

B. Development of Next-Generation Programmable Preforming Process

Principal Investigator: Robert E. Norris, Jr.

Oak Ridge National Laboratory (ORNL)

P.O. Box 2008, Oak Ridge, TN 37831-6053

(865) 576-1179; fax (865)-574-8257; e-mail: norrisrejr@ornl.gov

Field Project Manager, Composites: C. David Warren

ORNL

P.O. Box 2008, Oak Ridge, TN 37831-6065

(865) 574-9693; fax: (865) 576-4963; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph A. Carpenter

(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov

Expert Technical Monitor: Philip S. Sklad

(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

Contractor: Oak Ridge National Laboratory

Contract No.: DE-AC05-00OR22725

Objectives

- Develop the next-generation of low-cost fiber-preforming technologies based on programmable, robotic-controlled, directed chopped-fiber processes for the application of
 - low-cost carbon fiber
 - reinforced thermoplastics
 - hybrid glass-carbon
- Develop supporting technologies required to successfully implement the process technology including
 - preform characterization (e.g., permeability, areal density uniformity)
 - perform-process modeling for process effects analysis
- Conduct parametric process studies to investigate fundamental process effects and establish process-property relationships.
- Conduct requisite molding investigations—experimental and through modeling—to elucidate relationship between preform characteristics and moldability.

Approach

- Establish a base-research, programmable, robotic preforming system for which advanced capabilities (e.g., new chopper designs) can be developed and evaluated.
- Establish a highly-instrumented and controlled research molding capability to isolate and investigate the effects of process variables on moldability and mechanical properties.
- Develop new severing technology to facilitate the implementation of low-cost-carbon-reinforced thermoplastics, and hybrid glass-carbon products.
- Benchmark and implement process modeling into experimental work to guide parameter selection and to provide tools for longer-term implementation of preforming and related technologies.

Accomplishments

- Completed construction and installation in ORNL composite laboratories of a 750-ton, intelligent-leveling research press and general-purpose experimental mold to support evaluation of preforming process advances as reflected in actual composite articles. Completion of acceptance testing and installation of this equipment fulfilled an ORNL/DOE “Critical Outcome” milestone for this fiscal year (FY).
- Completed required laboratory floor structure and utilities up-grades to accommodate the equipment as described above.
- Completed checkout and began implementation of radial-flow permeability measurement system and associated controls and data acquisition systems specifically configured for the ORNL-developed sensor system. Demonstrated consistency and repeatability of measurements that compare with literature values.
- Initiated actual experimentation to validate earlier estimated requirements to demonstrate feasibility of laser severing technology. Although initial experiments were impeded by apparent surface ionization of the carbon fiber using the parameters necessary for severing at the maximum rates envisioned, severing was demonstrated using both pulsed- and continuous-waveform laser exposure at less aggressive rates.
- Previously-developed general modeling approach was expanded to include a new algorithm that made possible quick simulation of tens of thousands of fibers, new algorithms for fast void discovery, an initial model for shaped substrate, and an initial model for mat compression.
- Obtained various combinations of fibers and binders to establish materials baselines for comparison with previous and ongoing programmable powdered perform process (P4) work (see 4.A) being conducted by the Automotive Composites Consortium (ACC) and to be used in establishing glass baseline for related permeability-test implementation.
- Initiated chopping experiments with glass tows fully impregnated with polypropylene (PP) using the Directed Reinforced Fiber Technology (DRIFT®) process and TwinTex commingled glass and PP fibers.

Future Direction

- Complete integration of injection/compression press and general purpose mold (procured during FY 2006) with associated heating system (deferred until FY 2007 due to budget reductions). Evaluate programmatic benefits versus costs and risks of refurbishing an existing injection machine for Structural Reaction Injection Molding (SRIM) to complement current focus on other molding technologies and implement if justified.
 - Conduct permeability measurements on preforms made by simulated split-tow products of varying tow size.
 - Evaluate preform process models relative to physical preform characteristics and expand model capability as resources permit.
 - Initiate preforming experiments utilizing hybrid combinations of carbon and glass fiber to evaluate potential advantages of combining these materials to achieve performance and/or economic benefits. Continue preforming studies with various product forms incorporating reinforcement and thermoplastic-matrix materials “co-processed” through the preforming machine including forms with low-cost carbon fiber as available.
 - Construct and test through-thickness permeability rig as funding and other resources permit.
 - Advance bench-top studies of advanced severing technology to determine technical feasibility of utilizing equipment that can be practically adapted and implemented for this application within one to three years. Initiate complementary investigation of cutting tribology issues to determine if alternative materials and techniques might improve variations of current severing technologies.
-

