A Few Unique Thoughts

High Volume Production of Carbon Fiber Reinforced Epoxy

Structural Automobile Components

Donald M. Lasell
President & Chief Engineer
Think Composites, L.L.C.

“What-if”

Carbon-fiber and epoxy composite structural components and assemblies can be produced at rates “nearly” equivalent to formed steel?

• Increasing production volume capability yielding significant manufacturing cost reductions.

•High volume capability is a requirement for entry into “main-stream” automotive operations.

This is Important

Significant mass reductions are realized compared to Steel Body Structures (60-70%) or Aluminum (50%), enabling impressive increases in fuel economy, reducing and eliminating dependence on hydro-carbons (fossil fuels)

Competitive emerging material and manufacturing technology require many of us, engineers for the next 100 years. Replacing what was lost as the steel industry matured and moved off-shore.

Carbon Fiber precurser is grown from renewable Lignin as the U.S. Dept of Energy is endeavoring.

The transportation system produces millions upon millions of vehicles using this carbon fiber technology. The production and use of carbon fibers begins to reverse Global Warming removing carbon dioxide from our environment.

“What-if”

The technology for producing CF/Epoxy at high volume has existed for decades?

- The industries using the materials “for structural applications” didn’t care about producing high volumes? (Aerospace & Military)
- The industries using the materials “for semi-structural applications” at high volumes didn’t care to share outside of their niche? (Sporting Goods)
- The industries using the materials at very high volumes were considered… non-structural or were not considered at all? (Electronics)

“What-if”

One of the oldest polymers known could yield the highest production rates?

Epoxy was first commercially sold in the late 1940’s.

“What-if” people forgot how?

“Eventually, much of this information (Epoxy Chemistry) gained through experience will pass away if not well documented on the written page”

“Epon Resin Structural Reference Manual”
Shell Chemical, 1977

We are told…

- Cost, Cost, Cost
  - Steel is the cheapest (and will always be)
  - Weight reduction is important, but it has to be cost effective.
  - Automation drives down cost eliminating waste
  - Automation enables production at very high volume.
  - Carbon fiber composites has to be automatable
  - Carbon fiber has to be produced at very high volumes.
    - The initial production rate objective for the C5-Z06 hood was simply 10 hoods a day or approximately 2500 hoods off of one set of molds in a year of production.
    - This proved to the Chief Engineer and his team, that production of 10,000 fenders a year for the C6-Z06 using 6 sets of molds, exactly the same manufacturing process was feasible
    - All of the above was successfully accomplished over 5 years ago!

Known to be true…

1. Press mold GF/E laminations, 0.8-1.4mm thick in four minutes with unsupported post-cure required to obtain maximum Tg. (Ref. Personal Experience, 1985)
2. Press molding grades of prepreg (GF/E and CF/E) are B-staged significantly more than hand-layup grades. Controlling excessive flow created by the extremely rapid heat-up rates and the resulting viscosity drop when the non-cured epoxy melts.
3. Copper-clad laminate prepregs are B-staged more than normal press-grade materials to the point where they require significantly higher temperatures and pressures to create flow permitting the many layers to melt and bond to one another.
4. Injection molded epoxy compounds typically used for encapsulating electronic components are preheated prior to injection and then are processed at extremely short cure or cycle times. Post-cure usually is required.
5. Hot oil can rapidly heat, cure then cool normal epoxy prepreg. Achieving acceptable laminate consolidation at exceptionally low molding pressures.
6. Preplying individual prepreg laminations into highly oriented preconsolidated blanks saves significant amounts of time in later processes. These preplied laminations are not much different from steel tailored blanks.
7. Aerospace composite component suppliers are beginning to utilize relatively conventional steel forming capital equipment to automate the material forming processes.
8. These same aerospace composite suppliers are inventing automation technology for handling CF/E materials in order to reduce cost and improve quality. Eliminating hand or touch labor to the maximum extent possible.
9. Epoxy can be treated like a thermoplastic when it is in the B-stage condition. The resin viscosity will be steadily increasing as the materials B-stage degree of cure (conversion) advances. Formability or moldability will require increased temperatures and pressures. Formability parameters requires characterization at multiple stages of cure.
10. Bonding or assembly operations will benefit from the technology referred to as “Melding”. Selective non-cure of areas to be joined can be later melted, reformed and bonded to one-another.
11. We should spend more time developing selective cure manufacturing concepts.

