A UNIQUE APPROACH TO THE HIGH VOLUME PRODUCTION OF CARBON FIBER REINFORCED EPOXY STRUCTURAL COMPONENTS

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Abstract

Fiberglass reinforced epoxy (FG/epoxy) and carbon fiber reinforced epoxy (CF/epoxy) composite components are known to be produced in high volumes using the compression molding process. This same molding technology can reasonably be expected to produce high volumes of CF/epoxy automotive body structure and chassis components.

The author discusses epoxy unique chemistry, forming and molding processes possible due to the thermoplastic stage-of-cure referred to as the epoxy B-stage. B-staged epoxies are discussed and then compared to what is commonly referred to as a B-staged Sheet Molding Compound (SMC).

A progression molding assembly line concept similar in configuration to existing automotive sheet metal forming lines is discussed. This conceptual molding operation would be capable of producing complex CF/epoxy structural composite components at a rate of at least 120/hour.

Background

The automotive industry has used unsaturated polyester resins reinforced with fiberglass in many semi-structural products for the past 50 years (more-or-less). The advantages of this resin are low cost, low viscosity at room temperatures and exceptionally rapid cure. Another advantage is with the addition of a low-profile polymer the contraction of the polyester cross-linkage can be counteracted during the cure process resulting in improved dimensional stability and more importantly Class-A surface finishes. A final advantage, there are probably many more, is the fact that compounders are able to use internal mold releases.

Typically the automotive industry uses Sheet Molding Compounds (SMC's) for the molding material. These SMC's are basically, 25% by weight, chopped fiberglass (1" long) in a blend of polyester resin, low profile additive and a fairly significant amount of calcium carbonate used as a filler/extender. SMC is normally chemically thickened using terminology called B-staging. This chemical thickening does not increase the molecular weight of the polyester and is employed to improve handle-ability of the molding material. The chemically thickened SMC material is normally cut into rectangular charges, then laid or thrown into hot chromed steel molds and compression molded at over 1000 psi for 2-3 minute cure cycles. The green parts emerging from the hot molds are dimensionally stable enough to be trimmed and stacked for subsequent operations.

The epoxy resin cure mechanism on the other hand is quite different. The composite materials are approximately 40% epoxy resin and 60% fiberglass cloth and have been used in printed circuit boards (PCB's) for over 50 years in most of our electronic products. The focus of this discussion will be more on these epoxy resins than those currently used in the automotive industry. A B-staged epoxy is not the same thing as a B-staged SMC.

B-Staged Epoxy

Epoxy resins arrive at a prepregger in normally a solid form, typically powdered, granular or in large chunks. These are then typically dissolved in a solvent (normally acetone), then mixed with catalysts and other ingredients, then the fiberglass reinforcement is dipped into baths, excess resin is squeezed off and then the solvent is evaporated away in heating towers or tunnel ovens. These tunnel ovens drive the state of cure of the epoxy further, but not to completion. This is called B-staging the epoxy material. B-stage is defined as, "To cure an epoxy to a pre-determined degree of chemical conversion." (Arnold and Thoman, 2001). Another method of mixing the solid epoxy resins is by heating and melting them in reactors or mix vessels effectively reducing the viscosity to a point where the other key ingredients can be compounded into the mixture. At this stage in the cross-linkage process the epoxy resin truly is technically still a thermoplastic or at least it can be melted, although the molecular weight of the polymer is steadily increasing, reference figure #1 below. The molten resin is then cast onto paper or can be directly applied to the reinforcement at this time. When cooled the resin hardens and returns to the original semi-solid form. The sticky or tacky characteristics can be controlled by the amount of time at temperature and directly correlates to the degree of conversion or cure.