Introduction

Polymer-matrix composite materials offer a number of benefits in “lightweighting” of automotive and heavy vehicles, including greater stiffness and strength per unit weight than conventional materials, easier formability, less corrosion susceptibility, the ability to tailor properties to specific load requirements, and enhanced noise and vibration damping. However, widespread implementation of carbon-fiber composites, which offer among the greatest mass savings potential, requires lower-cost materials and processes than are currently available. Advanced preforming processes offer opportunities to facilitate the widespread use of carbon composites.

Robotic-controlled, programmable, directed-fiber preforming processes have demonstrated exceptional value for rapidly preforming large, glass-reinforced, automotive composite structures. Due to their unique features and flexibility, and to their inherently low scrap rate, they are among the most viable candidate processes for making affordable carbon-fiber preforms for a variety of structural automotive components. The ACC has implemented the P4 with glass fibers very successfully in its truck box program—Focal Project 2 (FP2). Original equipment manufacturers (OEMs) have transferred the technology to commercial applications such as the General Motors (GM) Silverado pickup box and the Aston Martin Vanquish body-side.

Analyses have indicated a potential for greater than 60% mass savings for a carbon-fiber-intensive body-in-white (BIW) under the assumption of a thickness design constraint of 1.5 mm. The analyses also indicate the potential of saving an additional 15% if the thickness constraint is reduced to 1 mm; unfortunately, evidence suggests that 1.5 mm may be a practical limit for liquid molding. However, thermoplastics preforms, in which the matrix and fiber are both deposited in the preforming step, offer a potential path to obtaining thinner sections, and consequently additional mass savings as well as greater potential for recyclability. Hybrid-fiber preforms offer another potential benefit in terms of economics and property enhancement and may be a

good route for actually introducing more carbon fiber to automotive applications.

Preforming Developmental Approach

The objective of this project is to advance directed-fiber preforming processes to effect a further reduction in vehicle mass—relative to glass-fiber composites—while maintaining the economical advantages of net-shape preforming. The project is pursuing three focus areas corresponding to three materials systems: reinforced thermoplastics, carbon fiber, and hybrid glass-carbon fiber. Each focus area consists of four main tasks concentrating on 1) materials developments, including introduction and evaluation of alternative and/or new fiber product forms and binders; 2) machine developments, particularly new severing technology; 3) process developments, for example, to control areal-density uniformity and preform anisotropy; and 4) development of supporting technologies such as modeling and preform characterization techniques. Furthermore, this project will undertake to develop sufficient understanding of fundamental aspects of the process and their effect on preform quality and mechanical properties in the molded part. As such, this project will support, augment, and facilitate the current and future research activities undertaken in related ACC projects (see 4.A and 4.D).

A preforming system, which will serve as the base for hardware and associated technology developments was completed and installed in the polymer composites laboratories at ORNL in the second quarter of FY 2005. Several combinations of fibers and binders have been obtained to establish materials baselines for comparison with previous and ongoing P4 work being conducted by the ACC and to be used in establishing glass baseline for related permeability test implementation. This machine is currently being used to build preforms for evaluation utilizing the various forms of glass reinforcement and glass fiber commingled with thermoplastic fiber to serve as the matrix. Smaller amounts of carbon fiber have been processed as well as glass impregnated with thermoplastic resin utilizing the DRIFT® process.

ORNL has been working at a low level with Polycomp (inventor of DRIFT®) and Fiberform (a

key licensee) to evaluate possibility of chopping the DRIFT® product form in the ORNL preforming machine. Polycomp made sample quantities of glass-impregnated polypropylene using a 2400 tex glass tow which had been processed into a ribbon about 0.2 inch wide and .035-inch thick. As expected, the ribbon handles more like a solid strip of plastic than a pliable fibrous tow and does not cut as easily as the glass tow, even with scissors. In initial trials, ORNL was able to get some of the material through the preformer chopper, but with only very small amounts cut before beginning to break blades in the chopper.

