C. High-Volume Processing of Composites

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Objective

- Develop and demonstrate high-volume manufacturing technology to produce lightweight composite automotive body structures.
- Achieve higher fiber volumes in thinner sections than were successfully achieved in Automotive Composites Consortium (ACC) Focal Project 2.
- Support the goals of ACC Focal Project 3.

Approach

- Investigate the structural reaction injection molding (SRIM) process at high fiber loadings using carbon fiber.
- Design and build a shape tool to investigate the complex preforming and molding processes required for the ACC Focal Project 3 program.
- Team with supplier partners to investigate alternative liquid molding processes.
- Assess the potential for the LFI (long fiber injection) process and materials to meet both the more demanding structural applications of Focal Project 3 and its potential to meet Class “A” automotive requirements.
  - Establish an ACCP “Surface Acceptance Standard” to gage progress of LFI development–benchmarking established Class “A” automotive exterior materials using known quantitative methods.
  - Conduct a series of designed experiments (DOE) to screen the parameters that contribute most significantly to surface quality.
  - Evaluate these plaques for physical properties to assess their potential for use as structural components.
  - Ultimately, lead the program to incorporate carbon fiber into the LFI for additional weight savings.

Accomplishments

- Continued B-pillar molding trials with 40% glass fiber preforms to evaluate and improve the preforming process and to produce panels for structural analysis.
- Conducted plaque molding evaluation of candidate Hexcel carbon fibers.
- Molded initial carbon fiber B-pillar panels.
- Completed the initial LFI molding trial.

- Assessed the effects of glass type, glass length, thickness, demold time, and surface veil via the experimental design.
- Constructed an LFI plaque tool based on an existing RRIM tool at Bayer but incorporated shear edges and a polished show surface.
  - Finish painted plaques and they were subjectively ranked by the ACC team.
    - Identified a “Surface Acceptance Standard” linked to specific quantitative techniques for use in subsequent studies based on extensive benchmarking of typical class “A” exterior substrates.
    - Agreed upon physical testing protocol. Mechanical property testing is completed, and data analysis is under way.
    - Designed a new LFI molding trial based on the observations of the first trial.

Future Direction

- Develop B-pillar modling process with Generation-2 preforms.
- Initiate carbon fiber B-pillar development when the fiber is available.
- Determine whether that process can be used for structural or structural cosmetic applications via the LFI program.

Introduction

The purpose of this project is to further develop the liquid composite molding technology previously demonstrated in the Automotive Composites Consortium (ACC) Focal Project 2 with the large structural truck box.[1–3] This project will extend the liquid molding process into more structurally demanding application of the ACC Focal Project 3 (FP3) body-in-white. This will be accomplished by using carbon fiber reinforcement at 40% by volume. To maximize the weight savings, the minimum section thickness will be reduced to 1.5 mm.

There will be two basic approaches running in parallel. The first is the extension of conventional structural reaction injection molding (SRIM) technology to carbon fiber preforms of reduced section thickness in support of the ACC FP 3. This involves both material and process evaluation. The ACC instrumented plaque mold is used for material and initial process evaluations. The ACC B-pillar mold is a shaped panel, which represents the B-pillar section of the FP3 body side. This mold has deep draws, and it is used for more detailed process studies of SRIM molding. This portion of the program is under the direction of, and includes direct participation of, ACC personnel.

The second approach will be to work with supplier-partners to adapt their liquid molding process toward being compatible with the material property and processing requirements of FP3. For this activity, a program was initiated with Bayer to investigate the feasibility of adapting the long fiber injection (LFI) process to the needs of the ACC.

The project team includes personnel from the Big Three automotive companies and Oak Ridge National Laboratory. The support team includes personnel from the National Composites Center (NCC). Bayer is a supplier-partner in the LFI portion of the program.

Carbon Fiber Plaque Molding and Data Acquisition

A new riser was built to use the ACC plaque mold in the 1000-ton French Oil press at NCC. Thus, for a plaque molding trial, the B-pillar mold can be parked on the press shuttle and not have to be removed from the molding cell. This allows for rapid switching between B-pillar and plaque molding. Figure 1 shows the new plaque molding setup at NCC. The molding data acquisition system was also upgraded to current generation computers.