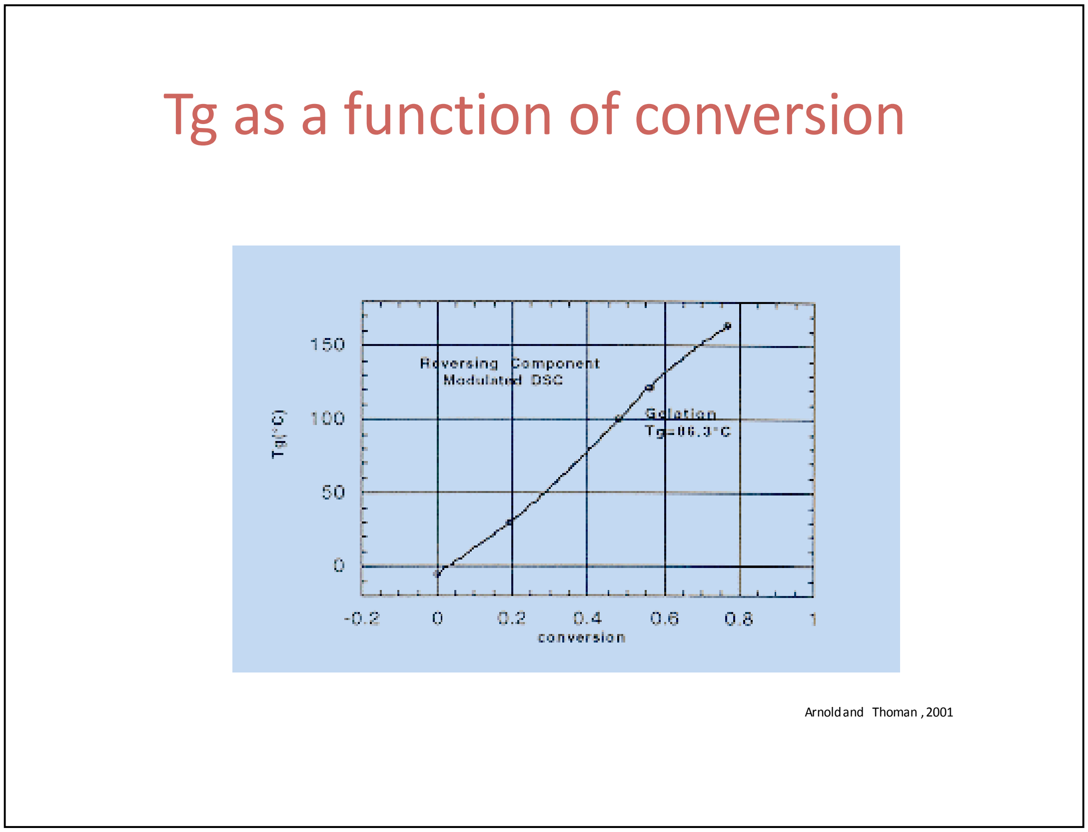

Figure 1: Glass Transition Temperature (Tg) of epoxy resin charted by degree of cure/ Conversion.

B-staging an epoxy is, in the opinion of this author, more complex than simply what Arnold and Thoman discuss. Their examination of B-staged epoxy using Tg does not comprehend the gradual increase in viscosity of the polymer as the molecular weight increases during the cure process. PCB manufacturers receive solid laminations of epoxy with fiberglass and copper foils. These copper clad laminates are photo-etched, dipped into chemicals, baked and then stacked into multiple layers. Then these complex laminations are compression molded at 200-300 psi normally under vacuum. The seemingly solid epoxy resin of the composite lamination has been B-staged to a high degree of conversion, but it still melts and is moldable. The partially cured resin softens/melts and flows enough to bond the laminations together creating a tough composite printed circuit board after completing the cross-linking process. Transforming from a meltable thermoplastic resin while in the B-stage to a non-melting thermoset resin. Or as Arnold and Thoman declare the chemical conversion is approximately 90% complete having achieved the maximum glass transition temperature possible for that formulation of epoxy.

B-staged epoxy prepregs are normally characterized by aerospace composites manufacturers by their degree of resin flow, stickiness, drape, formability or sag. Some manufacturers utilize press molding grades of epoxy prepreg. Press molding grades have been B-staged to significantly higher degrees of chemical conversion. There are other grades of B-stage referred to as being low-flow, ultra-low flow and finally no-flow prepregs (Arlon Inc, 2009). Flow characteristics of the prepreg are usually measured by applying standardized pressures using a platen (compression) press. Hand lamination grades will have a typical flow of 15-25% when subjected to 25 psi. The flow of a PCB grade prepreg isn't normally even published by the manufacturers. The processing guidelines for the material provide a fairly good indication of the degree of conversion (or cure). Park Electrochemical Corporation's Nelco Advanced Circuitry Materials group provides processing guidelines for their prepreg specifying cure pressures of between 200 and 300 psi in a vacuum assisted hydraulic press at 340-375^{o}F. Shimadzu Scientific Instruments discuss the measurement of epoxy flow for a typical PCB application on their website (Shimadzu, 2010). The data provided (Reference Figure 3) indicates flow of the epoxy resin at 165^{o}C stops after approximately 20 seconds.