Plans are to make some more DRIFT® samples in FY 2007 using a smaller tow size (probably about 1150 tex, which is about the size of the current TwinTex product) in order to get a thinner ribbon. Once it has been established that the material can be rapidly chopped using the existing rotating blade configuration or one similar to that currently in the preforming machine, we will work to establish more optimum material forms and chopper configurations that might be economically feasible for implementation. Fiberform has also put ORNL in touch with a cutting equipment supplier who has developed cutting equipment for them in the past. With related equipment experience provided by the supplier, we will be able to better address alternative means for processing the DRIFT® materials form.

Procurement of a Press and Mold for Composites Evaluation

Key to being able to demonstrate the advances achieved in preforming technology is the ability to demonstrate that these advances translate into improvements in actual representative composites. The best way to effect this demonstration is through adequate evaluation of the preform itself as well as full consolidation of the preform and resin in a composite in the manner in which this would be accomplished in actual composite manufacturing.

During the last fiscal year, efforts were initiated to identify the most appropriate equipment necessary to do this on a research basis. ORNL staff worked with members of the ACC's Processing Group to quantify process equipment requirements and initiate activities necessary to procure a research

press, general purpose mold, and injection machine. These requirements were turned into formal requests for quotes (RFQs) for designing and building these systems, which were issued to companies that had been identified through ORNL and ACC interactions as having potential to meet or exceed all performance targets. The intelligent-leveling press was specified to accommodate various molds and molding processes and to be instrumented above routine standards in order to provide more process details in experimental research. Nominal pressing capacity is 750 tons. The general-purpose plaque mold is specified for instrumented experiments using SRIM, compression molding of reinforced thermoplastics, and sheet molding compound (SMC) processes. This equipment will allow ORNL to demonstrate preform advances while further investigating advances in the various molding processes themselves.

During FY 2006, the bid package reviews for the press and mold were completed and formal contracts placed with Williams White of Moline, Illinois, for the press and Service Mold of Windsor, Ontario, for the mold. Although originally a portion of this process, procurement of an injection machine has been deferred due to higher than expected bid costs and less current focus on the SRIM process. Programmatic benefits for utilizing an existing, older model SRIM machine having capacities close to those identified as targets for the procurement process are being evaluated versus costs and risks for possible refurbishment and upgrade to employ when SRIM capabilities are needed. Acceptance testing for the mold was conducted at a test facility contracted by Service Mold in Windsor, Ontario, in May while acceptance testing for the press was conducted at Williams White in June; both activities were supported by ACC representatives. Although minor issues were observed during the testing of both pieces of equipment, in general, the reviews were considered quite positive and shipment to ORNL upon implementation of minor adjustments was authorized for both. After completion of these adjustments, both press (Figure 1) and mold (Figure 2) were shipped to ORNL and installed in July and August.



Figure 1. Intelligent-leveling, 750-net-ton, Williams White injection/compression press installed in ORNL composite processing laboratory.

As part of planning for installation of the press in the ORNL composites laboratories, an engineering study was conducted to determine structural needs for operation of the new equipment. Although the facility was originally designed to accommodate heavy processing equipment, this particular press presents a loading scenario that is larger statically and significantly larger dynamically than the equipment envisioned when the facility was designed. Beyond structural capacity, vibration from the dynamic loading to the floor was a major

concern due to highly sensitive equipment in the vicinity. Accordingly, the engineering study determined that the floor needed to be reinforced well above current capacity. Adding supporting members to the existing floor was determined to be impractical structurally and other modifications would also be necessary for the vibrations. The result of this study is the design of new flooring to accommodate the press which required tear out of the existing floor and excavation to nearby bedrock. The floor was replaced by an isolated structural base



Figure 2. General-purpose flat-plaque mold for SRIM, SMC, and thermoplastics.

and new three-foot concrete slab as shown in Figures 3 and 4. In addition to the structural modifications, necessary utilities were provided to the new equipment as part of this activity.

Due to budget reductions during FY 2006, plans to procure and install a heat-transfer system for the mold have been deferred until FY 2007.

