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

Nancy Johnson
GM Research & Development
MC 480-106-256
30500 Mound Road
Warren, MI 48090-9055
(586) 986-0468; fax: (586) 986-0446; e-mail: nancy.l.johnson@gm.com

Field Project Manager, Composites: C. David Warren
Oak Ridge National Laboratory
P.O. Box 2009, Oak Ridge, TN 37831-8050
(865) 574-9693; fax: (865) 574-0740; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Contractor: U.S. Automotive Materials Partnership
Contract No.: FC26-02OR22910

Objectives

- 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 (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

- Conducted preforming and molding trials, which are ongoing.
- Fabricated second-generation preform tools, being used at NCC.
- Completed flow modeling studies for B-pillar.
- Completed cost modeling.

- Tested bonded parts successfully with pulsed thermography to check bondlines.
- Developed modeling approaches for joints.

Future Direction

- Complete the optimization of the B-pillar preforms with the second-generation preform tools.
- Develop mold filling flow model for the full bodyside design.
- Define a B-pillar structural test, develop a model for the test, and carry out the testing to confirm the model.
- Conduct preforming, molding, and mechanical testing evaluation of new low-cost carbon fibers.
- Complete B-pillar molding of carbon fiber preforms.

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

We continue to develop 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 performing studies see the Automotive Composite Consortium (ACC) 040 annual report (4.A). For additional information on molding, see ACC 115's report (4.C).

B-Pillar Preforming Development

In support of the ACC's Focal Project 3 (FP3) program, researchers have been performing process development to facilitate manufacture of B-pillar inner and outer preforms.

Original B-Pillar Tooling

Preform development was conducted with the original B-pillar tooling that utilized the designed 'A' surface as the fiber deposition surface on both the B pillar inner and outer preforms. Extensive robotic programming efforts were performed in an attempt to achieve uniform areal density distribution throughout the parts. Despite these efforts, poor material distribution remained on both B-pillar inner and outer preforms when manufacturing preforms at a targeted fiber volume fraction of 40%. Material distribution issues were predominantly evident in 1.5-mm regions (Figure 1) of the components and in the 1.5-mm sections of thickness transition areas of 4, 6, or 8 mm to 1.5 mm.

Figure 1. Areal density distribution issues, 1.5-mm section.

Large areal density variability within the preform (±30%) has led to subsequent molding issues including fiber wash and dry regions in the parts. Excessive material density creates "dry spots" in the molded components, as highlighted in Figure 1, that are unacceptable. Additionally, incompatibility between the preform ('B' surface as the consolidation side) and the lower molding tool ('B' surface) created a less than optimum fit when the preform was placed in the molding tool. Due to this issue, the preform was sheared along the edge of the part up to 5 mm during tool closure, thus creating "racetracking" and fiber wash in the mold tool leading to inconsistent filling of the preform.

Based on the aforementioned issues, researchers determined that a redesigned B-pillar preforming tool could possibly improve preform processing (robot reach) and preform characteristics (areal density distribution) and would ensure preform and molding tool compatibility (i.e., replication of the design B-surface in both lower tools).

Revised B-Pillar Tooling

A revised preforming tool was designed and fabricated in an inverted state relative to the original B-pillar preform tooling. In the revised tooling, the 'B' surface serves as the deposition surface and the 'A' surface as the consolidation surface. This configuration would allow easier robot access to deep draw sections of the part, thereby easing preform optimization efforts and improving areal density distribution. Additionally, a relatively rigid 'B' surface of the preform (i.e., deposition surface) will allow a more precise fit in the molding tool, thereby minimizing the preform and molding tool compatibility discrepancies and subsequent shearing of the preform edge during tool closure.

The revised preform tooling (Figure 2) was received and commissioned in the preforming machine located at NCC in Kettering, Ohio, during the third quarter of FY 2004. Robotic programs were developed using offline programming software and downloaded to the machine upon receipt of the tooling. Upon completion of tool commissioning, preforming development and robotic programming optimization efforts were initiated.

Although the preform and molding tool compatibility issue has been addressed with the revised preform tooling, the inverse orientation of the deposition surface has created unforeseen issues during the material deposition process. Excessive material density now exists in 1.5-mm regions, mainly the flange regions, immediately adjacent to thicker sections of the component (4, 6, and 8 mm). Areal density sampling data indicated regions exceeding 100% by volume for the target fiber volume fraction of 40% at a 1.5-mm thickness. In

Figure 2. Revised B-pillar inner/outer preforming tool.

the inverted tooling state, the high material density required for thicker cross sections requires material to conform on outside radii. These features were previously inside radii and more forgiving to the material deposition required for thicker cross sections in the original tooling configuration. Additionally, the inherent material deposition characteristics force material to be deposited beyond the outside radii and into regions not intended, thus creating both excessive and poor material distribution. Optimization efforts are ongoing in an attempt to resolve these issues.