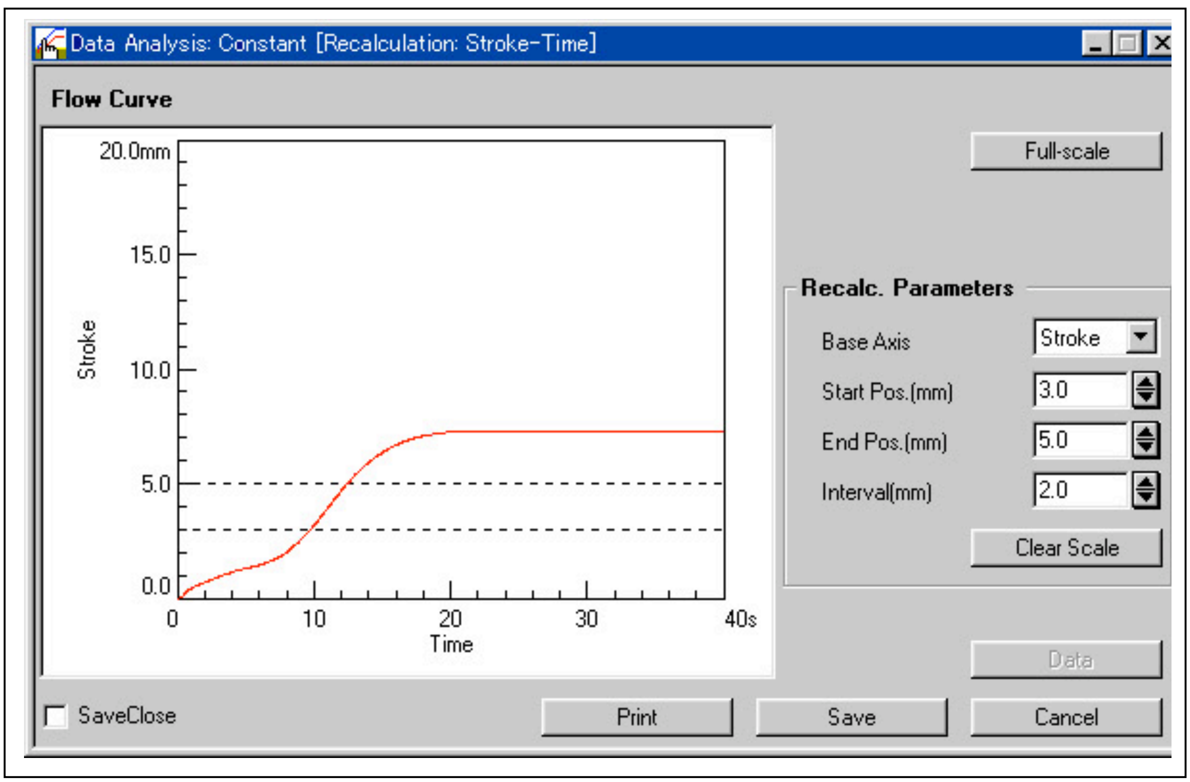

Figure 2: Epoxy flow curve at 165^{o}F using Shimadzu Capillary Rheometer CFD-500D

Advanced Composites Group Ltd (ACG) has documented the effect of an epoxy resins glass transition temperature (Tg) on a dimensional stability of a composite component. They define Tg as: “The temperature above which a resin will begin to soften, loosing stiffness and strength. Generally the maximum end use temperature for a resin should be at least 20^{o}C below the Tg.” (ACG, 2010).

The data sheet for ACG’s MTM-46 indicates that the epoxy impregnated material is dimensionally stable when cured for 5 hours at 176^{o}F and has obtained a Tg of only 169^{o}F. The post-cured parts will eventually achieve the resins ultimate Tg of 356^{o}F. ACG has formulated the epoxy resin chemistry to permit very low temperature cure. Allowing a composite tooling manufacturer to use inexpensive wood or foam die models for the production of the composite molds. The low cure temperature drives the state of cure beyond what is considered (normally) to be a B-stage, but for all extensive purposes the epoxy is only achieved a 50^{o} conversion based on the differences between the two Tg’s.