Permeability Measurements

It has been found that injection-compression offers distinct advantages over injection-only liquid molding for the infiltration of high-volume-fraction preforms. Both the in-plane permeability and the through-thickness permeability affect the moldability of the part. Accordingly, development of two novel research instruments was commissioned in order to provide experimental data to characterize the three-dimensional permeability of the fiber-mat preform.

During this fiscal year, work on the development of the in-plane rig (see Figure 5) with a flow capacity of 0.33 gpm and a fluid capacity of 2 gallons was completed and checkout testing conducted. The test rig can be operated in either constant-flow or constant-pressure mode under feedback control. Maximum pressure and fluid viscosity are 100 psi and 5 poises, respectively. Both platens are

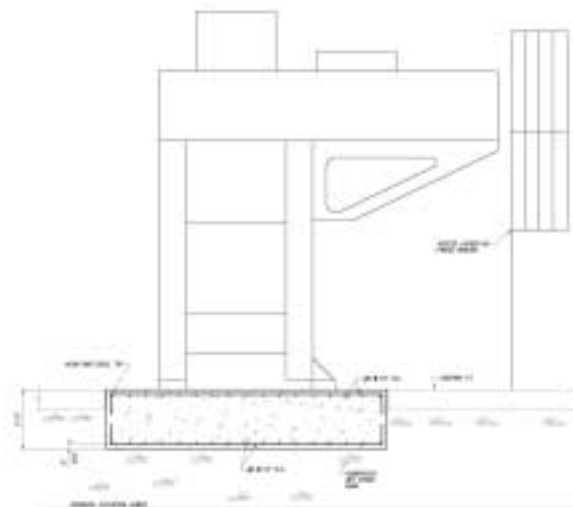


Figure 3. Floor up-grade required to accommodate ORNL press.



Figure 4. Site preparation for press installation.

instrumented with sensors—a total of 218 sensors—to monitor the flow-front with resolution of 0.25 in.

A data acquisition and control system was developed by ORNL based on National Instruments' PXI hardware and LabVIEW software.

Stand-alone program modules have been written to evaluate sensor performance, to conduct the permeability experiments, to analyze the collected data and calculate permeability value, and to review the experiment at reduced speed. The modules that



Figure 5. Radial-permeability test rig showing associated data acquisition and monitoring station.

monitor the sensors have been developed for both conductor and thermocouple-based sensors evaluated for this rig.

An analysis module that takes the elliptical flow front and calculates the in-plane components of the permeability sensor has been developed from expressions provided by Professor Richard Parnas. Full characterization of the analysis module has now been completed following resolution of sensor reliability and accuracy issues and a variety of preforms are currently being evaluated. Consistency and repeatability of measurements that compare with literature values has been demonstrated with standard commercially available preform materials (Figure 6). Characterization of permeability for developmental preforms versus process parameters is being conducted as materials and resources permit. A limited amount of testing has also been conducted on some natural-fiber preforms fabricated by a small business under a DOE Small Business Innovative Research (SBIR) grant as shown in Figure 7.

A through-thickness rig has also been designed and fabrication of a portion of the hardware has been completed. Maximum pressure and viscosity are the same as the in-plane rig. Due to the change in focus and budget reduction, resources have been redirected and further development and implementation of this system deferred.

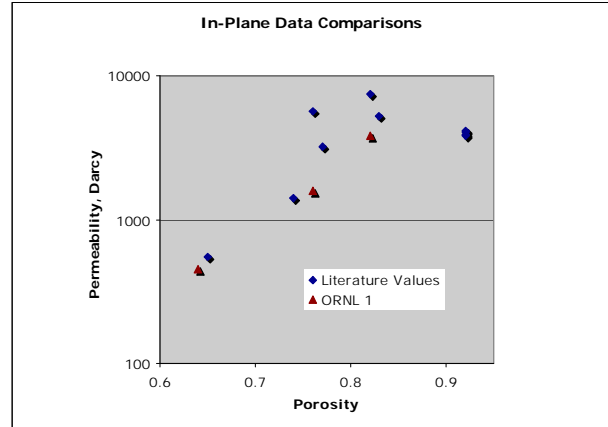


Figure 6. Permeability test data showing comparison with various continuous- strand mats.