Conclusions for Preforming

Extensive preforming development efforts were conducted using the original B-pillar preforming tools. However, a fully optimized preform could not be realized due to several issues including inadequate material distribution and preform-to-molding-tool incompatibility. A revised preform tool was designed and manufactured to address the previously mentioned issues. This tooling has been commissioned, and preforming development is ongoing. Based upon the preforming development performed to date using both preforming tools, the results suggest that a 1.5-mm part thickness at a fiber volume fraction of 40% is extremely challenging and may be at or beyond the current process capability.

Carbon Fiber Cost Modeling

A cost modeling study on carbon fiber manufacture and the effect of increased volume and advanced technologies was carried out by Kline and Company. The three phases of the project were

1. review the existing baseline cost model from ORNL,
2. develop a cost model for increased volume production in higher capacity plants,
3. work with ORNL on the cost modeling of advanced technologies being developed for low-cost carbon fibers.

The baseline case assumes 50k PAN precursor in a 2-million lb/year plant, with a line speed of 1,378 ft/h, and uses conventional ovens for oxidation and carbonization. This shows variable costs (mostly PAN) of 55.2% of total, fixed costs (including labor, maintenance, and indirect overhead) of 29.5%, and depreciation of 15.3%, with a total production cost of $8.12/lb.

The high-volume case utilizes the same conditions as the baseline, except for a production volume of 24 million lb/year. Economies of scale decrease the total production cost to $7.00/lb, with variable costs 64% of the total, fixed costs 21.5%, and depreciation 14.5%.

For both of these scenarios, the precursor is the largest single element of the cost. Two alternative precursors that are being studied at ORNL were investigated. The modified commodity-grade PAN is not only less expensive than the baseline PAN, it also requires less residence time in the stabilization/oxidation oven. The lignin precursor is much less expensive than baseline PAN and may also have savings in the oxidation step. Adding the savings for these precursors to the high-volume case give production costs of $4.93/lb for the commodity-grade PAN, and $3.89/lb for the lignin.

The Microwave Assisted Plasma (MAP) has the advantage of reducing the carbonization time for the fibers, as well as reducing capital costs. Adding the savings from MAP to the savings from lignin, the high-volume case would have a production cost of $3.66/lb.

The use of microwave oxidation replaces the large conventional ovens with lower cost capital equipment. Combining the savings for the MAP and lignin with the microwave oxidation gives a high-volume production cost of $3.36/lb.

A summary of production cost improvements for the 2-million lb/year plant and for the 24-million lb/year plant are shown in Figures 3 and 4. The high-volume case also includes estimates for