Two separate plaque molding trials were performed in support of the Hexcel carbon fiber program. The first plaque trial was for different fiber volumes (ranging from 30 to 40%) and plaque thicknesses (1.5 to 3.0 mm). From this study, the

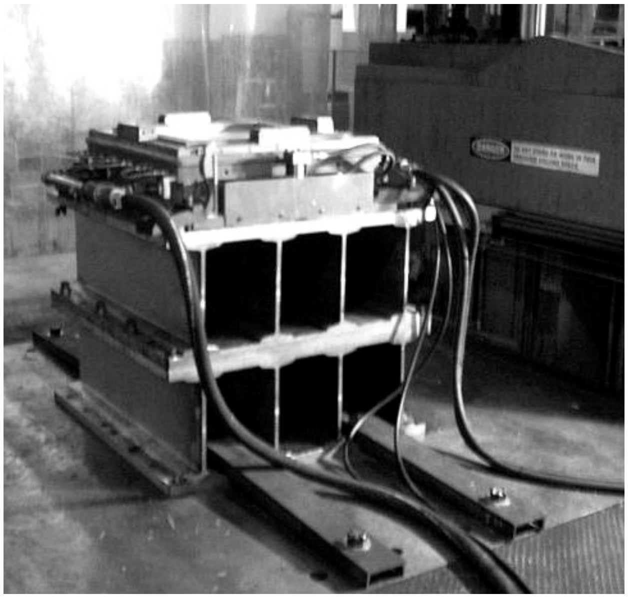

Figure 1. ACC plaque mold mounted on pedestal in 1000-ton press at NCC.

condition of 35% fiber and 2.0-mm plaque thickness was selected for the fiber size study. This was the condition of highest fiber volume and thinnest dimension that gave constant thickness plaques. Thinner plaques and higher fiber volume caused tool distortion, resulting in nonuniform plaque thickness.

The fiber-size-study rovings were constructed by combining smaller tows into 36K rovings. Preforms of rovings containing tow sizes of 0.5 to 12K were made and molded. Figure 2 shows typical molding traces from this trial, showing the pressure developed in the mold cavity from the mold closure and the resin flow. In general, as the fiber ends became larger, the pressure spike during compression became broader, but lower. The detailed results of this study are given in the "Development of Next-Generation Programmable Preforming Process" report (4.D).

All SRIM molding, both plaque and B-pillar, was by the injection/compression technique, where the polyurethane resin is injected into a partially open mold. As the mold closes fully, the compression stage, the resin is forced through the preform, filling out the mold. Thus, the observed cavity pressure is developed by the dynamics of the mold closing, and not the injection pressure.

B-Pillar Molding Program

Several B-pillar molding trials were carried out early in the year to support preform development. After satisfactory preforms were being delivered, a series of B-pillar sets were molded for the structural analysis group. Some of these B-pillars were also structurally bonded.

At this point it was judged by the preforming and molding teams that the quality of the preforms, primarily the fiber distribution uniformity, was not significantly improving. Fiber volume ranged from