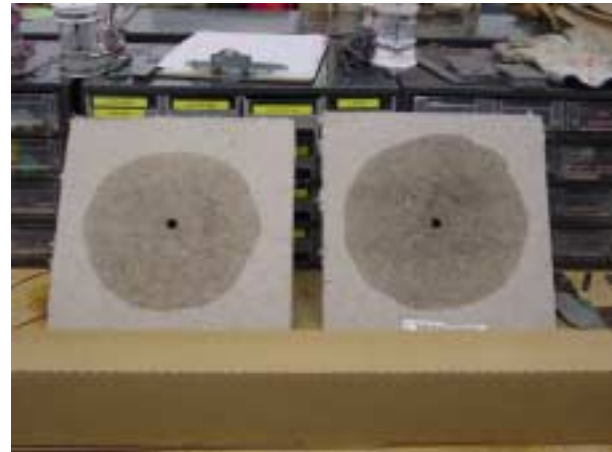


Figure 7. Natural-fiber preforms tested for a SBIR partner.

Fiber-Severing Technology

Due to significant differences in the physical properties of various reinforcement fibers as well as their available product forms, chopping technology that has been successful for glass fibers systems has demonstrated less-satisfactory results for the carbon-fiber products that are currently available. It is expected that similar results will occur for reinforced thermoplastics and hybrid glass-carbon products. Accordingly, consideration is given in this project to identifying alternative severing technology. A literature and patent search was undertaken to assess promising technologies for bench-top investigation. Possibilities identified include mechanical-based, laser-based, CO₂ pellet, liquid nitrogen, water-jet, and ultrasonic. Based on the information available in the literature and

consideration of project-team experience in related activities, laser-based choppers appear to offer the most promise.

During this period, initial effort to identify laser types and projected power levels required to sever carbon-fiber tows in sizes close to those likely to be employed in performing, was expanded to actually demonstrate the potential for laser severing. A neodymium:YAG laser system was set up in the laboratory and experiments with a carbon-fiber tow were conducted at the bench-scale to evaluate feasibility. Calculations based on the enthalpy of vaporization of carbon indicated that the laser identified for this work should be able to comfortably deliver the energy required to sever a large carbon-fiber tow (roughly 50,000 filaments) at about 1,000 cuts per second, which would represent a tow traveling at close to the maximum velocity as would be encountered in the ORNL chopper and chopped at a rate sufficient to yield a 0.5-inch cut length. Initial trials were conducted using laser-processing parameters thought to be representative of pulse time length, pulse physical shape, and delivered energy required to sever at this rate. However, at these conditions, we were unsuccessful in getting the necessary power delivered into the entire fiber bundle to effect severing. It appeared that the surface of the outer fiber ionizes and prevents further energy deposition and penetration into the bundle. Additional experiments were conducted with this same laser using a variety of laser power levels and with alternative environmental conditions to determine if the "ion cloud" could be mitigated by immersing the fiber with different inert gases or if the cloud could be quickly dispersed by a large flow rate of these gases being drawn across the fiber at the point of laser impact. Again, these efforts were unsuccessful in producing more than minimal severing of the outer fibers.

In order to determine if laser severing might be possible at somewhat different regimes that might not match our aggressive requirements directly, but possibly still adaptable to work in this area, we conducted experiments using a continuous-wave CO₂ laser as well as an excimer laser and a more tunable (and slower pulse rate) neodymium:YAG laser. With all three of these systems, we were able

to demonstrate severing of carbon fiber, although none has yet been accomplished at the rates described above, which would be representative of the most aggressive cases we had thought possible with the original neodymium:YAG laser. At the time of this report, we are continuing work with the more tunable neodymium:YAG laser as its associated operating environment offers us the most flexibility in terms of controlling the process and more thoroughly investigating the cutting mechanisms we have encountered.

If successful with one of the alternative systems, these results will be utilized to define the more-detailed laser parameter and control requirements in order to be able cleanly sever a moving carbon-fiber tow at the speeds required for utilization in the P4 system. Initial work will continue to be done in static tests to determine beam width, power levels versus time, and other necessary information before moving to low-speed tests, and then tests at speeds more representative of actual fiber deposition rates. With this background, plans are to then scale up the hardware for on-machine experimentation and demonstration. In addition to severing carbon fiber, future work will address other reinforcing fibers, as well as fibers used as binders, and blends of reinforcing and binder fibers.

