

## Feature Project

### Experimental Analysis and Computer Simulation of Pultrusion and Resin Injection Pultrusion (RIP) Process by Zhongman Ding and Shoujie Li (Lee)

The objective of this project is to establish the relationship among materials, process, and composite properties by conducting a systematic experimental study and to develop a computer simulation code for the optimization of the RIP process.

#### Simulation

Darcy's law is employed as the flow governing equation, with consideration for the moving speed of the fiber. Variations of porosity and permeability in the taper portion of the injection die are also taken into account. The compressibility and permeability of both fiber mats and fiber rovings have been measured and modeled in a way that various fiber materials and stacking patterns can be analyzed. The reaction kinetic model for the resin system was determined by DSC.

Fig. 1 shows the transition process of resin impregnation during the start up of the RIP process. The flow front position is determined when the pressure flow caused by resin injection is balanced with the drag flow caused by the moving fiber stack. Pressure distributions along the injection die at different injection pressures and the influence of the taper angle

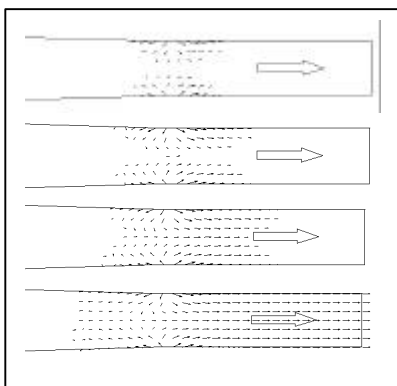


Figure 1. Transient velocity field of resin flow during start up.

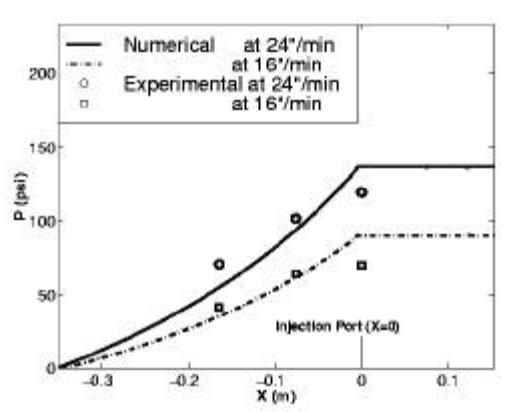


Figure 2. Pressure distribution along the injection die for different line speeds.

of the injection die on the process have been investigated. Heat transfer and resin curing in the pultrusion die have also been simulated to provide information, such as temperature and degree of cure distributions along the die.

Computer simulation is compared with experiments carried out at Dow Chemical, Freeport, TX. Three pressure transducers were used to measure the pressures along the injection die and at the injection port. The computed pressure distributions are compared with the experimental data for two different line speeds as shown in Fig.2.

#### Experimental

A series of injection-pultrusion experiments were carried out at Dow Chemical Laboratory with Herbert Engelen and Mac Puckett. The pultrusion line has the capacity of measuring temperature and pressure profiles along the die, and the pulling force. Three types of dies are available, i.e. high injection pressure, low injection pressure, and conventional pultrusion. Figure 3 shows typical experimental results. At

the same line speed, the pulling force for a pure vinyl ester resin is much larger than that of the same resin with 40 pbw of fillers, although the former has a much higher viscosity.

#### Future Work

High pulling force, limited line speed, part blistering, and cracking are the major concerns of the pultrusion process. In our future study we will investigate the origin and magnitude of these issues as a function of die geometry, resin formulations, additive type/concentration, fabric type, and fiber content.

For simulation, we are currently developing a PC based code with a user-friendly interface. We will extend the model to include resin shrinkage/expansion and composite-die surface friction in order to predict the pulling force. For more complex profiles, 3-D flow simulation and die heat transfer analysis will be implemented. We'll also compare simulation results with more experiments at both Dow Chemical and the CAPCE Composite Processing Lab.

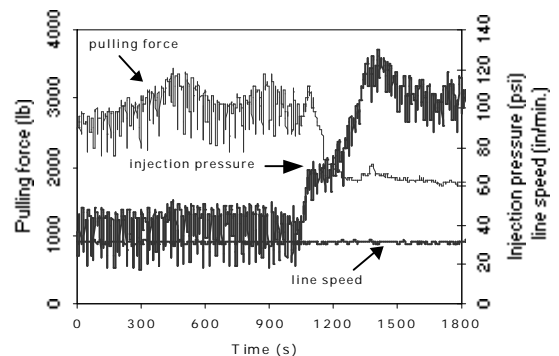


Figure 3. Pulling force changes with/without filler and slip-stick phenomena.