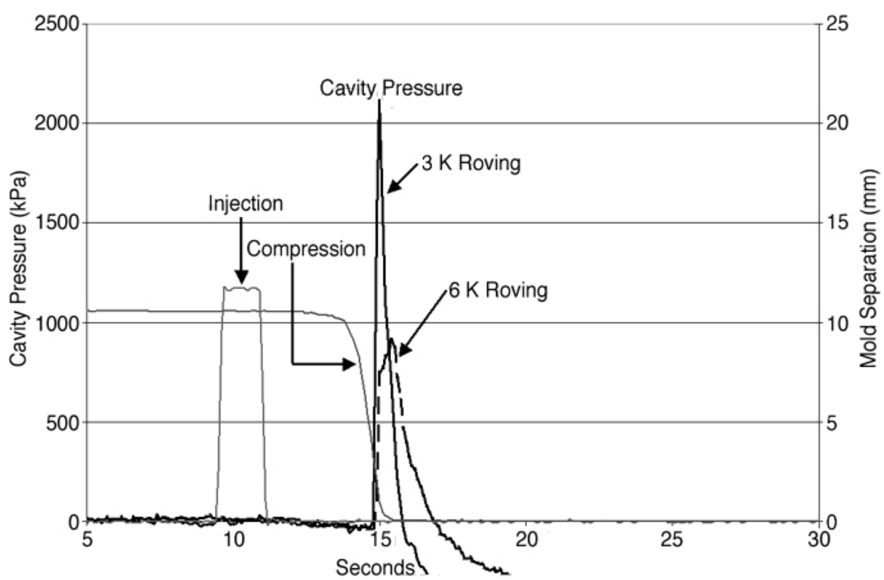

Figure 2. Molding data traces from Hexcel fiber size study showing pressure response for two fiber bundle sizes.

less than 20% to greater than 50% and is discussed in more detail below. A significant contributing cause to this broad range of fiber distribution was believed to be the geometry of the preforming screens. Some areas were difficult for the robotic arm to direct the fiber spray into, and others collected excessive overspray. Also, in the original screen design, the loft side of the preform was placed against the molding tool. This springy loft pushed the preform away from the side of the mold, and caused part of the flange area to be sheared off when the mold closed. Therefore it was decided to temporarily halt preform and molding development and design and build new preforming screens (discussed in 4.B). This shutdown time was used for the carbon fiber plaque study discussed above.

The new preforming screens were completed during the year, and the B-pillar mold has been reinstalled in the press. In a quick, initial look at the new preforms, the new preforms seem to fit into the molding tool better and do not have as much spring out.

B-Pillar Fiber Distribution

The distribution of the glass fiber content in a B-pillar inner and outer set molded in January of 2004 was determined by a series of burn-off tests. A chart of the overall fiber distribution is shown in Figure 3. Even though only one set of preforms was examined in detail, the robotic P4 process gives good reproducibility between preforms. In addition, sampling of other preforms and visual observations of the flow patterns support the repeatability of the fiber distribution results.

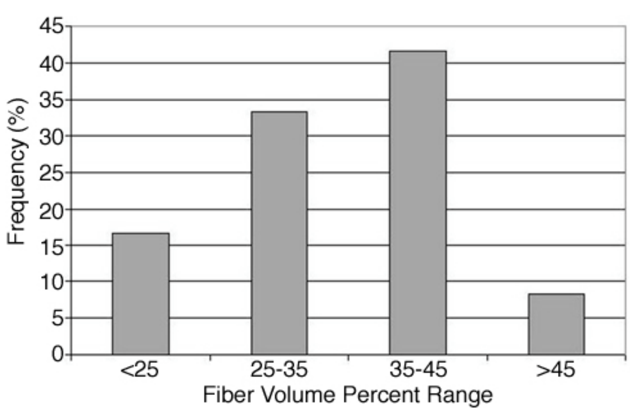

Figure 3. Fiber volume distribution in molded B-pillars with Gen-1 preforms.

The fiber content for the inner panel ranged from 13.5% to 55.0%, with a mean of 33.5% and a coefficient of variation of 29%. Although some areas of the part were within the target range of 35 to 45%, many other areas were not, as shown in the fiber distribution chart. At some points fiber content well above the target range was adjacent to areas of low fiber. Several instances of this occurred where the fiber was heavier around the corner and decreased on the walls and the flange.

The fiber content range for the outer panel was even larger, ranging from 3.2% to 60.7%, with a mean value of 38.2% and a coefficient of variation of 30%. Note that along the flanges of the molded part, the fiber was sometimes caught in the shear edge and torn away from the preform, causing the low fiber content. It is anticipated that the preforms from the new screens will have less spring-out and be less susceptible to this action.

The effect of the fiber content on molding can be demonstrated by two areas on the roof rail end of the B-pillar outer panel. One area of 47% fiber appeared to form a dam of denser glass, which impeded the resin from filling out the end of the roof rail, leaving an area of dry fiber, shown in Figure 4. In the other case, an area on the flange contained almost no fiber and acted as a runner during mold fill, allowing resin to flow preferentially to areas on the edges, and trapping air and causing unwet areas.