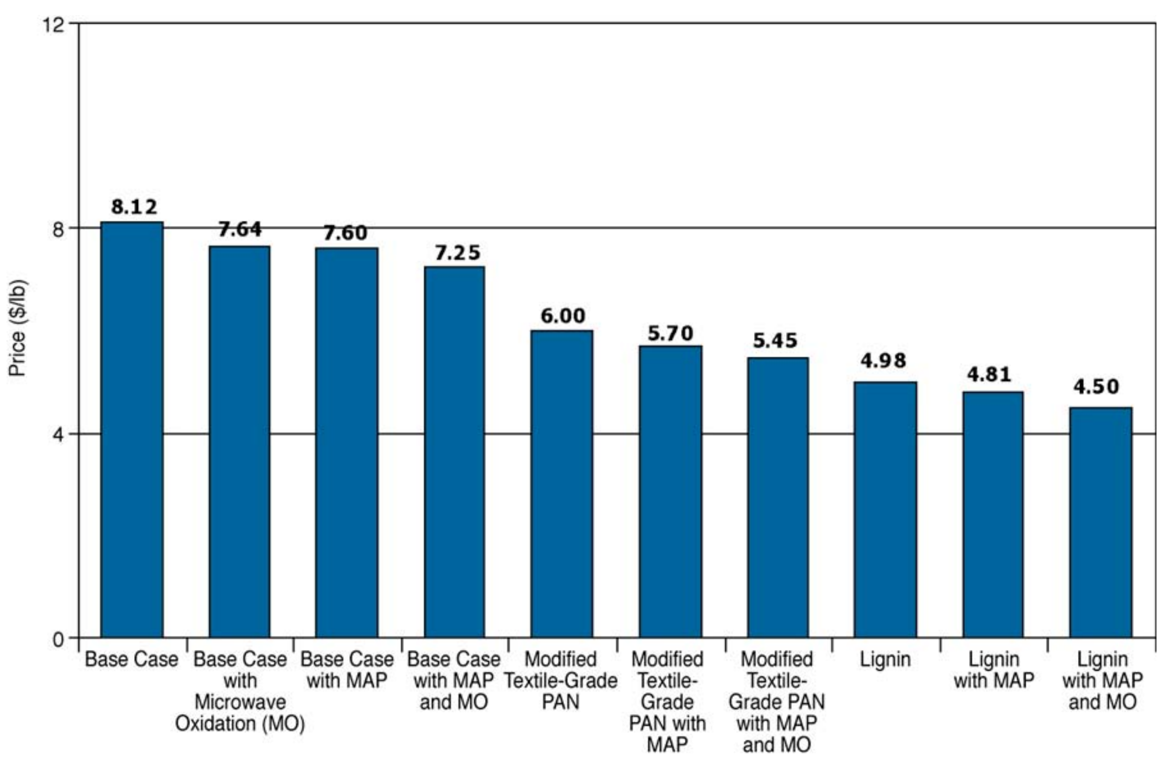

Figure 3. Summary of cost improvements for 2-million lb/year plant.

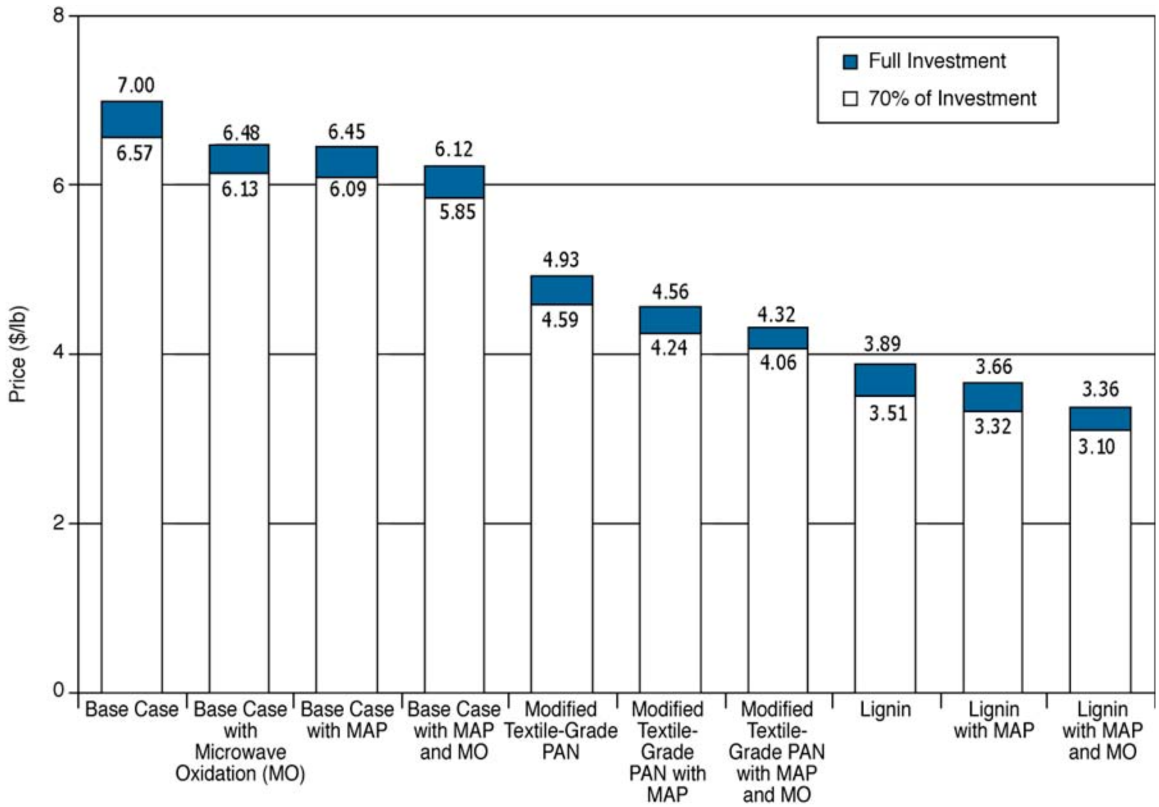

Figure 4. Summary of cost improvements for 24-million lb/year plant.

reduced capital costs (70%), which may be available due to synergies from producing multiple production lines at once. These charts show the compounding of all of these technologies, which taken together may give production costs as low as $3.10/lb.