Selective Region C-Staging of Epoxy

- It is possible to “nearly” completely cure (C-stage or thermoset) epoxy, leaving adjacent areas B-staged (thermoplastic or meltable) (Corbett, et all, 2005)
- There is no loss of mechanical properties in adjacent areas once these are compressed and taken to C-stage
- This increases forming and molding options permitting progression molding of complex shapes.
- B-staged laminations can be reformed once heated above melt point (Tg).
- Dimensional stability utilizing minimum cure time permitting unsupported post-cure or secondary processing operations.

Walking through a composites operation.

That is a press brake. They are brake forming CF/epoxy. "*It's not quite a simple as it looks. We're heating some areas and cooling other areas, softening the (epoxy) area we're going to bend and holding everything else in place."* The timer dings, the brake acts and the formed composite is ready for cure!

That was pretty fast… wasn't it?

Fig. 7.

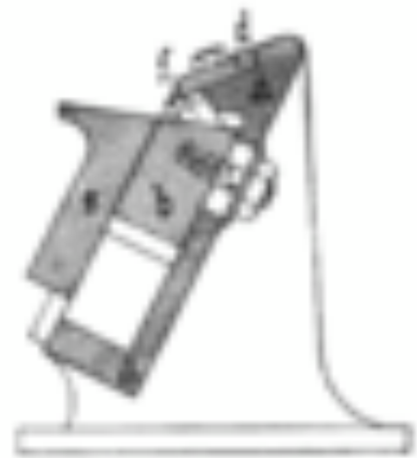


Fig. 8.

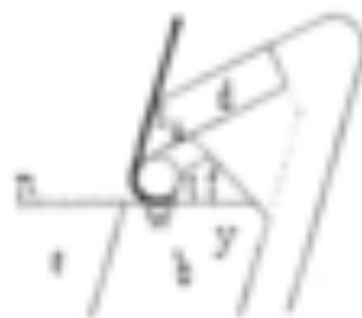
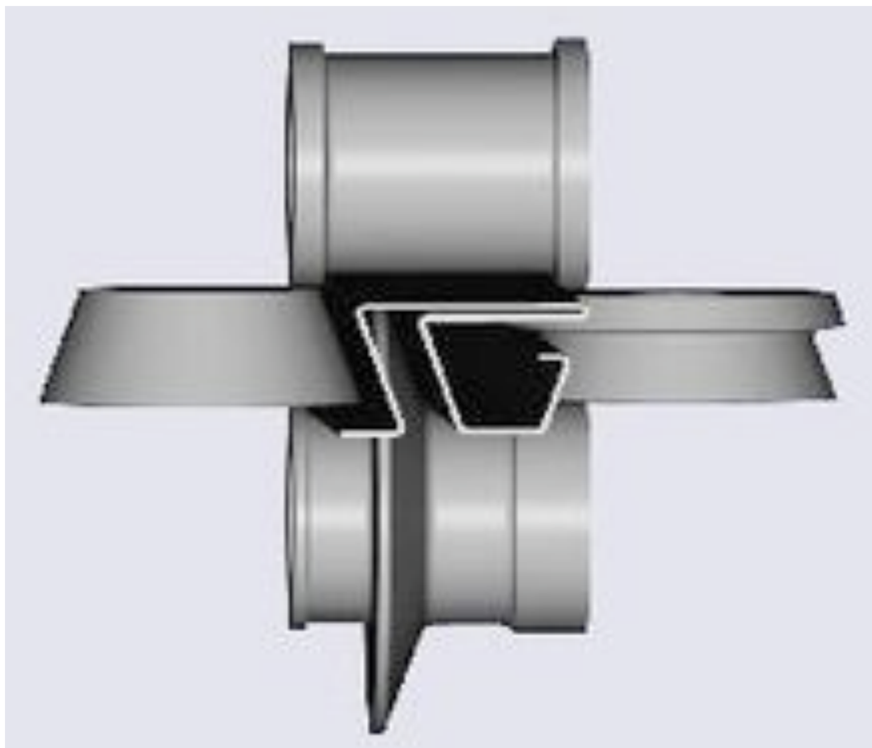


Fig. 9.

