4. POLYMER COMPOSITES R&D

A. Development of Manufacturing Methods for Fiber Preforms

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-95OR22910

Objective

- Develop and demonstrate new fiber preforming processes to decrease cost, increase manufacturing rates, and improve reproducibility of large preforms for composite molding.
- Provide process development support to the ACC Focal Project-3 (FP3).

Approach

- Identify carbon fiber properties required to permit rapid processing and achieve desired performance levels.
- Investigate materials, process equipment, and tooling technology to further reduce the cost and enhance the quality of chopped fiber preforms.
- Explore the extension of automated preforming technology to make preforms with thermoplastic matrix.
- Investigate methods to achieve rapid orientation of fibers.

Accomplishments

- Conducted preform optimization and carbon fiber preforming trials in support of ACC's FP3 B-pillar.
- Investigated 2Phase tooling material for random fiber performing.
- Developed program proposal and initiated program for carbon fiber roving bundle size reduction program with Hexcel Carbon Fibers.
- Developed program proposal and have contract in place for a carbon fiber roving development program with Fortafil.

Introduction

This project has focused on the development of the P4 process, a fully automated robotic preforming process. A prototype, two-station manufacturing cell was designed, fabricated, and installed at the National Composite Center in Kettering, Ohio.

To obtain higher mass savings with composites relative to steel (50–70%), carbon fiber must be utilized as the reinforcing fiber. The extension of this technology to manufacture carbon fiber preforms is now in progress to support the development of ultra-lightweight structures.

Carbon fiber requirements to permit rapid processing while achieving desired composite performance levels will be identified. This will provide guidance for fiber manufacturers to develop new products. Opportunities to extend automated preforming technology to make preforms containing a thermoplastic matrix, which can be consolidated to form the final part will be explored. Methods to achieve rapid orientation of reinforcing fibers will be investigated. Advances in preforming technology will be demonstrated in the structural automotive parts designed and prototyped as part of the ACC FP3 (see report 4.B).

B-Pillar Preforming Development

In support of the ACC FP3 program, researchers have been performing process development to facilitate manufacture of the FP3 B-pillar test section (Figure 1).

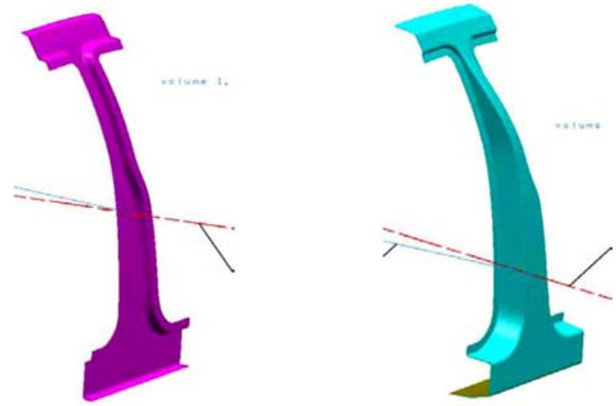

Figure 1. B pillar test section: inner and outer.

Preform optimization is an ongoing, iterative effort to enhance preform characteristics including areal density distribution. To enhance preform quality, substantial robotic programming has been required to achieve the appropriate fiber volume fraction in regions of the components that vary from 1.5 to 8.0 mm in thickness. As part of the carbon fiber preforming development, B-pillar inner and outer preforms have been manufactured using carbon fiber rovings (Figure 2).

Several preforming related issues have been identified when attempting to utilize carbon fiber rovings as the reinforcement material vs glass fiber rovings. The most significant obstacle at this time is the relatively poor fiber distribution on the part surface when compared with glass fiber. This issue is more prominent in the 1.5-mm sections of the components when attempting to

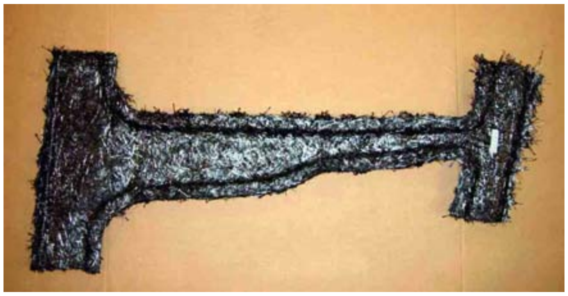

Figure 2. Carbon fiber B-pillar inner preform.

manufacture preforms at a fiber volume fraction of 40% (Figure 3).

The image in Figure 3 is a carbon fiber B-pillar outer preform that has been photographed on a light table. The white regions indicate regions of zero fiber content, an undesirable preform characteristic. Regions of zero fiber content will create regions in the molded component of reduced strength and stiffness and contribute to structural reaction injection molding (SRIM) issues, including fiber wash. In the same way, although not visible on a light table, are regions of excessive fiber content that lead to issues in the SRIM molding process, including dry spots.

Figure 3. Carbon fiber distribution issues.

To minimize the fiber distribution issues present on the surface of the component, a fundamental change to the material format is required. It has been demonstrated that carbon fiber rovings utilizing smaller individual bundle sizes (i.e., 3k vs 6k) will yield improved surface distribution of the fiber. These material format issues are being addressed in carbon fiber roving development programs with several carbon fiber manufacturers.

2Phase Tooling Technology

The ACC contracted with 2Phase Technology to investigate the use of their patent-pending reconfigurable tooling as a potential technology for P4 preform tooling. 2Phase's tooling technology is a method of forming prototype tooling rapidly and relatively inexpensively. This technology potentially could substantially reduce the cost of preform tooling.

Preliminary investigation indicated two areas of concern when attempting to incorporate 2Phase tooling in the P4 process; material strength and air flow through the tool. It was determined that the addition of reinforcement fibers and an increase in particle size as the reconfigurable tooling would be the best options to increase both strength and air flow, respectively. To address these issues, 2Phase fabricated flexural test samples and test preform tools from a variety of materials to investigate the effect.

Flexural test samples were initially made from the standard state-change reconfigurable tooling material. Additionally, two materials with larger particle sizes and two materials with reinforcing fibers in the largest particle size material were also fabricated for flexural testing. The flexural test results are shown in Table 1.

Table 1. 2Phase tooling flexural test results

Particle size (mm)	Fiber length (mm)	Flexural strength (MPa)
0.10–0.25	N/A	2.3
0.42–0.85	N/A	2.7
0.60–1.40	N/A	1.8
0.60–1.40	6	1.4
0.60–1.40	25	1.8

The maximum tensile and compressive stresses in an unsupported section of flat panel perform tooling (350 × 350 × 6 mm) due to bending when subjected to a uniform load of 100 kPa would be approximately 100 MPa. This load of 100 kPa will be experienced within the process regularly and is approximately 50 times the measured strength of the tooling materials tested. Based upon this calculation, the flexural strength of the 2Phase tooling materials tested was deemed insufficient for P4 preform tooling.

Four plaque preform tools were submitted for testing in the P4 preforming process. The details of these four tooling materials are as follows:

- Material A: 0.42- to 0.85-mm particles
- Material B: 0.60- to 1.40-mm particles
- Material C: 0.60- to 1.40-mm particles plus 15% 25-mm fibers
- Material D: 0.60- to 1.40-mm particles plus 15% 25-mm fibers with a surface veil

The test tools were evaluated by measuring the airflow at six points behind the screen, with several damper openings to determine the air velocity through the screen relative to perforated materials. The preform tools were mounted vertically to investigate the most severe requirement for air flow during material deposition. The experimental setup is shown in Figure 4.

Based upon the experimental test results, the air velocity through the 2Phase tooling material is approximately an order of magnitude lower than standard perforated materials when compared with high internal backpressure (i.e., flow valve equal to 0%). However, when compared with lower internal backpressure (i.e., flow valve greater than 0%), the 2Phase tooling shows no increase in air velocity through the tool. This indicates that the tooling is creating a backpressure nearly equal to the flow control valve even with the flow control valve completely open. This is not the case with standard, perforated materials as indicated in Table 2. Reduced air velocity through the tool creates performing

Figure 4. Experimental testing of 2Phase tooling.

issues such as lack of material adhesion to the tool surface. In fact, this same issue was experienced during glass deposition trials using the four experimental tools. The experimental air velocity measurements for these materials are listed in Table 2.