The post-cure process cautiously heat treats the component and gradually increases the degree of conversion. Once the key or critical Tg for a particular epoxy resin system has been obtained the laminate will be dimensionally stable, in this case 169^{o}F for the MTM-46 the component when cooled to at least 20^{o}C below the Tg is then dimensionally stable. The incomplete cure of the component permits controlled reforming whenever the temperature of the laminate is sufficiently above the current Tg of the epoxy resin system.

Case Examples

Gatling Gun Ammo Handling Helix

A known compression molded part was the FG/epoxy helical disk in the ammunition handling helix assembly of the 20mm Vulcan Gatling cannon/gun (M61A1). The primary sub-component of the helix was approximately 20 inches in diameter and resembled a thin helically shaped disk. It was nominally 1.0 mm thick and was produced from 5 plies of what was then Ferro Corporations E293FC epoxy (currently being produced by Park Electro Chemical) impregnated in a 7781 fiberglass cloth.

The FG/epoxy prepreg disk shapes were die-cut, pre-plied or laminated in a clean room and then transferred 25 assemblies at a time to the press molding operation. The compression molds were classical P20 chromed steel with telescoping sheer edges. Because the bulk factor of the prepreg was nominal, the molds were designed with only ¼ deep shear edges. The disks had quite a few contours or features on them that were designed to control the movement of the ammunition and these shapes had to be dimensionally stable. The disks also had many molded in 1” diameter evenly spaced dimples that were used to bond the disks back to back in the final assembly process using structural film adhesive, these had to be dimensionally stable.

The pre-plied un-cured hand lay-up grade prepreg was placed directly onto the 350°F molds and the press was immediately closed to within 1/8 inch of the stops. The press dwelled for approximately 30 seconds permitting the resin to gel and begin to thicken (increasing the B-Stage). If the pressure was applied too soon the resin would squirt or flow too fast and far, resulting in unacceptable voids on the ammunition handling surfaces. The cure time was 3.0 minutes for a total cycle time of approximately 4 minutes. The batch of 25 disks was then simply supported and post-cured in a small oven for several hours at 350°F, completing the chemical conversion and achieving ultimate Tg.

Approximately 25 years ago this high performance composite part was molded at fairly high volumes utilizing a 4 minute cycle time! The technology of compression molding FG/epoxy laminates has progressed a lot in the last 25 years. The total cycle time could be reduced and quality improved incorporating today's technology with a similar epoxy resin system. First, the tackiness or B-stage of the epoxy in the helix prepreg was way too sticky! The flow of the resin in this material was 15-25% at 25 psi and 350°F. The operation was press molding using a hand lay-up grade of prepreg. Many prepregers can and do commonly drive the B-Stage of their press molding grade epoxy impregnated materials further yielding a stiffer & slightly board like material. The resin still softens when it gets hot and the flow is more controlled. 30 seconds of that 4 minute cure time could have saved by eliminating the need for a dwell time. The cure time could have reduced further by preheating the preplied lamination prior to placing it into the hot compression press. By cautious preheating and the use of a press grade prepreg the total cycle on a 1mm thick FG/epoxy laminate could be realistically expected to be 3.0 minutes or 180 seconds.

Lite-Flex Springs

The Lite-Flex FG/Epoxy composite springs have been compression molded for many years. "Liteflex springs have been in production for over 25 years. They are in use on over 15 million vehicles, including GM, Ford, Range Rover, DaimlerChrysler, Iveco, Kenworth, Peterbilt, Freightliner and Navistar, and others." (Liteflex, 2010) These composite intensive components are significantly thicker than the thin-walled components typical in a conventional body structure. The fact that this supplier has been able to compression mold very high volumes of thick walled composite springs is proof that the epoxy chemistry can be utilized for an even greater percentage of a typical vehicle or truck chassis.