Walking through another composites operation. There is a roll forming die line. They are roll forming CF/epoxy into beams.

"*It's not quite a simple as it looks. We're heating some areas and cooling other areas, softening the area (epoxy) we're going to bend and holding everything else in place."* The operator feeds the material blank through the roll former and the formed composite is ready for cure!

That was pretty fast… wasn't it?



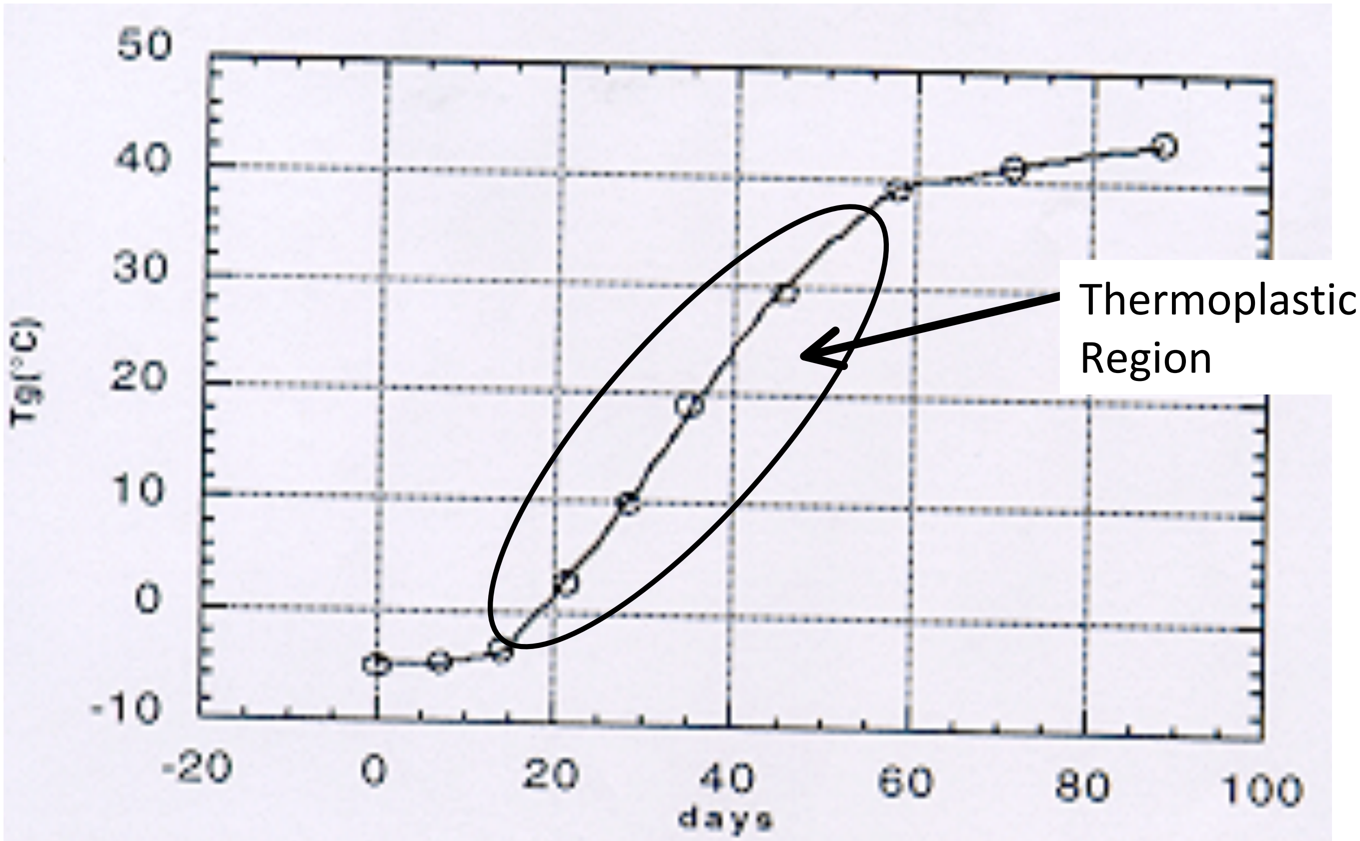
Rheology

Rheology is the science that studies the flow of materials under heat and pressure.

In layman's terms it allows us to characterize the viscosity (which relates to flow) of a material as a function of temperature, rate of heat rise, applied shear, and so forth, permitting us to provide data relevant to press lamination.

"Everything you wanted to know about Laminates but were afraid to ask."
Arlon (2008)