Table 2. Air velocity measurement results

Flow valve (%)	Air velocity (m/s)						
	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Mean
Material A							
0%	0.55	0.81	1.45	1.56	1.5	1.5	1.23
100%	2.17	1.36	1.6	N/A	1.66	1.73	1.70
Material B							
0%	0.94	3.41	4.21	1.21	1.2	0.98	1.99
100%	0.65	4.47	3.96	1.29	1.27	1.08	2.12
Material C							
0%	4.11	3.7	2.11	1.74	1.46	1.12	2.37
100%	4.59	4.53	2.65	1.84	1.56	1.21	2.73
Material D							
0%	1.58	2.71	0.72	0.53	0.5	0.42	1.08
100%	1.7	2.14	0.44	0.49	0.48	0.52	0.96
Perforated steel without 2Phase tooling							
0%	9.52	9.03	9.55	9.95	9.91	10.05	9.67
10%	22.23	21	22.06	23.33	22.72	23.64	22.50

Based upon the testing performed, 2Phase tooling was determined to be unsuitable for P4 preform tooling. For this technology to be suitable for chopped fiber preform tooling, airflow through the tool must be increased, and material strength/toughness must be dramatically increased.

Carbon Fiber Roving Development

To date, research and development of chopped carbon fiber preforming and molding has been limited due to material format and supply issues. To address these fundamental material format issues present with current carbon fiber rovings, development programs have been initiated with carbon fiber manufacturers to expedite material research. The focus of these programs is to investigate the technology required to achieve a reduction in bundle size and the effects of bundle size reduction in the preforming and molding processes.

Hexcel Carbon Fibers

A carbon fiber roving development program to investigate the effect of individual bundle size on preforming, molding, and composite material performance has been developed with Hexcel Carbon Fibers and is currently under way.

The development effort is focused on assessing the effect of individual bundle size on P4 preforming, SRIM molding, and the resultant composite material performance. It is theorized that a reduction in bundle size will improve material distribution in the preforming process and, therefore, positively impact the mechanical performance of the molded structures. To evaluate these materials, the program has been divided into four individual tasks (Table 3).

Table 3. Hexcel Bundle Size Reduction Program

Task 1	Carbon Fiber Roving Manufacture
Task 2	P4 Preforming Evaluation
Task 3	SRIM Molding Evaluation
Task 4	Material Characterization

Task 1. The work contained within Task 1 is to be performed by Hexcel Carbon Fibers under a subcontract with Oak Ridge National Laboratory (ORNL). To investigate the effect of individual carbon fiber bundle size, the research program calls for manufacture of seven different combinations of carbon fiber rovings. The remaining effort then includes precursor manufacture for all combinations to be investigated. Following precursor manufacture, all precursors will be carbonized on production equipment simultaneously. The carbon fibers will then be packaged according to the experimental matrix and shipped to the ACC for evaluation in the preforming process.

Task 2. Upon completion of Task 1, the entire matrix of carbon fiber rovings will be evaluated in the P4 preforming process using the ACC/DOE preforming equipment at NCC, Kettering, Ohio, by the ACC. The rovings will be tested and assessed within the preforming process, and flat panels preforms will be manufactured for in-plane permeability testing, light transmission testing, and flat panel molding trials. In-plane permeability measurements will be conducted on each carbon fiber roving evaluated utilizing ACC/ORNL equipment at NCC, Kettering, Ohio. These data will be analyzed to determine the effect of bundle size on in-plane permeability. Light transmission testing will be performed to determine the coverage characteristics of each carbon fiber roving evaluated. Winona State University will be contracted to perform this work based upon their past experience in developing an analysis technique under a previous purchased services contract with the ACC. Finally, flat panel preforms will be fabricated from all carbon rovings under investigation for SRIM molding trials.

Task 3. Upon completion of Task 2, flat panel preforms will be made available for SRIM molding trials. This effort will consist of molding approximately 10 panels of each carbon fiber roving under evaluation. Molding process data will be acquired and analyzed to determine the effect of individual bundle size in the SRIM molding process. Subsequently, the molded carbon fiber panels will be used for characterization of the composite material.

Task 4. Upon completion of Task 3, molded flat panels will be available for composite material characterization. To determine the effect of individual carbon fiber bundle size on composite material performance, the current evaluation plan will consist of performing tensile and compressive mechanical testing in both the 0° and 90° directions throughout the range of carbon fibers evaluated. Additional characterization will be performed if determined necessary to fully ascertain the effect of carbon fiber bundle size. Additionally, fiber volume fraction via acid digestion will be performed on each tested panel to confirm the fiber content within each panel.

Summary. To date, the required precursor has been manufactured and is awaiting carbonization to complete Phase 1 of this program. Phases 2, 3, and 4 will commence using these experimental carbon fiber rovings in the second quarter of FY 2004.

Fortafil

A research program to develop carbon fiber rovings more amenable to the P4 preforming process has been developed and initiated during FY 2003. This program will focus on developing cost-effective methods to reduce the individual carbon fiber bundle sizes within a roving. A carbon fiber roving specification was developed jointly between the ACC and Fortafil as the target material for this program. The overall program is comprised of five phases to be completed over a 20-month time period.

This research program was officially started in August 2003. To date, administrative functions relative to the program have commenced as well as preliminary technical efforts related to Phase 1 of the program. Upon development of candidate carbon fiber rovings within this program, preforming and molding evaluations will be conducted by the ACC to determine the performance of these materials.

Conclusions

Process development on the B-pillar inner and outer is an ongoing and iterative effort in support of the ACC's FP3. Progress has been made in improving the material distribution and will continue to be an iterative effort between preforming and molding. The application of carbon fiber is currently proving to be challenging due to the current material format. However, development of carbon fiber rovings with various carbon fiber manufacturers will improve carbon fiber rovings and, subsequently, preform processing.

An alternative tooling technology was examined to ascertain the feasibility for application as P4 preforming tools. Prototype tools were manufactured and tested in the P4 process. Test results highlighted several issues with the technology as it relates to the P4 process, and it was determined that the technology was not applicable.

A carbon fiber roving bundle size reduction project proposal was developed within the ACC and Hexcel Carbon Fibers were selected as the carbon fiber supplier for this program. This program was initiated in FY 2003, and Task 1 is approximately 75% complete. Evaluation of experimental materials will begin following receipt of materials in the second quarter of FY 2004.

A carbon fiber roving development project was developed with Fortafil during FY 2003. A contract is now in place, and the program was officially kicked off on August 1, 2003. Preliminary administrative and technical work within Phase 1 has commenced.

Based upon the carbon fiber roving development projects with Hexcel and Fortafil, there is now an opportunity to advance the current carbon fiber roving technology and product form to make it more suitable for high-volume, chopped fiber preforming applications such as P4.

As materials from these programs are made available, the new and improved carbon fiber rovings will continue to be tested in the P4 preforming process to evaluate chopped fiber material processing and performance.

B. Composite-Intensive Body Structure Development for Focal Project 3

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objective

- Design, analyze, and develop the technology to build a composite-intensive body-in-white (BIW), offering a minimum of 60% weight savings over steel at a cost close to that of steel, while meeting manufacturing, assembly, and performance targets.
- Provide a focus for bringing together technology developed by each of the Automotive Composites Consortium (ACC) working groups through emphasis on carbon-fiber-reinforced composites and the use of hybrid materials, faster manufacturing processes, design optimization including crashworthiness, and rapid joining methods.

Approach

- Optimize the design, and complete the finite-element analysis (FEA) (Phase 1—completed).
- Build one part of the BIW to demonstrate high-volume processing methods, including the component as well as the needed assembly fixtures (Phase 2). Test the component before continuing with the construction of the complete BIW.
- Build the complete BIW (Phase 3). To reduce cost, not all parts will be made from production tooling; however, care will be taken to ensure that the properties of each part are consistent with those that will be obtained from production tools.