Carbon fiber selling prices will also include costs for selling, administration, and research (SAR), as well as provide an acceptable return on investment (ROI). For the high-volume production, SAR is estimated to be about $0.20/lb. An acceptable ROI is usually 10%. Figure 5 shows that with SAR and ROI added to the production costs, the use of the lignin precursor and the alternative processing can give a selling price below $5.00/lb. Current selling prices are also included on this chart. (It should be noted that current selling prices are influenced by competitive pressures, and at least one producer is believed to be selling below cost.)

This study concluded that in order for carbon fiber to be sold profitably at less than $5/lb, the lignin precursor and the alternative processing methods will need to be used. The commodity-grade PAN may also give selling prices near the $5/lb level. As work continues on these processes, confirmation of the assumptions used in the study is advised.

Flow Modeling

Professor Suresh Advani of University of Delaware was contracted to develop a flow model for the injection-compression molding of the B-pillar. The intention was to develop and confirm a flow model, and then use this as a design tool assist in optimizing the location of the injection locations for the full-body side mold.

The starting point for this effort was the Liquid Injection Molding Simulation (LIMS) program that the Delaware team had already developed. To this was added the dynamics of the compression stage. In this problem, the resin is injected into the gap between the mold surface and the preform. Some of the resin penetrates into the preform. As the mold fully closes during compression, the resin progressively flows into the surrounding areas.

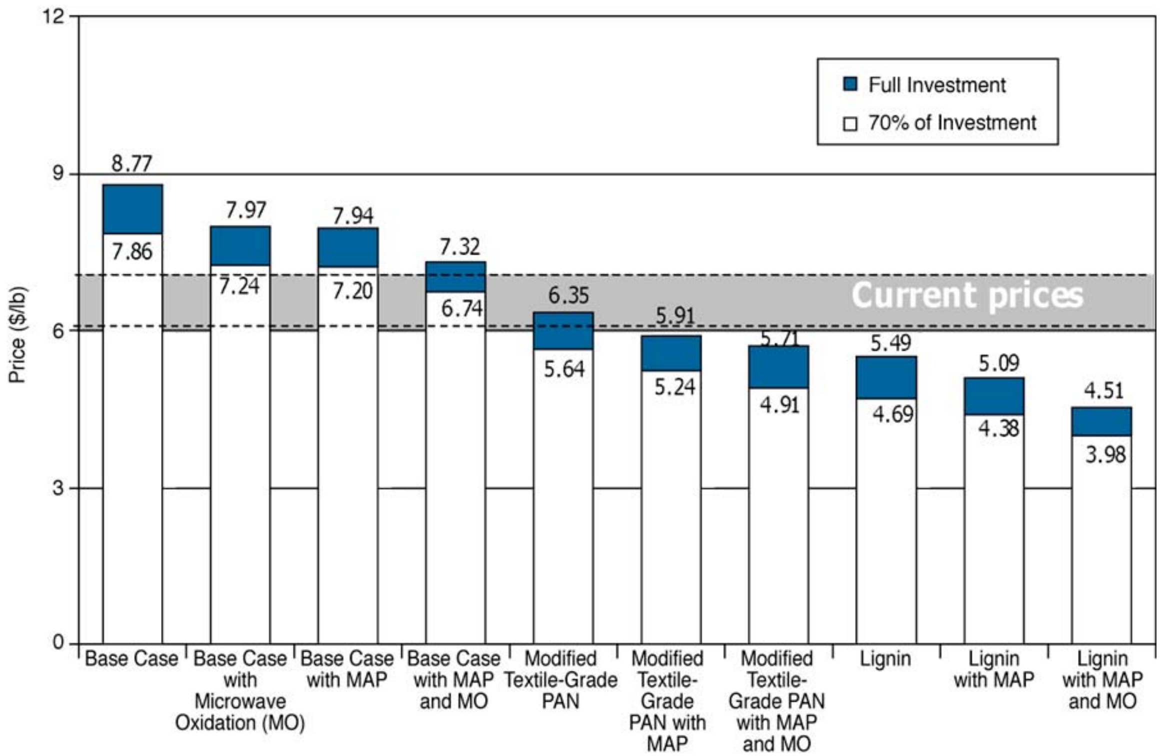

Figure 5. Estimated selling prices.

The solution approach was to model this problem in three phases. The initial phase was resin injection into the mold gap. The other phases were the initial and final compression stages and were modeled as a change in the cavity thickness and preform permeability as the mold closed.

Phase 1 is injection into the gap between the top of the preform and the mold cavity surface.