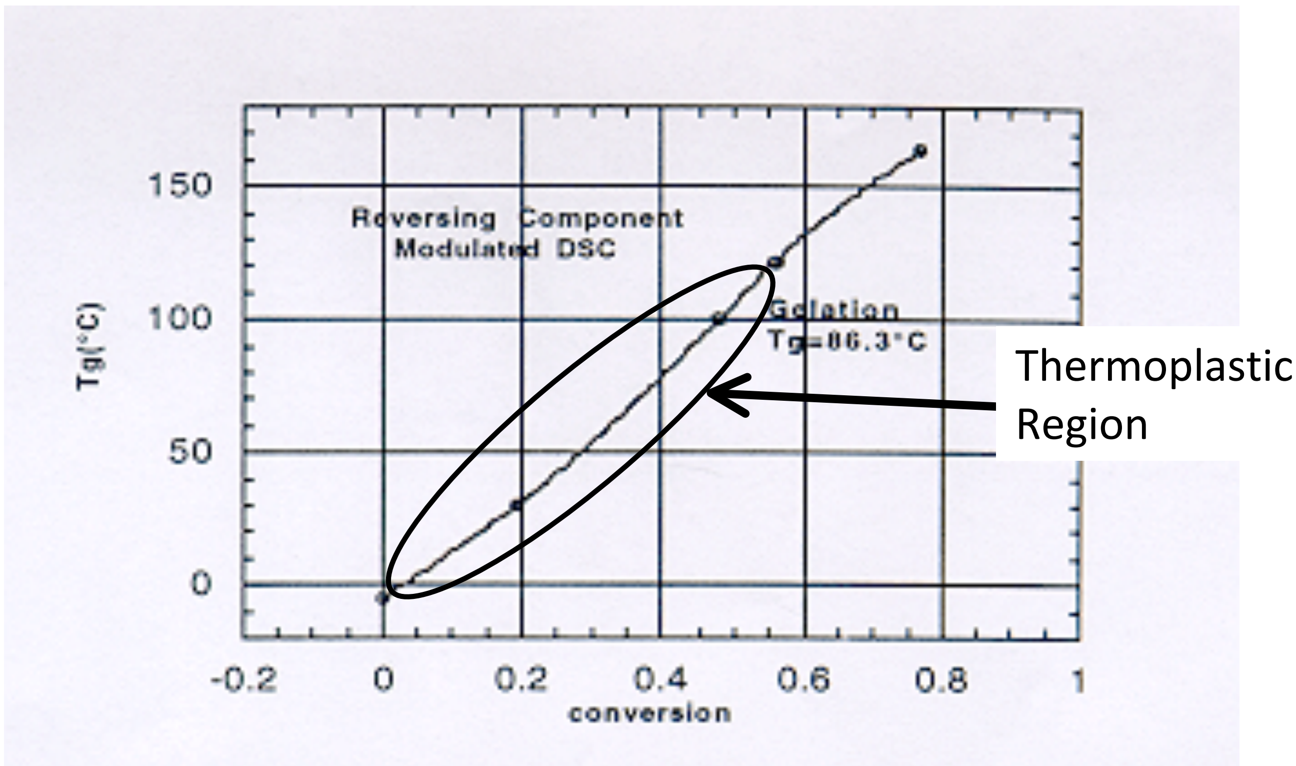
Tg of green epoxy at 23^{o}C



$T(t) = T_o + Bt$ $dQ/dt = C_pB + f(t,T)$

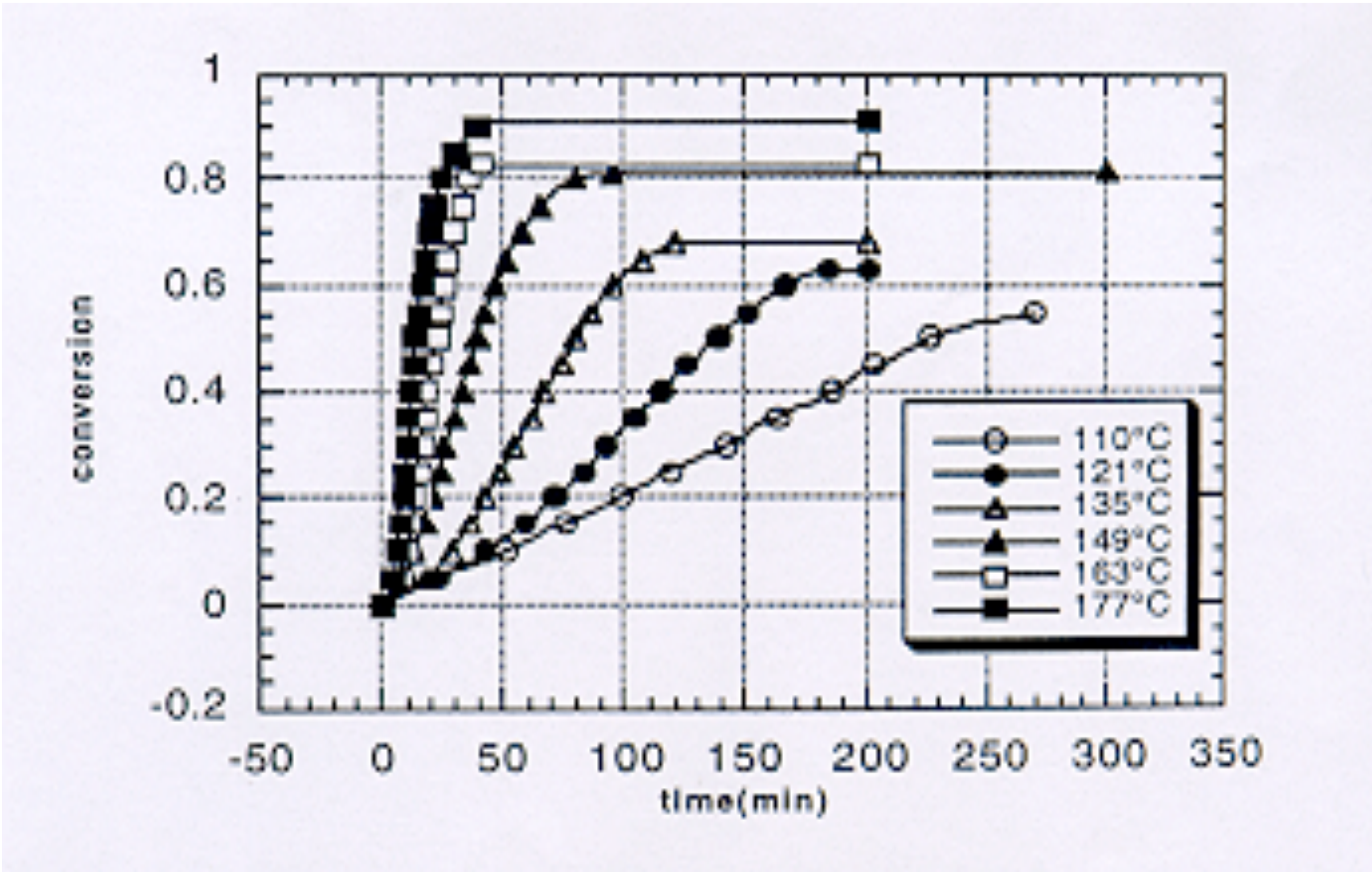
Arnold and Thoman, 2001

Tg as a function of conversion



Arnold and Thoman, 2001

Conversion and Isothermal cure



Arnold and Thoman, 2001

Shimadzu's CFT Flowtester is a constant shear stress type capillary rheometer used mainly for the collection of viscosity data and its effect on various types of polymers.