Accomplishments

- Installed learning tool and preform screens at NCC in Dayton.
- Continued preforming and molding trials.
- Bonded B-pillar parts successfully.
- Completed cost estimates for body side.

Introduction

All of the materials, manufacturing processes, and fabrication and assembly methods to be considered in this project are to be consistent with the following overall objectives:

- High-volume production techniques (>100,000 units per year)
- Cost parity with equivalent steel structures
- Overall 60% mass reduction relative to steel BIW structure
- Structural performance equivalent to or better than that of a steel structure
- Dimensional tolerance equal to or better than that of steel

Much of FY 2003 was devoted to developing the manufacturing processes necessary to build the body side. Preforming and molding trials continue with the B-pillar learning tool. For more details on the preforming studies see the report on P4 preforming (4.A). For additional information on molding, see the report on High-Volume Composites Processing (4.D).

Learning Tool/B-Pillar Related Studies

A learning tool was designed to conduct the processing and materials research necessary to enable production of the body side. A section representative of the B-pillar portion of the design for the body side was selected for the learning tool, which had many of the features of the final part. The tool was made to be versatile for use in multiple processes such as structural reaction injection molding (SRIM), long-fiber injection (LFI), and sheet molding compound (SMC). It has a polished surface so that it can be used to develop class A surface techniques later if desired. The tool incorporates many challenging features not yet addressed by the composites industry, including liquid molding of variable-thickness sections at high-volume fractions.

Molding process development was initiated this year with the new B-pillar mold. The initial development work was with glass preforms, but at the 40% by volume targeted for the body side. The early molding showed that improvements were needed in the tool, especially seals to better contain the injected resin in the cavity. Seals were designed and installed in to B-pillar mold.

O-rings were installed in the vertical shear edges to provide a sliding seal against the resin while the mold was partially open at the injection gap (see Figure 1). Because the O-rings could not follow the sharp

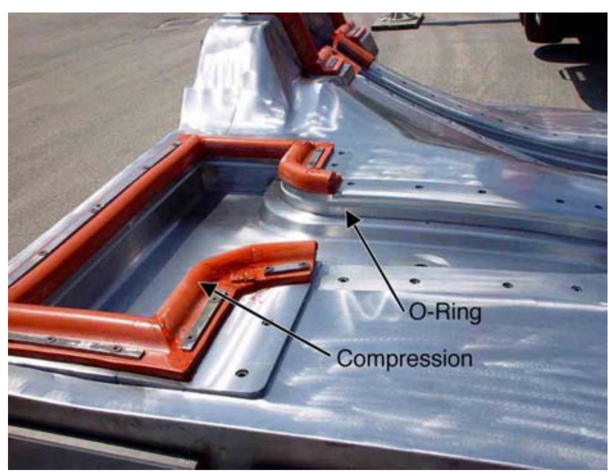

Figure 1. Modified tool with O-ring and resin seals highlighted.

curvature in the rail areas, a second compression seal was used in this area to seal the final stage of the compression stroke, when the resin would have reached the ends of the cavity. With the resin seals installed, it was now possible to hold pressure on the resin as the mold was closed during the compression stroke. As a result it was much easier to force the resin to the ends of the cavities and completely fill the preforms.

The effect of the resin seal is seen in Figure 2. Without the seal the pressure spikes and falls back to near zero. With the seal, the pressure holds at a high level after the initial spike. Flow modeling studies have been initiated with the University of Delaware to better understand the resin flow during molding.

Bonding

The Joining and FP3 Work Groups agreed, after considering four quotes, to contract with RP/C Alliance to design and build a hot-air impingement bonding fixture, as well as a CMM fixture (for dimensional checking), for bonding the two-piece B-pillar. RP/C Alliance also agreed to facilitate the bonding trials at EMC^2 and the CMM testing at Division Two. During the bonding fixture "buy-off" (the first bonding trial), six sets of B-pillar outers and inners were bonded. With some minor adjustments to the cure conditions and air orifices, the final two bonded parts were deemed acceptable. The latter two parts were then taken to Division Two for CMM testing. Based on the design data used to manufacture the molding tools for the inners and outers [where the computer-aided design (CAD) data was modified to be as if the parts were in vehicle position], the bonded assemblies exhibited good dimensional control. That is, the parts were, with a few exceptions, within approximately ±1.0 mm of the design.

Structural Testing

A subgroup of the Focal Project 3 team was formed to specify and conduct structural tests on the B-pillar. The objective of this effort is to assess the quality of the as-molded parts to provide feedback for process development and/or design modification. Notably, this effort is not intended to validate the BIW design or FEA analyses of the B-pillar performance.

The effort will eventually be extended to the demonstration part—the body-side assembly—but is initially focused on the B-pillar because it contains most of the generic geometric features that present the most significant processing challenges and consequently is being used for process

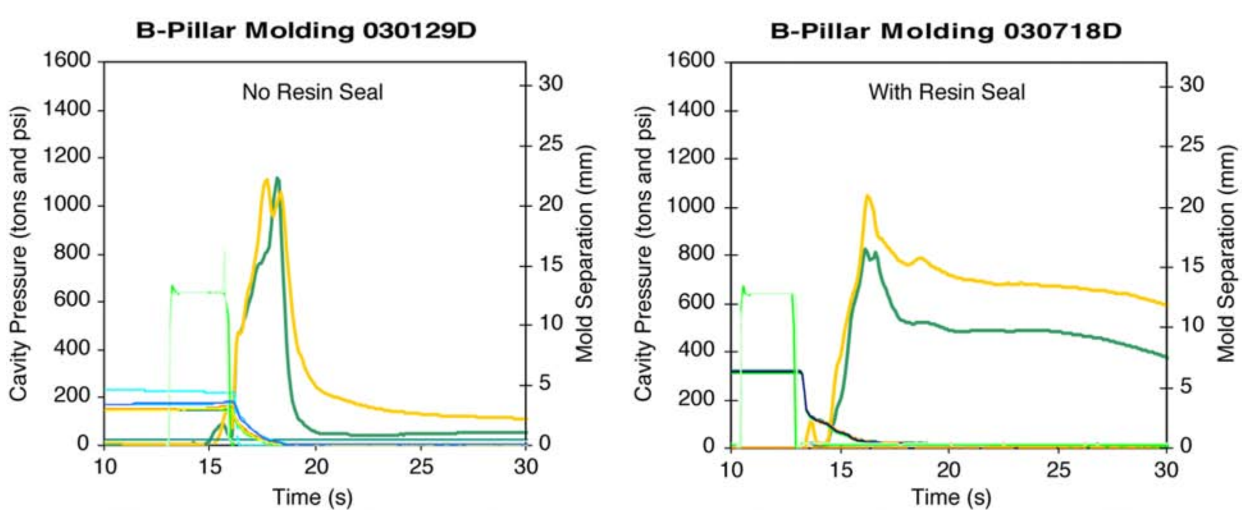

Figure 2. Effect of seals on cavity pressure.

"learning." The B-pillar inner and outer will be investigated individually and also as a bonded assembly.

The most straightforward approach to assess the quality would appear to be to completely characterize the structure, i.e., measure mechanical properties, at every point in the structure and compare these values to design properties. Clearly, this approach would be too costly and time-consuming and would present significant difficultly in measuring properties at potentially the most critical areas (e.g., corners, edges, etc.). Additionally, it is unclear how sensitive the global response would be to local variations. Because body structures are designed largely with respect to global stiffness, the approach adopted here is to conduct full (B-pillar) structural tests to compare with the response of a uniform, idealized good part, as predicted by FEA. Selective coupon testing will also be conducted as shown in Figure 3.

The criterion for selecting the physical tests is to ensure that they will highlight the effects of defects likely to occur in the part. Consequently, the specific approach taken is to first categorize the potential defects as to type, location, and magnitude. Then a FEA is carried out for a variety of loading conditions to assess each load condition's sensitivity to the defects. The loading conditions indicating the most sensitivity to specific defects will be selected for physical testing and correlation.