ORNL plans to continue initial evaluation of laser severing and to initiate a more basic study of mechanical chopping in FY 2007 for various materials forms. It has been mentioned earlier that plans are being developed to evaluate modifications to the chopper equipment with respect to processing the DRIFT® materials. With a better understanding of chopping mechanics and developing experience with varying blade designs, blade materials, and cutting mechanisms, we will be able to better address a variety of cutting issues associated with carbon fibers specifically as well as with other materials and material blends.

Modeling of Fiber Deposition

A C-based program is under development to analyze the effects of process variables on preform characteristics. The program will be used to evaluate preforms in terms of measures such as fiber run length, fiber connectivity, distribution of voids, etc.

When correlated with permeability data and areal-density measurements, the program will provide an understanding of the effects of process variables on resulting preforms and their “moldability.” Recent advancements to the program have included continued enhancement of the previously-developed general modeling approach by addition or improvement of many of the capabilities. Examples of these enhancements include correlation of processing parameters with density variations, and improved models for fiber deformation. Work is in progress towards mat compression, consolidation, surface roughness, models for fiber splitting, tow fiberization, deposition variations, and deposition on variable geometry substrates. Also underway is conversion of the model to more widely available platforms to facilitate more widespread utilization and correlation with processing experience. A core portion of this model has been ported for internal evaluation. Further development of the model will be continued as program data are available to support model expansion and verification.

Summary and Conclusions

The Development of Next-Generation Programmable Preforming Process effort will continue to build on past development and application of directed-fiber preforming processes, namely, those of the P4, to extend the process to new material systems. Developments are expected to facilitate the use of low-cost carbon fiber, reinforced thermoplastics, and glass-carbon hybrid materials as effectively as is the current state-of-the-art with glass. Utilizing these materials is expected to lead to further reductions in vehicle mass in a more cost-competitive scenario than is currently possible. A preforming system, which will serve as the base for hardware and associated technology developments, was completed and installed in the polymer composites laboratories at ORNL in the second quarter of FY 2005. This machine is currently being used to build preforms for evaluation utilizing various forms of glass reinforcement and glass fiber commingled with thermoplastic fiber to serve as the matrix. Smaller amounts of carbon fiber have been processed as well as glass impregnated with thermoplastic resin utilizing the DRIFT® process.

Also during FY 2006, fabrication and installation of a complementary advanced research press and general-purpose plaque mold were completed providing the requisite equipment necessary to demonstrate the advances achieved in preforming technology through actual experimental composite manufacturing.

Development has been completed and testing is in progress utilizing a novel permeability rig designed to characterize the preforms resistance to in-plane resin flow during the molding process.

Initial fiber-severing experiments were conducted utilizing a neodymium:YAG laser system set up in the laboratory for static cutting of a carbon-fiber tow. Although initial trials were unsuccessful in severing carbon fiber at all using a laser system and process parameters that had been estimated as meeting the most aggressive of project requirements, subsequent trials using three alternative systems have demonstrated that carbon fiber can indeed be severed via laser exposure. Additional experiments with these alternative laser systems are being conducted to determine beam width, power levels versus time, and other necessary information representative of actual fiber-severing requirements for preforming and related processes.

Modeling of the fiber-deposition process continues through the development of an in-house code. The program will be used to evaluate preforms in terms of measures such as fiber run length, fiber connectivity, distribution of voids, etc. Results will be correlated with permeability data and areal-density data to assess the effect of process parameters on preform quality as well as the mechanical properties of molded parts. Work is underway to provide availability of the model to operate on a standard desktop “Windows” platform and a core portion of this model has been produced for internal evaluation.

Collectively, the technology under development in this project will advance low-cost processing on two fronts. First, it will provide the opportunity to employ additional materials in the net-shape preforming process, which is expected to lead to additional mass reduction and/or better performance. Second, it will provide the requisite

tools to evaluate the effect of process parameters on the utility and performance of preforms and molded parts.