After this part was made, a great deal of effort went into tweaking the spray pattern of the P4

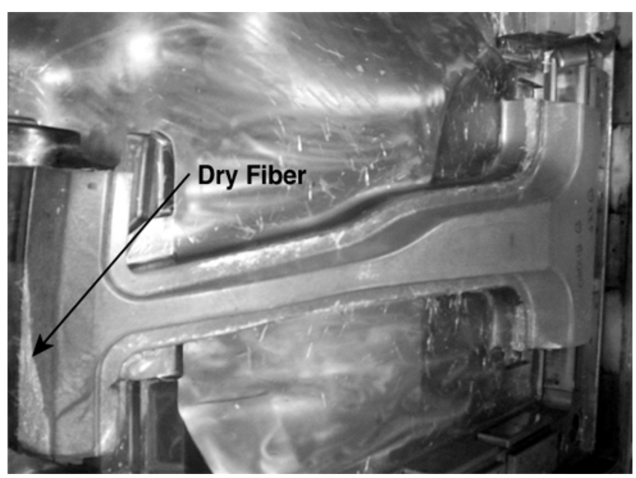

Figure 4. B-pillar molded from early Gen-1 preform showing an example of a dry area caused by flow restriction.

preformer. While the mean fiber contents for parts molded with this new spray pattern were similar (33.3% for the outer and 33.5% for the inner), the range was tighter. The outer range was 16 to 49%, and the inner range was 21 to 47%. While these ranges are an improvement, they are not yet acceptable. Work going forward will focus on a new set of screens, made to sit in the core position, instead of the cavity position as the current screens do.

Carbon Fiber B-Pillar Molding

Very little work has been done with molding of carbon fiber B-pillars to date, due to the shortage of the automotive-grade fiber. There was a brief look at two fibers, the Zoltek fiber being used in the ACC program for several years and a Hexcel fiber currently under development for this program. The preforms of the Zoltek carbon fiber had a very coarse fiber distribution, as was observed in the earlier plaque molding study with this fiber. There was some fiber wash with the preform tearing and resulting in resin-rich areas. Because the decision had already been made to build new preforming screens, it was decided to not use any more of the limited supply of the Zoltek fiber at that time.

A similar brief look was taken at the Hexcel fiber, which was preformed with the new screens. The 12 × 3K roving was preformed and successfully molded. While these performs were not at full weight, this result was very encouraging. Photos of perform and molded panel are shown in Figure 5. The molding chart in Figure 6 shows that carbon fiber preform had a much higher cavity pressure than did the glass at a similar fiber content. This is an indication of a higher resistance to flow with the carbon fiber preforms under this molding condition.

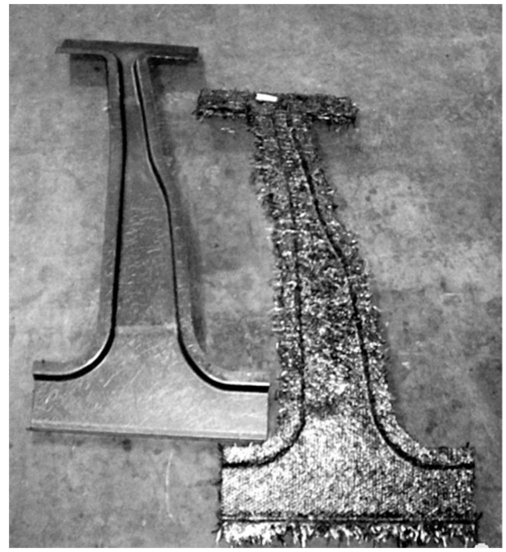

Figure 5. Hexcel carbon fiber preform and molded B-pillar.