For this effort, it is assumed that the most significant defect will be variations in the fiber content: specifically, low fiber volume in critical areas. Fiber content measurements (e.g., resin burn-off) are conducted throughout the part to determine a reasonable range of fiber volume fraction variation (see Figure 4). Both the B-pillar inner and outer were segmented into zones, as shown in Figure 5, such that the material properties could be varied, corresponding to fiber content variations, in a systematic fashion.

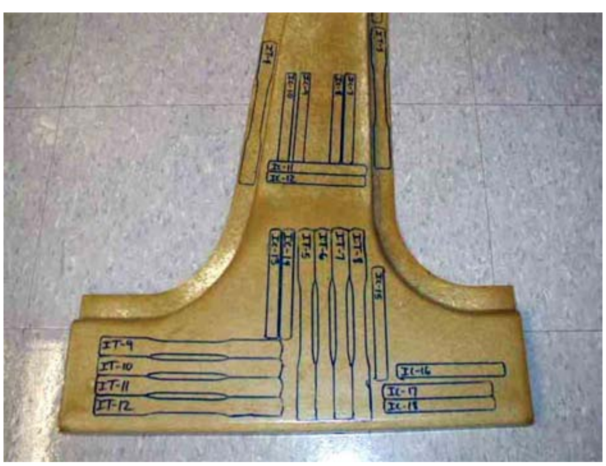

Figure 3. Selective coupon testing will be conducted where standard tensile and compressive coupons can be extracted.

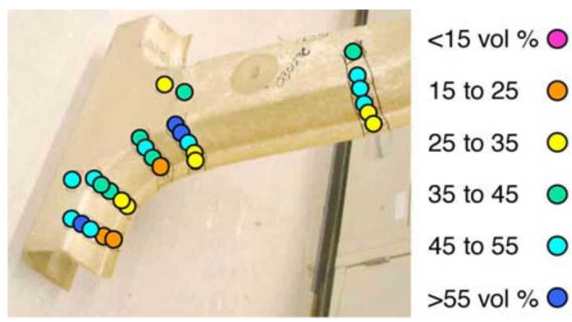

Figure 4. Fiber volume fraction variations are taken at discrete locations as shown for an early glass B-pillar outer molding.

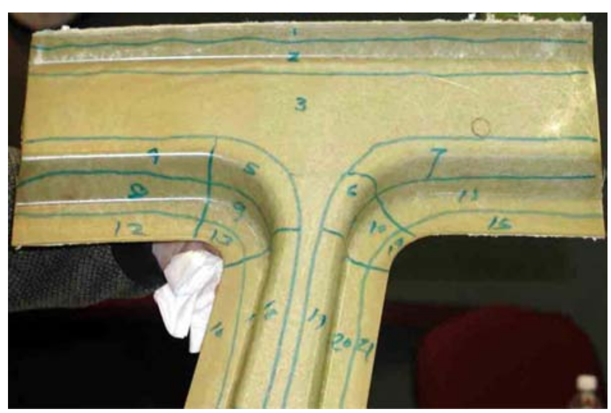

Figure 5. The B-pillar sections are segmented in discrete zones to permit an FEA sensitivity study on fiber volume fraction variation for a variety of load conditions.

Initially, six loading conditions are considered for the effect of defect sensitivity analysis—tension, lateral bending, rocker compression, torsion, lateral line at base of pillar, and distributed lateral rocker. These loading conditions are shown schematically in Figure 6 for a B-pillar outer. Note that the upper rail was omitted in this sketch but will be included in later detailed analyses.

The input properties will be varied systematically within the zones to determine which load conditions will highlight specific defect locations. These results will be used to down select to one to three physical tests to conduct.

The results of the physical tests will be compared to the predicted results for an idealized (e.g., uniform property) part to assess the overall quality of the part. Coupon data (Figure 3) will supplement the structural response data in this determination.

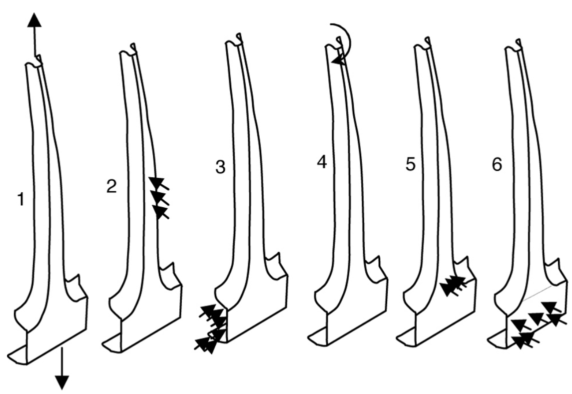

Figure 6. Six loading conditions are considered for effect of defect sensitivity analysis.

Status

Defect type, location, and magnitude have been defined and initial sensitivity analysis completed for the loading conditions shown in Figure 6. The FEA models are being refined to include the upper-rail section and recent minor modifications to the geometry, if determined to be significant. Discussions with a test lab have been held, and tests will be initiated when suitable parts are available and after the final sensitivity analysis results are obtained identifying the most relevant tests.

Bonded Joint Modeling

Phase I of the generic bonded joint modeling project continues at the University of Michigan (UM). This work is intended to validate the modeling approach taken previously at the University of Texas-Austin. The original work predicted that an all-composite bonded hat/flat section with an initial crack would fail (propagate the crack). In testing at ORNL, this did not occur. During the new work at the UM, it was determined that the issue with the initial prediction was that the large-scale bending of the composite flat section was not accounted for in the model. Therefore, a new model (UM) was developed to account for the actual behavior of the flat section. Calculations were performed which indicated that the most likely way to ensure crack propagation would be to fabricate the part using the same dimensions as the original part, but to make it out of steel. This new part has been prepared and bonded, and testing at ORNL should occur in the next quarter.

Meanwhile, the next phase of this project was initiated at UM. For this work it was decided to focus on a mixed material system. The hat section will be a commercial Quantum Composite material (essentially a carbon-fiber SMC) bonded to a flat steel plate. (Carbon composite)/steel strips were bonded to generate the “coupon-level” lab tests required for the initial modeling studies. The coupon-level tests have been completed, and the model has been verified at the lab scale. A publication, the first in what is planned to be a series of papers on this subject, is currently in editing. The Quantum Composite hat sections were molded earlier in the year, and the bonded parts will be prepared by next quarter.

C. High-Volume Processing of Composites

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Contractor: U.S. Automotive Materials Partnership
Contract No.: DE-FC05-02OR22910

Objective

- To develop and demonstrate high-volume manufacturing technology to produce lightweight composite automotive body structures.
- To achieve higher fiber volumes in thinner sections than were successfully achieved in ACC Focal Project 2 (FP2).
- To support the goals of ACC Focal Project-3 (FP3).

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 FP3 program.
- Team with supplier partners to investigate alternative liquid molding processes.

Accomplishments

- Performed initial B-pillar molding trials with 40% glass fiber preforms.
- Modified the mold to incorporate the following improvements:

  - resin seals added to each cavity,
  - the transition regions between the thin and thick sections smoothed out, and
  - an additional pressure transducer added to each cavity.
- Molded parts for bonder evaluation.

Introduction

The purpose of this project is to further develop the liquid composite molding technology previously demonstrated in the ACC FP2 with the large structural truck box. This project will extend the liquid molding process into more structurally demanding application of the ACC FP3 body-in-white. This will be accomplished by using carbon fiber reinforcement at 40% by volume, compared to the 30% glass fiber reinforcement used earlier. To maximize the weight savings, the minimum section thickness will be reduced to 1.5 mm.

Two basic approaches will run in parallel. The first is the extension of conventional SRIM technology to carbon fiber preforms of reduced section thickness in support of the ACC FP3. The plaque molding program demonstrated the ability to mold the 40% carbon fiber preforms at the required thin sections. The glass and carbon preforms at 40% required about the same molding pressure, which was substantially higher than required for 30% fiber reinforcement. The molding is now extended to the shaped panel, which represents the B-pillar section of the FP3 body side. This approach is under the direction and includes direct participation of ACC personnel.

The second approach will be to work with supplier-partners to adapt their liquid molding processes in the direction of being compatible with the material property and processing requirements of FP3.

