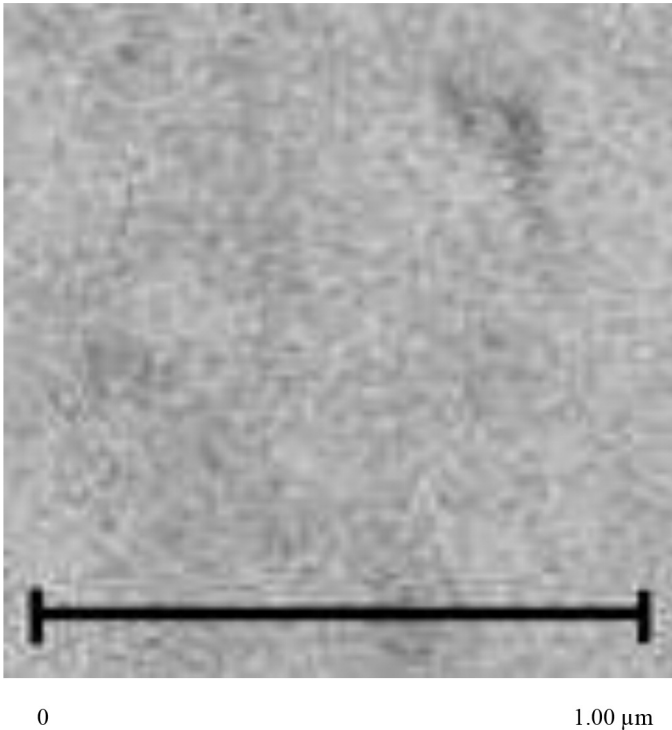


Figure 4. Microphase structure of a radiation cured epoxy-acrylate.

Vehicle Component

While there are many parts of a vehicle that can benefit from the strength-to-weight benefits of carbon fiber composite technology, it was decided to pursue one component that is already being made using carbon fiber, an Aston-Martin hood, which is an area subjected to the heat emitted by the engine, in contrast to fenders, doors, trunk lids, which are not exposed to such thermal history. Nordan Composite Technologies is familiar with this hood design as well as with racing and performance vehicles that use carbon fiber.



Figure 5. Commercial Aston-Martin carbon fiber hood.

Thermal Curing

Inexpensive, temperature resistant polyester 1.49 m wide by 1.53 m long (58.5 × 60.0 inches) fiberglass reinforced molds for the Aston-Martin hood were made. Plies of carbon fiber pre-pregs were cut and then laid up onto the mold, nylon vacuum bagged and then

autoclave cured. The facilities of the Composite Prototyping Center (CPC) were used for these test purposes. The CPC has two autoclaves, one being 2.4 m (8 feet) in diameter by 6.1 m (20 feet) long. Four and six ply hoods were made and thermally cured per the pre-preg manufacturer's instructions. For a Cytec automotive pre-preg, a cure cycle of one hour ramp up at 1.7°C (3°F)/minute was used to reach a 121°C (250°F) curing temperature and then holding at that temperature for an hour and then allowing another hour for the cured piece to cool down. Vacuum was maintained within the nylon bag and external heat and pressure applied by the autoclave. Figure 6 shows the vacuum bagged hood within the autoclave and Figure 7 the bagged cured hood being taken from the autoclave.[4] Figure 8 is the first Aston-Martin hood cured for this program.



Figure 6. Vacuum bagged mold with carbon fiber lay-up in autoclave.



Figure 7. Vacuum bagged mold being taken from the autoclave.

For test purposes, four ply 25.4 cm (10 inch) square lay-ups of both the Cytec and the Renegade Materials pre-pregs were made. These were used in Dynamic Mechanical Analysis (DMA) from which the glass transition temperatures (T_g) could be determined.