<u>Supplier-Partner Liquid Molding Program—LFI</u>

The project team initiated a study of the LFI process, where the polyurethane resin and the chopped fiber are co-sprayed directly into the mold. The goals are to assess the potential for achieving a Class "A" exterior automotive surface and to characterize the material for its structural capability. The initial step for the team was to establish an "ACC Surface Acceptance Standard." After benchmarking a cross section of materials currently used for exterior Class "A" applications, Wavescan, QMS,

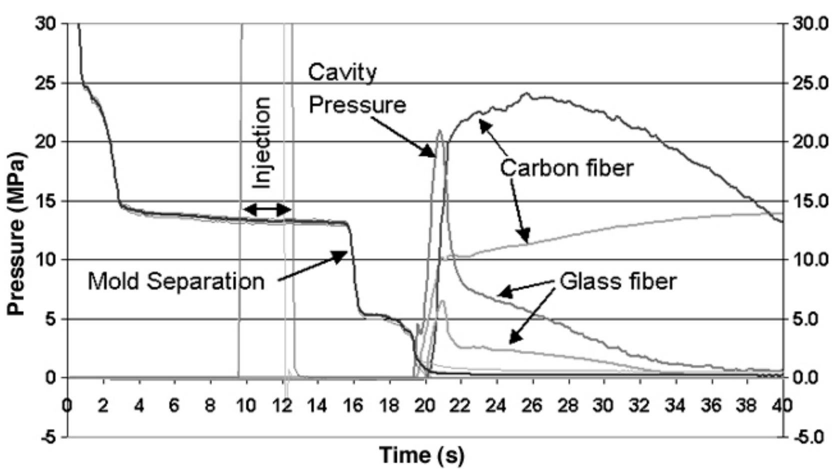

Figure 6. Carbon fiber and glass fiber performs cavity pressure profiles.

and jury evaluations were utilized to quantify and rank the samples. Consensus was reached on the following targets for this standard:

QMS: Combined score value > 65
Wavescan: Short-term waviness value < 20
Wavescan: Long-term waviness value < 5

These represent the lower range of values compiled in the benchmarking exercise.

Concurrently, the ACC had an existing Bayer SRIM plaque tool modified for LFI. The core surface was highly polished to a SPI A2 finish, and interchangeable stop blocks were built into the mold to vary plaque thickness. Figure 7 shows this tool prior to conversion.

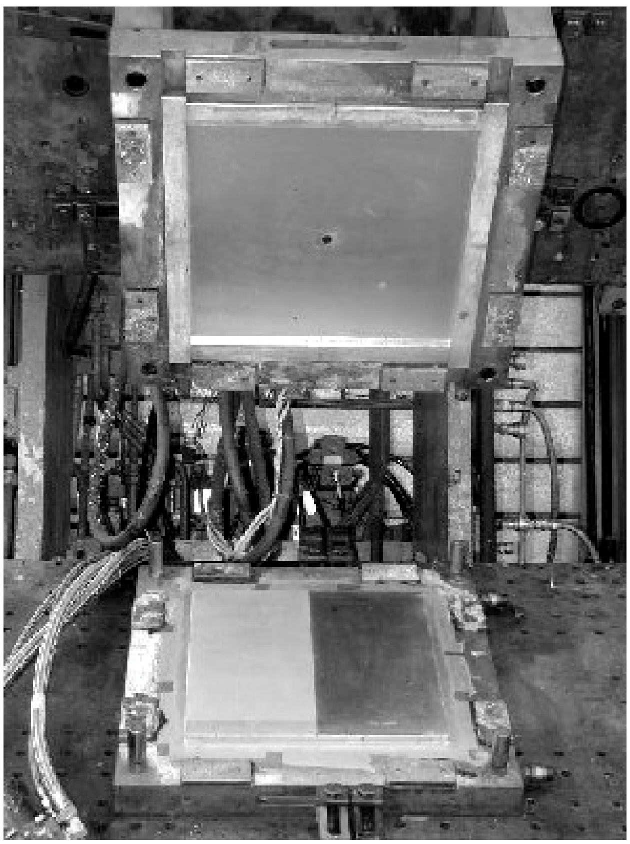

Figure 7. Plaque mold for LFI molding trials.

The next step involved an appropriate design of experiment (DOE) to evaluate the various design parameters that could potentially impact surface quality. Originally the proposal was to run two smaller DOEs sequentially. To save time and still attain statistically significant results, the DOEs were combined into one—a partial L32 Taguchi array. Variables included PUR density, glass type and length, glass content, plaque thickness, demold time, surface veil and postcure. Test plaques were painted using a low-bake (190°F) system.