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 Long Fiber Injection (LFI) portion of the program.

B-Pillar Molding Program

The B-pillar molding is a joint program between this project and FP3. It is the process development step between the plaque molding and the FP3 body side molding programs. This mold is a simplified version of the B-pillar section of the full body side. The mold contains the minimum (1.5-mm) and maximum (8-mm) thicknesses of the full part and the bonding flanges. It will be used to generate data on the molding characteristics of the high-volume fraction carbon fiber preforms of complex shape and assist in the final design of the body side molds. The mold contains both the inner and outer cavities in the same base and will produce parts for bonding and structural analysis studies.

The molding during this time period was done with 40% glass preforms. There was only a limited supply of the Zoltek carbon fiber available, and it was decided to conserve that supply until the preforming and molding of the high fiber volumes were characterized with an available fiber.

After a set-up period, the molding program was kicked off in the fall of 2002. Mold filling was characterized by a number of techniques, including a series of short shots (Figure 1), data traces (discussed below), and observation of any patterns of dry fiber areas. Where appropriate, this information was fed back to the preforming team.

The initial molding study looked at the effect of injection gap height, time between injection and compression, and press

Figure 1. Flow characterization by short shot experiments: 25%, 50%, and 75% fills.

tonnage on the preform filling behavior. The injection gap height was found to be an important parameter due, in part, to the significant curvature of the B-pillar. To accommodate the mold draw, this curvature caused a large vertical separation between the ends of the cavities. Also, the part is designed with a thin section between the two thicker ends; this prevents an excess of resin in one end from flowing back toward the other end of the part. It was found that if the injection gap was too large, then excess resin flowed toward the lower part of the cavity, and the opposite end of the part did not fill. If the injection gap was too small, then the flow resistance was too great, and the mix-head faulted out. However, by controlling the injection gap to between 3 and 7 mm, a good resin distribution was obtained.

A major tool in the molding program was the data acquisition system. This allowed the resin injection and press closing dynamics to be observed. An example is given in Figure 2. The mold is paused at a gap of 3.7 mm above stops for injection. The injection time is shown on the chart followed immediately by full mold closure. This action forces the resin through the preform and pressurizes the resin in the cavity.

During this first phase of B-pillar molding trials, it was observed that resin leaked outside the mold cavities and that compression pressure could not be held on the parts (Figure 3). This also limited the capability to force the resin to the ends of the preforms. A temporary fix was devised by placing a veil over the perform, which partially sealed the cavity edge. This allowed

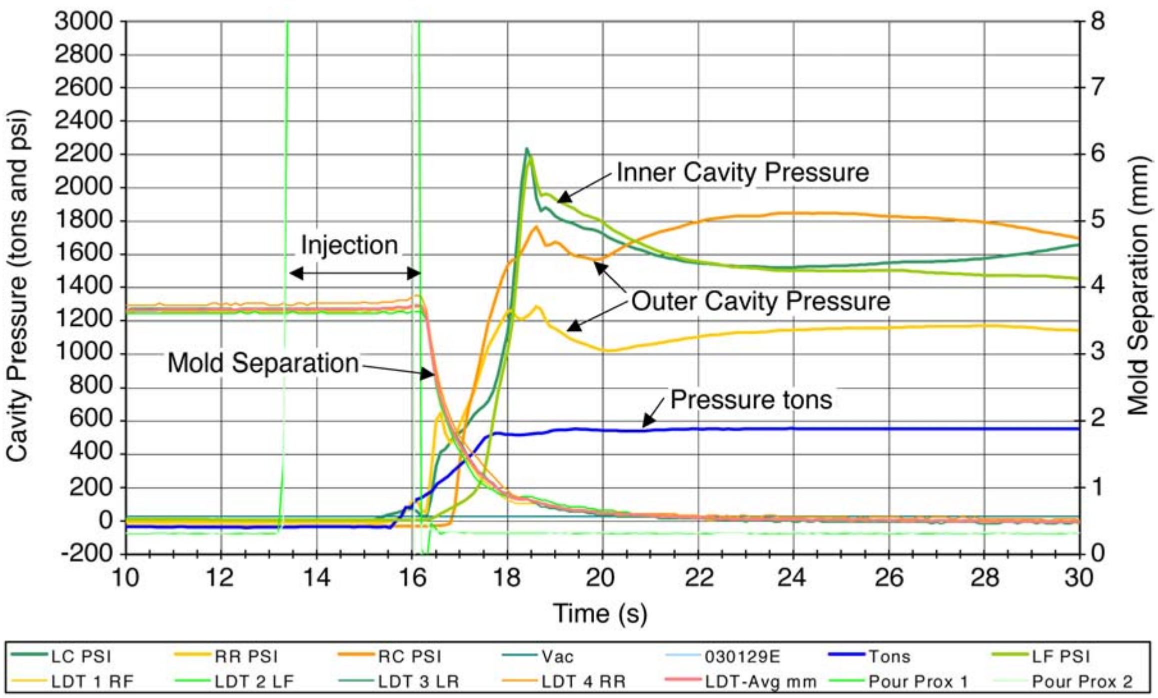

Figure 2. B-pillar mold dynamics showing mold half separation, resin injection, and cavity pressure as a function of time.

Figure 3. Photograph showing resin leaking outside the B-pillar mold cavities, and resulting dry preforms in rail areas.

the initial molding phase to be completed, to establish molding parameters, and to supply feedback to preforming.

It was decided to pull the mold and have seals installed around the cavities. At the same time, an additional pressure transducer was added to each cavity, and the transition zones between the thin and thick cross sections were reworked. The seals did contain the resin within the cavities and provided better compression within the cavities (Figure 4).

Some additional refinements will be made in the preforming program using glass before starting the carbon fiber work.

Figure 4. Nested B-pillar inner and outer set.

Supplier-Partner Liquid Molding Program-LFI

ACC Project 115 has previously included a segment focused on developing alternative liquid molding processes. This has continued in 2003 but has been expanded to assess the potential for achieving a Class A surface finish with these materials/processes. In this capacity the ACC Team has partnered with Bayer to investigate Long Fiber Injection PUR (LFI) processing and material properties.

The LFI process involves cospraying the urethane resin along with chopped fiber reinforcement into an open mold, then closing the mold and curing. One primary goal will be to characterize this process/ material for its ability to meet the more demanding structural applications of FP3. Concurrently, another challenge has been added: to assess LFI's potential for Class A surface optimization.

The first step for the ACC Team has been to establish a surface acceptance standard that could be used to gage the progress through stages of LFI development. Various materials used for automotive Class A exteriors were benchmarked, using a variety of known quantitative techniques as well as a subjective jury evaluation. Plaques were prepared and finished at a common source in various stages of the painting process (initial, E-coat, primer/sealer, topcoat). This work is in progress with a scheduled completion of mid-December 2003.

Having established the standard, the project was organized into distinct phases, covering the next 6 months. The initial step was to construct an LFI plaque tool with suitable surface finish and ability to vary thickness. It is to be used for molding trials at Bayer in their Pittsburgh labs. This tool modification is targeted for completion by the end of November 2003. Follow-up phases include two separate designs of experiment (DOE). The first will screen for such elemental parameters as glass type, fiber length, and percent by weight. A second DOE will build on these results to assess the effects of thickness, mold time, postcure, and surface veil. In both phases, the plan is to finish coat the plaques and evaluate them against the agreed-upon "standard." The DOE plans have been finalized, and the testing is anticipated to begin in early 2004.

Based on the results, the ACC Team will decide on the next most appropriate course of action. Use of in-mold coatings and other surface enhancement techniques are the most logical direction. Given a successful outcome of this plan, subsequent work could include evaluating critical design and process conditions (i.e., larger areas, irregular sections, molded-in features…). Continued progress could also drive the investigation of carbon fibers for additional weight savings.