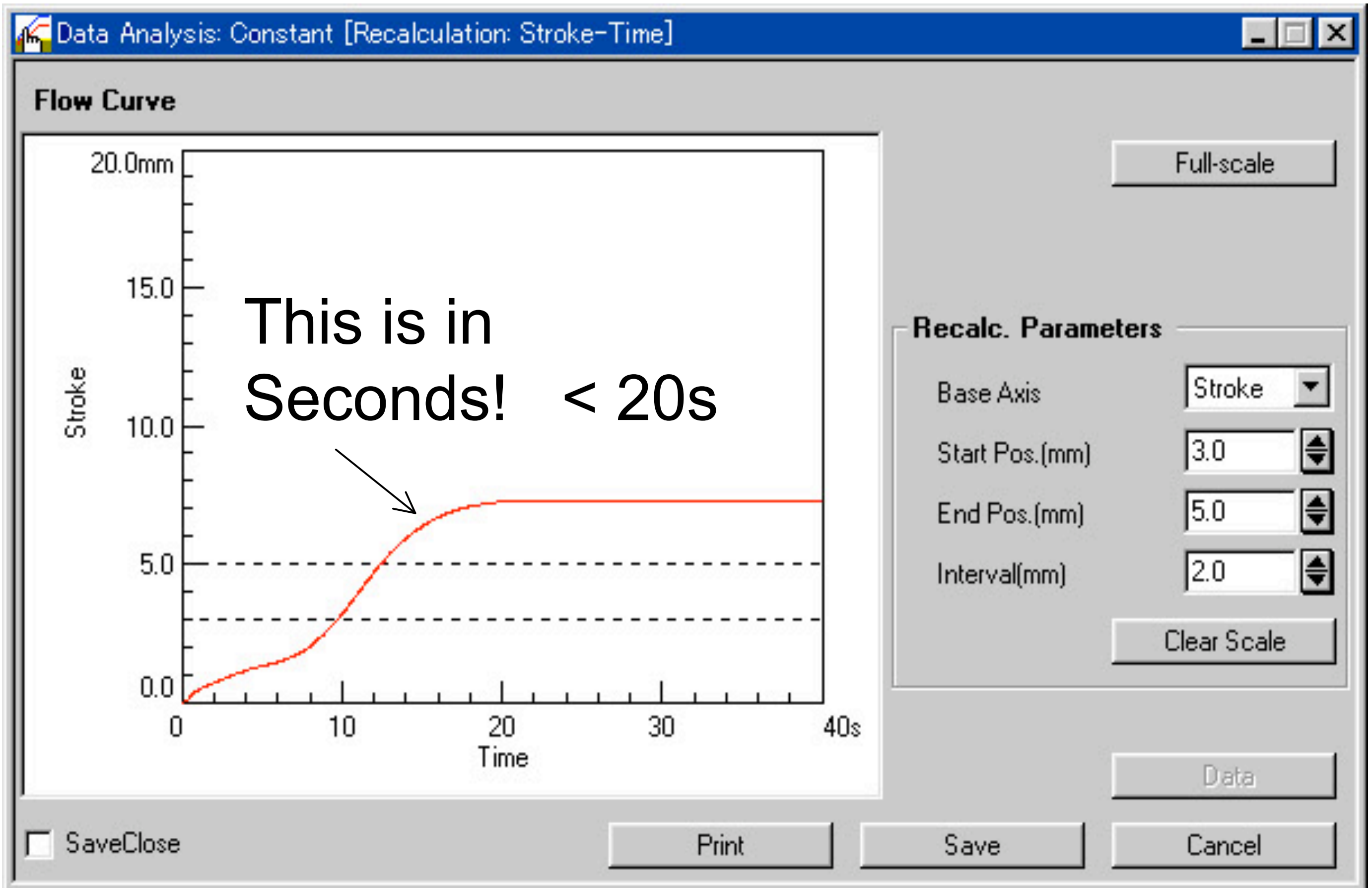


Fig.3: Flow curve of epoxy tested under 165°C
Shimadzu (2010)

Objective

2,400 parts per day
600,000 parts per year

- Current manufacturing concept requires 1 mold for 10 parts per day, using single sided autoclave molds . High volume will require 240 mold sets and many autoclaves.

- Proposed next step, transition to compression molding using conventional matched metal molds, classical manufacturing processes will produce 20 parts/hour or 480 parts/day. High volume will require 5 sets of molds using 10 compression presses with a post-cure conveyorized tunnel oven.

- Next step, Develop Progression Molding producing 120 parts/ hour utilizing (1) die-mold line, 5-6 forming presses, material handling equipment with a post-cure conveyorized tunnel oven.

Next Steps?

- Verify snap cure-ability of 1.0 mm CF/Epoxy
- Verify unsupported post-cure dimensional stability of CF/Epoxy
  - Mold release was a problem back in 1985. Hot (green) epoxy is soft, flexible & flimsy, not much different from flexible though!
- Verify progress cure-ability, staged and stepped cure
- Verify flow at degree of B-stages, high, med, low & no-flow
  - (correlate Tg vs. ultimate cure Tg)
- Develop design concept for body structure and chassis
  - Near “black” steel is the best place to start.
  - Start with preplied laminations “Blanks”
  - Tailored thicknesses with optimized fiber orientations
  - Copy Cat a current Aluminum (or steel) design, optimize and duplicate in CF/E
  - Possible to utilize current metallic (forming and stamping) capital equipment
  - Pierce and trim when epoxy is hot but pretty stiff (near C-Stage).
  - Optimize mold & die designs for nearly zero bulk factor materials
  - Characterize fold-ability, formability for progression molding