Phase 1

- Mold is stationary.
- Preform is modeled as three-dimensional (3-D).
- Gap is modeled as distribution media two-dimensional (2-D) with equivalent permeability.
- Injection conditions are as prescribed (any standard resin transfer molding option).

In Phase 2 the compression is started, and the gap above the preform closes.

Phase 2

- Mold starts closing.
- Gap thickness reduces with time, permeability changes and adequate flow source is created in filled nodes of gap.
- Preform deformation is neglected.
- Injection may be shut off.

Phase 3 is the completion of the compression stroke, with the preform being compressed into the final part thickness.

Phase 3

- Gap is closed; preform starts deforming.
- Fiber volume fraction and permeability of preform changes with time.
- Adequate flow source is created in filled nodes of gap.

This flow model did adequately represent the observed filling behavior for the B-pillar. We plan to apply it to the main fibers under consideration for the FP3 program. We intend to apply this flow model to the body side when the learnings from the B-pillar have been completed to the point that the team decides to fabricate the body side.

B-Pillar Bonding

The bonded B-pillars discussed in last year's report have been evaluated for bond quality by a pulsed thermography nondestructive test method (Thermal Wave Imaging, Inc. of Ferndale, Michigan). The part is subjected to a high-intensity, short-duration flash of light, which heats the surface of the part. The heat flow away from the surface of the part is observed with an infrared (IR) camera, and the resulting time/temperature images are evaluated, pixel-by-pixel, with sophisticated thermal image analysis tools. In this way an image is created that can show any feature of the part (subject to part thickness and flaw size limitations) that causes a deviation in the heat flow. Voids, cracks, and other flaws in the bonds can cause such deviations. Thermographic analysis was performed prior to any mechanical testing of the parts and will be performed again once the parts have been subjected to mechanical testing. In this way, we can evaluate the quality of the as-bonded parts and correlate any questionable bonded areas with any failures during the subsequent mechanical testing. Then, we can recheck after mechanical testing for any additional or new damage to the bonds. Because this technique will allow us to determine if the mechanical testing caused any visually unobserved damage to the parts, thermal nondestructive testing (NDT) has the potential to be used for in-service testing of parts and components.

The four bonded B-pillar assemblies tested in preparation for mechanical testing showed, in general, good bonds. There were only a few regions, around curves of the parts, which showed thinner than optimal bond width. This occurred because the adhesive was laid down by hand (rather than by an automated, metered dispenser). These thin bond areas might be expected to be the first to show any damage (if it occurs at all) resulting from mechanical testing.

Generic Joint Modeling

Bonded (steel hat)/(steel flat) and (carbon composite hat)/(steel flat) parts have been tested at ORNL. The results have been evaluated in terms of agreement between simulations and test results. The modeling techniques needed to obtain simulations that correlated with the observed tests were, finally, finite-element modeling in conjunction with Virtual Crack Closure Techniques (VCCT) using a continually varying loading mode with increasing load (based on measured fracture envelopes). This resulted in a predicted failure load for the steel/steel part of 8225 lb compared to an average test value of 8484 lb (–3.1% difference). For the composite hat, failure load was predicted to be 3145 lb where the average test result was 3054 lb (+2.1% difference). This excellent agreement validates this approach for predicting failure under locally mixed-mode loading conditions. A report, "Failure Analysis of Adhesively Bonded Structures: from Coupon Level Data to Structural Predictions" is in progress. This will complete the original Phase 1 of this project.

In addition, as Phases 2 and 3 have progressed, several additional modeling approaches have been investigated (and reported on, see below) and a new set of tools is being explored for ease of use in automotive applications. This new method has been entitled Element Failure Approach (EFA); by the end of calendar year 2004 it should be known whether this approach will be effective.

Publications

1. D. Xie, A. M. Waas, K. Shahwan, J. A. Schroeder, and R. G. Boeman, "Computation of Energy Release Rates for Kinking Cracks based on Virtual Crack Closure Technique," submitted to *International Journal of Fracture*, January 2004.
2. D. Xie, A. M. Waas, J. A. Schroeder, K. Shahwan, and R. G. Boeman, "Fracture Criterion for Kinking Cracks in a Tri-Material Adhesively Bonded Joint Under Mixed Mode Loading Part 1: Experiment," submitted to *Journal of Engineering Fracture Mechanics*, June 2004.
3. D. Xie, A. M. Waas, K. W. Shahwan, R. G. Boeman, and J. A. Schroeder, "Fracture Criterion for Kinking Cracks in a Tri-Material Adhesively Bonded Joint Under Mixed Mode Loading Part 2: Analysis," submitted to *Journal of Engineering Fracture Mechanics*, May 2004.