D. Thermoplastic Composite Sheet Manufacturing: Study of Thermoplastic Powder-Impregnated Composite Manufacturing Technology

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Prime Contract No.: DE-AC06-76RL01830

Objectives

- Demonstrate and develop glass and carbon-fiber-reinforced thermoplastic matrix composites at production rates consistent with high-volume automotive structural applications.
- Investigate and develop methods for shortening the process cycle times and improving materials performance.
- Develop methods for achieving a Class A surface finish requirement, consistent with outer body panels for automotive use.
- Investigate the potential for cored (sandwich) structure composites with thin-walled thermoplastic matrix composite skins.
- Determine the cost-effectiveness of thermoplastic matrix composites in production volumes consistent with automotive applications and the potential to achieve cost targets in the future.

Approach

- Use data from previously completed parametric studies of time, temperature, and pressure profiles required to achieve properties for structural automotive composites; and determine combinations of processing factors that will accelerate process cycle to under 1 min.
- Develop methods of heating and cooling, and process operations to achieve consistent cycle times.
- Analyze alternative methods of melt processing for the various operations required for consolidation, including experimental evaluation of cored structures.
- Apply a multiscale materials modeling approach to develop predictive numerical models for thermal and structural responses for constituent materials and architectures; and apply to

processing conditions for cycle optimization, material property predictions, and end-use performance predictions.

- Use data to influence materials suppliers in modification of base material feeds in ways that support increased cycle times.
- Use complex-shaped components to determine process limitations and factors for economic evaluation.
- Evaluate methods to achieve Class A surface finish with reinforced thermoplastic matrices and analyze them in production cycles on complex tooling.

Accomplishments

- Completed a two-press system installation and demonstrated the operation using a single, modified cone mold. The operation demonstrated the need for emphasis on tool design, specifically in optimization of tool mass and heating and cooling times.
- Concluded from results of the two-press system that current material forms cannot be processed in cycle times that are compatible with the higher volume automotive production cycle time goals, but they may still show potential for some of the lower volume ranges. The project is now investigating alternate thermoplastic composite materials that either require shorter consolidation times or are preconsolidated.
- Investigated preconsolidating of the powder-impregnated materials by melt and pressure and then reheating and stamping into final part shape, which offers the ability to reduce dwell time and meet cycle time goals. However, mechanical testing of materials processed in this manner showed property losses (compression strength) in the range of 30%. The reason for these property losses is being investigated.
- Developed a new processing method for continuous processing with multiple tooling sets, with optimized heat/cooling methods. Delphi has filed a record of invention for this process. This approach is being demonstrated as part of the two-press system development.
- Automated the two-press system partially to simplify and ensure proper operation of the system. All safety critical operations, such as closing the press, are still controlled manually to ensure that the operator is at an adequately safe distance.
- Investigated infrared (IR) heating as a means for preheating the tool surface.
- Created a finite-difference model of the effects of IR heating to explore and determine the feasibility of using IR energy as a means of rapid preheating and a reduction of thermal momentum.
- Completed a new seven-sided forming tool with flat sections at 0°, 30°, 60°, and 87° from perpendicular to the loading direction. This tool should allow structural testing and show the effects of slope angle on structural integrity.
- Initiated action to purchase alternate thermoplastic composite materials. Evaluation will include DRIFT woven into fabric form. To date the suppliers of DRIFT material have not been able to successfully deliver the required material, so this task will be dropped.
- Completed micro-scale models for simulating the behavior of unidirectional reinforced-fiber composites. The primary model is based on assumed hexagonal packing of fibers and is parameterized to allow any possible volume fraction of fibers and any desired finite-element mesh refinements to be applied.
- Developed a numerical model of a consolidated 4-harness satin fabric-reinforced composite.

- Developed a numerical model that predicts 2 × 2 twill unconsolidated fabric shear behavior for simulating properties useful for macro-models of stamp-forming process modeling.
- Developed relations between fabric openness, in-plane shear locking angle, and effective normal strains for better understanding of fabric formability characteristics.
- Constructed four different fabric (mesoscale) models. The model for simulating a consolidated plain weave lamina has been completed for mechanical property prediction. A model for a consolidated 2 × 2 twill weave has been completed for simulating thermal properties. The more complex weaves (2 × 2 twill and 4-harness satin) continue to provide difficulties for establishing mechanical periodic boundary conditions. However, many of the issues have been resolved, and rapid progress on three models is expected.
- Began development of a fabric shear model for the 2 × 2 twill material. A complex set of boundary conditions has been developed, and the final issue of contact conditions during shear locking is being resolved.
- Developed a number of variations on macro-modeling of the forming process. Results show a strong relationship between in-plane shear properties and propensity for wrinkle formation, die surface interaction, and the ability to suppress developing wrinkles, material and die surface characteristics. and forming pressure distribution in the die.

Future Direction

- Complete the final report with updated fabric modeling results.

Introduction

Polymer matrix composites are a class of materials identified as having a combination of properties required to achieve very significant reductions in vehicle mass as compared to conventional materials. Although widely regarded as having the most potential for future weight savings, their applications are severely restricted by fundamental issues in achieving required production volumes and cost of basic materials. These issues have been primarily studied and analyzed based on liquid thermosetting matrix composites, such as structural reaction injection molding (SRIM) as used in the ACC focal projects. Fiber materials cost and availability, especially for carbon fiber, are being addressed by the DOE program under the low-cost carbon fiber projects.

This project has identified the carbon fiber thermoplastic matrix composites as having significant potential to meet structural property requirements as well as to achieve rapid processing cycles similar to stamping of metal components. Automotive applications will be most widespread if two other fundamental issues can be addressed; namely, cored, thin-walled structures (for optimum structural performance and minimum weight) and Class A surface in a semi-structural component. Development of the thermoplastic composites to meet these requirements will require a combination of experimental approaches, materials and process modeling, and modification of materials forms and processing methods to achieve an optimum manufacturing process.

Project Deliverables

This multiyear program will develop and demonstrate knowledge concerning four areas of thermoplastic composite forming process technology, including (1) results of process cycle time and materials property achievements at high forming rates; (2) results of Class A surface finish trials; (3) methods for manufacture of thin face-sheet cored structures; and (4) modeling tools for predicting and optimizing the thermal and structural materials behavior for fiber-reinforced thermoplastics.

Planned Approach

Experimental and analytical methods are being used and developed for high-rate forming of thermoplastic composite sheet and cored structures. The research team is focusing on achieving automotive stamping production rates and materials modifications to achieve rapid flow and consolidation. By integrating these two approaches, we are able to determine where difficulties in the process and materials form occur and can suggest methods to overcome these barriers. Several significant invention disclosures have resulted. Further focus on the process and materials kinetics will allow the bench-scale demonstration of high-rate stamping. Recent experiments using complex three-dimensional (3-D) molds indicate that longer dwell times are required to consolidate materials in draw and draft angle portions of the dies. This points to the need to explore alternate material forms in future work, including preconsolidated thermoplastic sheet materials.

Experimental Methods—Manufacturing Tasks

The initial experimentation used flat plate molds and developed a process diagram based on achieving a predefined “acceptable” quality of consolidation, as measured by compressive strength of the coupons. These process conditions were used as a basis for processing a conical mold that had varying angles of fabric shear (deformation) and varying forming radii (both convex and concave) to provide an understanding of the forming limits under different process conditions. Coupons have been taken from the conical mold and tested in compression to match the consolidation results to the results from the basis flat plate mold.

Methods for achieving rapid process cycles were developed as an ongoing part of the conical mold trials. A two-press system (Figure 1) was developed during the past year to simulate a newly developed continuous cycle process. However, with the use of more complex, 3-D molds, experimental results indicate the need for increased dwell time to achieve consistent, full consolidation of the powder-impregnated materials. As a result, additional investigation will focus on the application of pre-consolidated thermoplastic composite materials, and the use of a new mold design that incorporates multiple entrance angles so that the influence of die geometry on cycle dwell times can be quantified.