The LFI team then used a jury evaluation to rank the plaques for surface appearance, ranging from best to worst. Generally, the strongest effects on surface were judged to be glass length, glass content, and the absence of a surface veil. Overshadowing these was postcure. Unfortunately, any real conclusive assessment of surface, especially using Wavescan or QMS methods, was not possible because air entrapment out-gassing was so extensive and resulted in an extremely poor overall surface quality. A directional statistical assessment based solely on subjective rankings resulted in the following conclusions:

Strongest effects:
Glass length = 75 + 12.5 mm
Glass content = 40%
Surface veil = no
Postcure = no

Because the surface quality of the initial DOE trial plaques was poorer than expected, the team focused its efforts for the balance of the reporting period on the elimination of the trapped air from the molded samples. Two potential approaches were considered. One was to design venting features into the ACC plaque tool shear edges. A second approach was to employ vacuum to evacuate the air during the molding process. When a separate existing sheet molding compound (SMC) plaque tool designed for vacuum became available, the team concentrated on adapting it to LFI. Preliminary results have been promising. Given that, the intent in the near term is to redirect the surface quality study and mold plaques using this vacuum setup.

Concurrently, the physical testing to characterize the LFI plaques from the initial DOE trial has been completed. The test program included tensile, compression, DMA, coefficient of linear thermal expansion, density, and glass content. All ACC team members, including our supplier partner, Bayer Polymers, participated in this physical testing phase. Data will be evaluated based on the statistical model used to structure the DOE initially. Results are expected in the late fall 2004.

While data analysis is continuing, some early observations can be made. The modulus depends strongly on the resin density and glass content. The molding experimental design utilized a low-density and a high-density resin and two levels of glass (25 and 40%) in each. The combination of resin density and glass content gave four levels of formulation density, target PFC (pounds per square foot). This is shown along with the tensile modulus values in the table below. The high-density, high-glass samples are about 2.5 times the modulus of the low-density, low-glass samples. The high-density, low-glass and low-density, high-glass samples fall between the other samples and have overlapping ranges of test values. The LFI samples all tested lower than expected for fiber content, so higher property values would be expected at the design-intent fiber levels.

Resin density	Fiber content (wt %)	Composite density (pcf)	Tensile modulus (GPa)
High	40	84	7.8
High	25	74	5.0
Low	40	59	4.5
Low	25	52	3.0

The next steps under consideration include further surface optimization, understanding the process variability that seems inherent to LFI, and studying the benefits of in-mold coatings. Ultimately, the team plans on addressing more complex molding features and replacing glass with carbon fibers.

Conclusions

During this year the molding of B-pillars with Gen-1 glass fiber preforms was completed. The B-pillar sets were provided to the adhesive bonding and structural analysis teams. There was limited molding of carbon fiber B-pillars, but much more work needs to be done in this area.

The LFI team completed the initial molding trial. Unfortunately, definitive conclusions could not be generated for surface appearance. Mechanical testing shows that a broad spectrum of properties can be generated with this process.

Presentations and Publications

1. D. L. Denton, C. H. Mao, D. E. Willertz, DaimlerChrysler Corporation, N. G. Chavka, J. S. Dahl, E. D. Kleven, Ford Motor Company, T. J. Dearlove, C. A. Di Natale, E. M. Hagerman, S. A. Iobst, J. A. Schroeder, General Motors Corporation, and R. A. Bergen, MSX International, “Development of a Cost-Effective SRIM Manufacturing Process for a Composite Pickup Truck Box,” presented at the SAMPE Advanced Composites Conference, Dearborn, Michigan, September 13–14, 2000.
2. S. A. Iobst (presenter), C. H. Mao, and D. L. Denton, DaimlerChrysler, “Use of Real Time Data Acquisition to Optimize the SRIM Process for a Pickup Truck Box,” presented at the SAMPE Advanced Composites Conference, Dearborn, Michigan, September 13–14, 2000.
3. N. G. Chavka and J. S. Dahl, “P4: Glass Fiber Preforming Technology for Automotive Applications,” 44th International SAMPE Symposium and Exhibition, May 23–27, 1999, Long Beach, California.