  - Vacuum assist with minimal shear-edges and clamp rings/rails

Just how important is carbon fiber composites to the automotive industry?

- The automotive industry has been using steel for over one hundred years.
  - Automotive steel manufacturing technology is mature.
  - Steel has moved off-shore, requiring significantly less technical support.
    - We have developed another promising technology to replace steel, carbon fiber.
- Global warming?
  - Global warming and the release of significant quantities of carbon dioxide.
  - Weight reduction and fuel economy improvements is NOT the only reason for considering carbon fiber composites.
    - We've heard about the US-DOE's efforts to develop carbon fiber from a renewable resource. Grow our own carbon fiber, harvesting it and then converting it into cars, trucks, trains and planes.
    - Removing large quantities of carbon dioxide from the atmosphere and converting it in to nearly pure carbon, releasing the trapped oxygen, we use to breath.
    - At the end of these vehicles life-cycles, at the end of the carbon fibers useful life-cycle.
    - It was converted in to a pure elemental, non-polluting form.
    - We can safely and permanently deposit it back into the ground.
    - Beginning to deplete our global warming (CO^2) problem producing our worlds' transportation vehicles.

50 year-old Technology
Corning's Gorilla Glass

- "An ultra-strong glass that has been looking for a purpose since its invention in 1962 is poised to become a multibillion-dollar bonanza for Corning Inc."
- "Corning is pursuing a well-worn strategy designed to keep rivals from gaining ground. Its patience is also well practiced. Executives know too well the gulf between inspiration and application is sometimes decades-wide."

Associated Press (8/2/10)