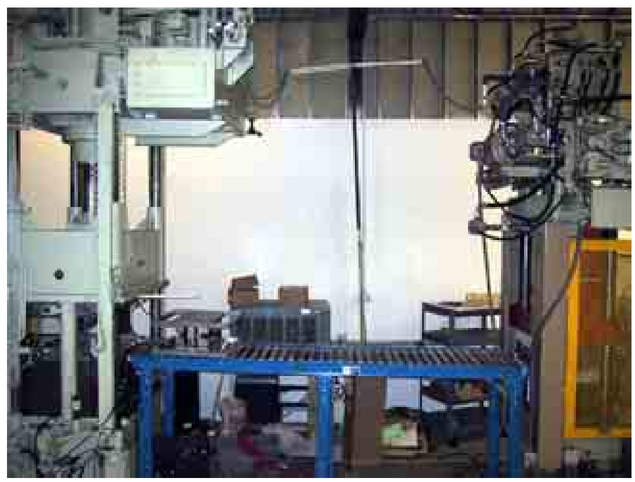

Figure 1. Two-press system with tool shuttle.

Approaches using combined hot stamping and consolidation as a single step have indicated a long dwell time necessary for fiber wetting and optimum resin distribution to occur when fabricating trial parts under realistic processing conditions. Although the materials properties can be developed for simple sections—here conditions of combined temperature, pressure, and time meet our original process map—we find that when working on areas with other high draft angles and lack of directly applied pressures, a longer dwell time is required. Although this is still consistent with the process map, it is operating further out on the boundaries of allowed conditions, which leads to a longer process cycle.

In an effort to reduce cycle time, preconsolidation of the powder-impregnated material was evaluated. With this approach, Delphi heated and pressed sheet layers into fully consolidated flat sheet, which could be done outside of the main forming press step and, thus, eliminate most of the dwell portion of the forming cycle. Experimentally, the pre-consolidated sheet was then reheated to forming temperature and formed into the die and final component shape. However, measurement of mechanical properties from the preconsolidated material stampings showed up to a 30% drop in compression strength. Although the reason for this property knock-down is not known, further investigation is planned.

Modeling Task—Analytical Methods

Approach

Apply a multiscale material modeling approach to develop predictive numerical models for thermal and structural response for constituent materials and architectures, and apply to processing conditions for cycle optimization, material property predictions, and end-use performance predictions.

Accomplishments

- Extended the numerical model of a consolidated four-harness satin fabric-reinforced composite to model inelastic behavior for in-plane shear loading.
- Obtained properties from previous work to predict 2 × 2 twill unconsolidated fabric shear behaviors that have been applied in macro-models of stamp-forming process modeling. Some qualitative comparisons with experiments have shown some key correlations that suggest the modeling approach is very good at predicting fabric wrinkling during forming.
- Started efforts to consolidate the documentation of modeling work performed during the course of this project.

Future Direction

Complete the documentation of the project modeling work.

Analytical Methods

A multiscale modeling approach has been developed and applied to demonstrate modeling tools with long-term value to the technology of fabric-reinforced thermoplastic composites. As illustrated in Figure 2, three important materials scales have been addressed. A description of and motivation for the multiscale approach is available in the FY 2001 annual report for this project. Here we will review some past results

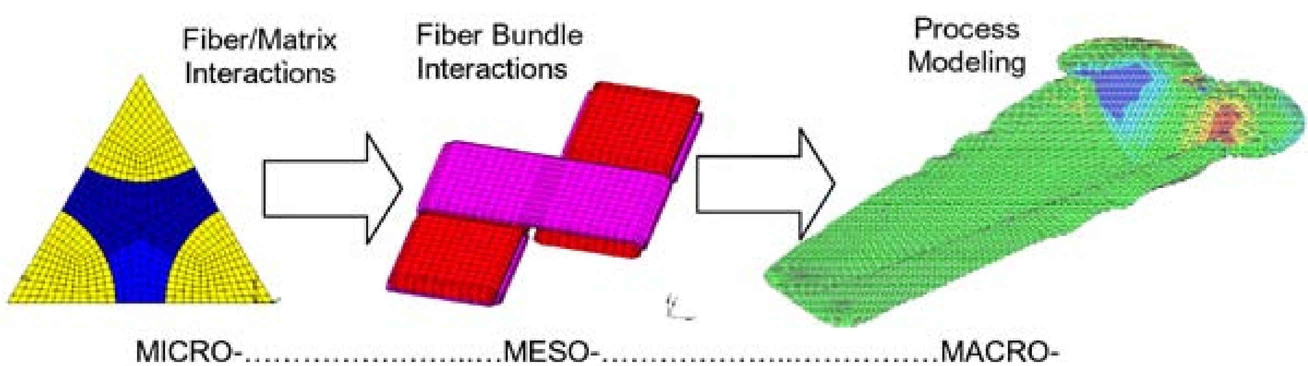

Figure 2. Multiscale modeling of fabric-reinforced composites. Shown are a hexagonal fiber pack unit cell for microscale modeling, a 2 × 2 twill fabric unit cell for mesoscale modeling, and cone forming process model results at the macro-scale.

and describe progress made concerning modeling activities during the past year.

The microscale models were developed in previous years. In addition, some mesoscale models were developed previously to predict thermal and structural behavior for the 2 × 2 twill woven fabric material in a consolidated form. Process (macro) models have been developed to study initially the effect of in-plane shear stiffness on formability and drape characteristics for the cone-shaped mold. Also, macro-models were applied to predict in-mold pressure distributions during forming.

Efforts since the last report (October, 2002) have been primarily to integrate results from the consolidated fabric shear model with the macro-forming model for the cone-shaped mold. Also, some new results have been generated for a four-harness satin weave model.

An image of the four-harness satin weave unit cell model is shown in Figure 3. A nonlinear material model was applied to study inelastic materials behavior for in-plane shear loading. The stress plot on the right in Figure 3 indicates where damage occurs due to microcracking in the matrix during in-plane shear loading. The constitutive law is base on micromechanics at the fiber matrix level (microscale model in Figure 2) with the kinetic theory of fracture applied to the polymer matrix.

The fabric shear model for the unconsolidated 2 × 2 twill weave and three deformed configurations of the same are shown in Figure 4. In the second image, the model has been loaded to simulate the geometry and

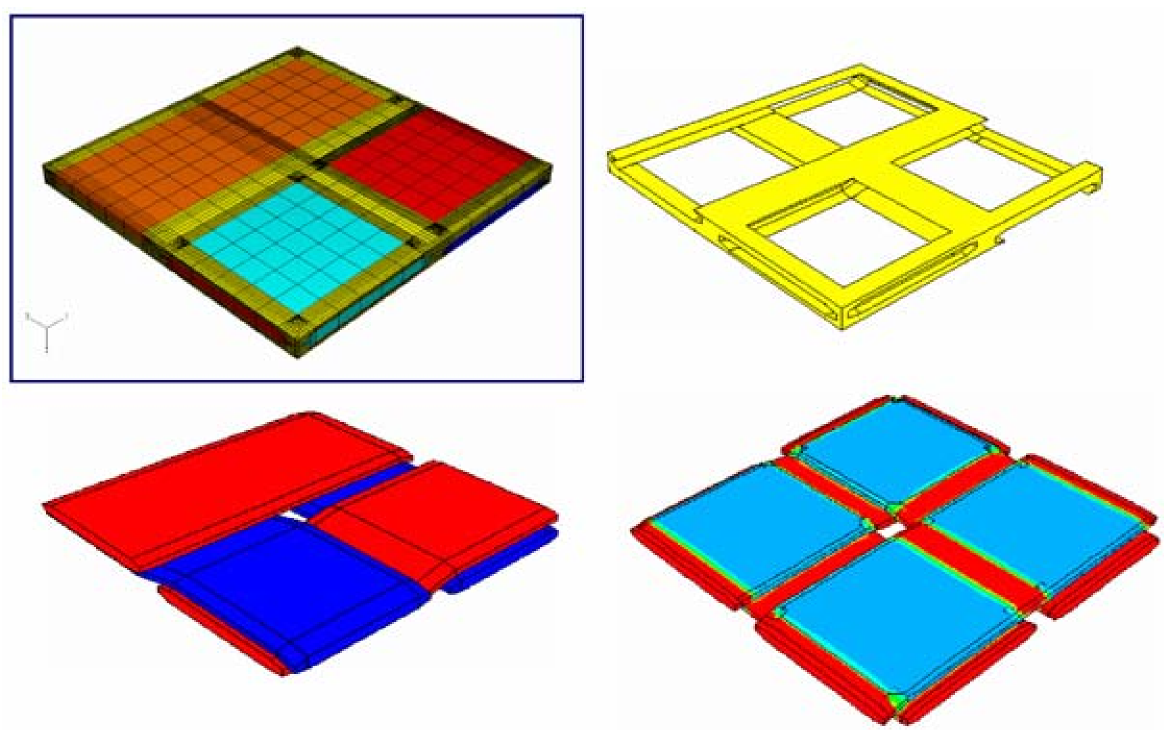

Figure 3. One-quarter periodic unit cell finite-element model for a consolidated four-harness satin weave reinforced composite with colors indicating separate tows in the weave (upper left). Pure matrix regions are shown in the upper right. The tow architecture is shown in the lower left. Contour plot on the lower right indicates regions where matrix damage has occurred (red) as well as low-damage regions (blue) for the case of in-plane shear loading.