"Liteflex lightweight composite springs weigh 75% less than steel, yet they last 10-times longer. This reduced weight can increase fuel efficiency, payload capacity, and horsepower to weight ratio for faster acceleration. Load-deflection testing has shown that the propriety mixture of fiberglass and epoxy, is virtually identical to steel. A fatigue life that is nearly 10-times that of steel eliminates the sagging that is common with steel leaf springs over time. Virtually indestructible Liteflex lightweight composite springs provide life-of-vehicle service." (Liteflex, 2010) Based on the on-going success of the Liteflex springs, a similar epoxy resin reinforced with a carbon fiber can be compression molded producing automotive body structure and large structural chassis components.

Development opportunities for consideration

Progression Molding

There are some scientists in Geelong, Australia at Deakin University, who have been experimenting with CF/epoxy laminations and two processes called "Melding" and "Quick-Step". Their research leads product development engineering to believe that extremely rapid press molding might be possible using manufacturing technology similar to sheet metal progression die forming.

Deakin University researchers have successfully selectively cured sections of CF/epoxy laminations leaving other areas uncured. (Corbett et al, 2005) The non-cured areas were joined to another laminate and then cured at a later time. They refer to this technology as "melding". Melding they define as an "alternative joining method to adhesive bonding and mechanical fastening" (Forrest et al, 2006). Mechanical tests have concluded that there is no detrimental effect on the properties of the resulting totally cured laminate. This epoxy unique technology enables the forming of complex shapes in multiple cure cycles/stages.

The fact that it is possible to start and stop the epoxy cure mechanism "B-Stage" without adverse effects on the final laminate mechanical and physical properties permits speculation about the feasibility of the following:

Every time a lamination of epoxy is heated sufficiently above its' current state of glass transition temperature (Tg) the epoxy in the composite material softens or melts and becomes formable. The lamination when pressed under sufficient pressure and temperature and then permitted to crosslink further up the Tg degree of conversion curve will assume the new shape and will be dimensionally stable once it has been permitted to cool below its' new Tg. A progression molding line could be expected to achieve higher rates than a solitary molding operation because the state of cure of the overall epoxy would be able to progress in managed steps/stages. The state of cure for a thermoset epoxy is additive depending on the total time at temperature and does not require a single cure step. It is assumed that the formability of the composite gradually decreases as the molecular weight increases and thus the viscosity of the epoxy increases. Therefore, the greatest amount of forming and shaping has to happen in the earliest molding steps of the process.

Because this hypothetical process involves holding the soft and uncooled material in position as the blank flows through the progression mold line, the operation will initially cure or clamp sacrificial tabs around the perimeter of the pre-laminated prepreg blank. These tabs would be used to properly position the blank through the molding operation and then would be removed during the CNC machining operations.

Instead of one complex mold forming every required feature and shape in one long cure cycle. A well designed progression molding process can form each key or critical feature in several staged cures or molding steps. A single press mold closed cycle of 180 seconds can easily be expected to be sub-divided into 6 equal cure steps/stages of 30 seconds. This hypothetical progression molding die line would then be producing 2 complex molded parts per minute or 120 per hour. This assembly line of 6 molds would be able to provide enough product to satisfy the demand for over 1/2 million vehicles per year!

The helical disks for the 20mm Vulcan Gun were press molded utilizing a 3 minute cure cycle. These required unsupported post cure for a few hours at 350oF. Any automotive structural composite component processed would be expected to require thermal processing in order for the resin to obtain maximum Tg. A requirement for post cure should not be considered unusual and a justification not to proceed. Metallic components all require thermal processing for the purpose of stress relief and/or hardening. Steel body shops of the world have successfully incorporated the use of tunnel ovens for decades and these same ovens can and will be used for "thermal processing" or post-curing of reinforced epoxy structures and chassis components.

Summary and Next Steps

Composites using epoxy resin can be formed and reformed whenever they are heated above their glass transition temperature. As the degree of conversion (Tg) nears the ultimate for that particular epoxy polymer, the reform ability decreases. An epoxy reinforcement in the B-staged condition can be treated as a thermoplastic material and can be melted and thermoformed.

The degree of cure can be increased in steps or progressions without significant detrimental effect to the mechanical properties of the composite material. Tailored blanks can be CNC cut, laminated, rapidly formed and B-staged. These formed and B-staged blanks can then fed into the progression molding operation.

There is a point in the epoxy degree of conversion when the cooled lamination is dimensionally stable enough to withstand unsupported postcure. This post-molding heat treatment will yield maximum degree of conversion for each specific epoxy.

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