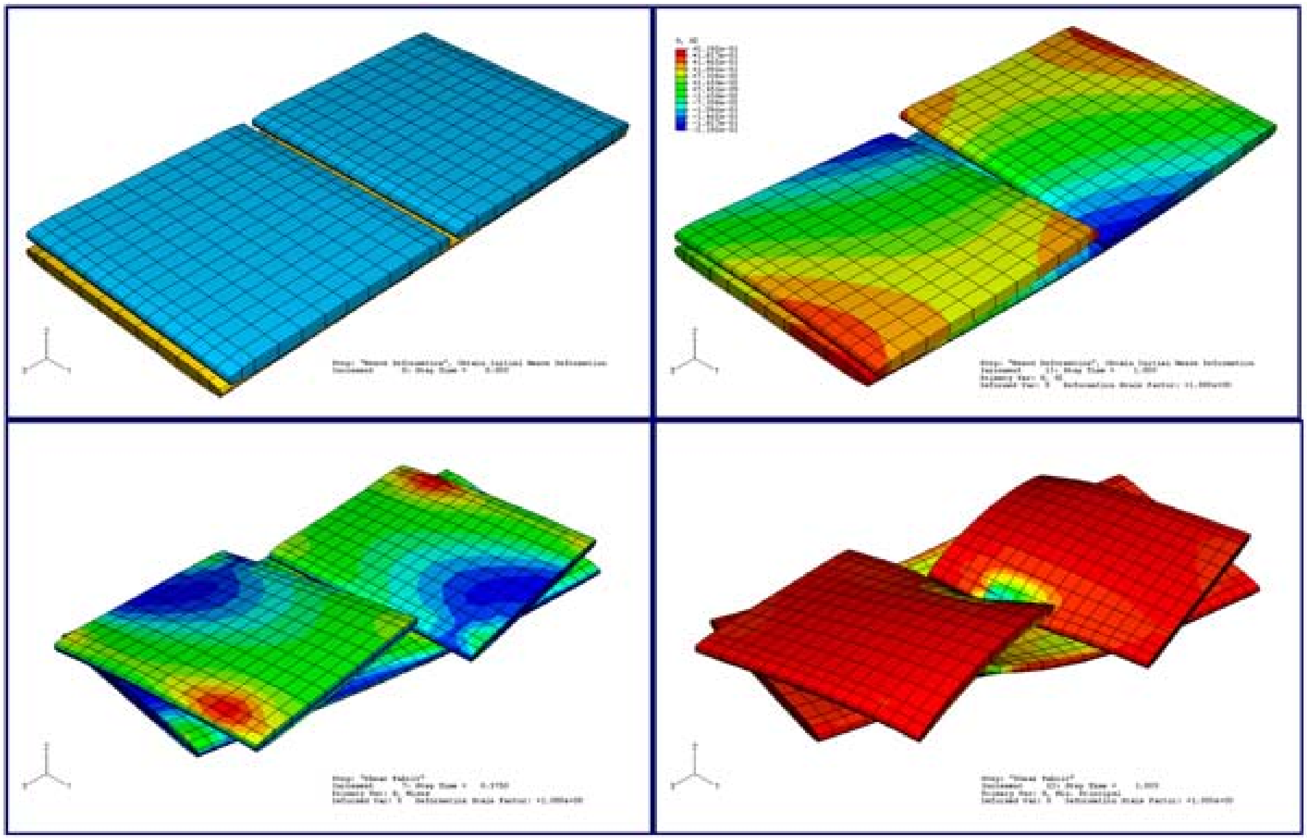

Figure 4. Fabric shear model for 2 × 2 twill weave. Initial model geometry and mesh (upper left); model deformed into weave pattern (upper right); shear deformation before tow edge contact (lower left); shear deformations after tow edge contact (lower right).

stresses due to weaving. In the third image, fabric shear is simulated where the shear angle is less than the initial locking angle so that contact between adjacent tows has not yet occurred. In contrast, the last image shows the deformation resulting from such contact. It is this contact between parallel tows that causes a dramatic rise in in-plane shear resistance as indicated in Figure 5. This resistance limits the formability because increased shear resistance causes in-plane stress and eventually causes buckling (wrinkling) of the sheet.

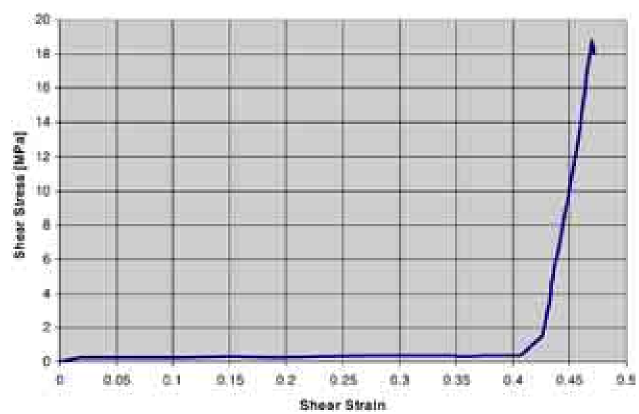

Figure 5. Shear force history showing sharp rise in shear resistance after two-edge contact.

The importance of the in-plane shear deformation mode for fabric formability was described in a previous report. The in-plane shear stiffness is of particular importance. As seen in Figure 5, the stiffness can be well characterized by a bilinear stress strain curve. The initial, very low, shear resistance is due to friction between tows as they slide against one another during shear deformation. The sudden change in resistance occurs when the gap between parallel tows closes, and additional shear deformation is accompanied by a buildup in compression between tows. So, as was also described in the previous report, the initial gap between parallel tows is a controlling factor in the overall in-plane shear resistance during forming. Large in-plane shear resistance causes in-plane compressive normal stresses that eventually buckle the fabric, thus creating wrinkles.

Recently, the results from modeling the in-plane shear behavior have been used to construct a nonlinear elastic constitutive law for application in forming process modeling. Prior process modeling efforts have used a range of hypothetical properties to study the sensitivity of model-predicted forming behaviors to material parameter variations. This recent effort was the first attempt to approximate actual material behavior with an appropriate set of nonlinear orthotropic material constants based on the in-plane shear behavior predicted by the mesoscale modeling. Previously, we had shown that high in-plane shear resistance could result in a large wrinkle or fold in the material at the large end of the cone-shaped mold.

A similar fold had been observed experimentally for a plain weave material known to have higher in-plane shear resistance than the 2 × 2 twill. Here, with the predicted properties we again predict a fold, although a small fold. A visual comparison of the model-predicted and experimentally generated folds is shown in Figure 6. The comparison would be remarkable except that they involve two different materials. The plane weave material would have a smaller locking angle and would be expected to have overall higher in-plane shear resistance and, therefore, less resistance to wrinkling than the 2 × 2 twill weave. The experimental fold/wrinkle for the plane weave is more severe than that predicted for the 2 × 2 twill weave. However, the experiments with the 2 × 2 twill material did not produce such a wrinkle.

Future work will be directed at consolidating and documenting the various models for future reference.

Figure 6. Comparison of model-predicted wrinkle defect and defect produced in a formed part.