## Analysis of SCRIMP and Low Temperature Cure of Unsaturated Polyester Resins

by Huan Yang (Lee)

Seemann Composite Resin Infusion Molding Process (SCRIMP) has been investigated in our laboratory in recent years. We have explored mold filling and curing processes through a series of experiments including flow visualization and SCRIMP molding. A computationally-efficient simulation code based on a leakage flow model was developed to predict both mold filling time and flow pattern during filling. A kinetic model in conjunction with a heat transfer model was also developed to simulate the SCRIMP process (see CAPCE Report T-98-02). Unsaturated polyester and vinyl ester resins are the two major resins used in SCRIMP today. We are currently compare the resin moldability and properties of SCRIMP molded composites based on these two kind of resins. Effects of resin type, initiator, promoter, inhibitor and retarder on the resin kinetics, chemorheological changes and resin shrinkage are being studied using DSC, RDA and dilatometry respectively. The surface quality of the molded samples is measured by a profilometer and mechanical properties of the samples are compared by tensile test and dynamic mechanical analysis.

## Tackification and High Temperature SCRIMP Based on Textile Fiber Preforms

by Chih-Hsin Shih (Lee)

Tackifier application, preforming and mold filling of tackified fabrics, and mechanical properties of molded composites based on PR500 resin were studied. It was found that both the elastic modulus of the tackifier (depending on degree of cure) and the tackifier location in the fabric play important roles on preform dimension control, preform integrity, preform permeability, and fiber wetting. These two variables are governed by tackifier concentration, powder size, temperature history during tackifier application, and preforming. If most of the tackifier is located inside the fiber tows, it could increase the permeability of the fiber preform significantly. However, it also results in more voids. We are currently studying how tackification affects the void formation

and removal in the fiber preform during mold filling, as well as its effect on the mechanical properties of molded composites. We also plan to apply the tackification technique to high temperature SCRIMP for aerospace applications. The major challenge there is to produce net-shape preforms with high fiber content (~60% by volume).

## Fiber Wetting in SMC Formation

by Shoujie Li (Lee)

The purpose of this study is to better understand how material variables (e.g. type of fiber roving, fiber content, resin paste composition, extent of paste thickening) and process conditions (e.g. ambient temperature and humidity, compaction roll design) affect the formation of dry fibers, porosity, and blisters. From this study, we may propose measures to minimize such defects in SMC molding.

Wettability characterization of selected fiber rovings was carried out by measuring the critical surface tension of each roving using a Zesman Plot. It was found that fiber rovings with different tow size have roughly the same critical surface tension, i.e. 35 mN/m, similar to the polyester resin. This means that the fiber rovings studied are all wettable. However, the tow size from the same lot varies quite significantly, which may affect the rate of wetting. The high viscosity of the resin paste may also affect the fiber wetting dynamics. We are currently measuring the dynamic surface tension of resin pastes using a bubble tensiometer (SensaDyne PC500). The results will be correlated with the rheological behavior of the pastes. To better understand the fiber wetting mechanism in SMC formation, we are also studying the fiber impregnation process under both compression and kneading modes using flow visualization techniques.

## Binder Application and Injection-Compression Molding Based on Directed Fiber Preforming

by Ling Li and Travis Horstman (Lee)

Effects of binder emulsions and fiber rovings on the preform permeability, fiber wettability, and preform integrity have been investigated in our laboratory. Our current effort focuses on the following three areas: 1) An in-depth analysis of the

interfacial reaction between fiber-binder-resin matrix using an FT-IR microscope with an ATR set-up. We are studying compatibility of different fiber rovings with selected binders, as well as compatibility between binders and resins. Development of new binders is being carried out with several CAPCE members. 2) A study of binder cure, water evaporation, and preform integrity during preforming. We are investigating how preform thickness, fiber type and content, and heating conditions affect the interaction between mass transfer (i.e. water evaporation) and reaction kinetics (i.e. binder cure) during preforming, and how the properties of cured binder affect the preform integrity. 3) An investigation of mechanical properties and void content in injection/compression molded composites. We are studying the mold filling pattern, the void formation/transportation/dissolution mechanism, and the mechanical properties of molded composites under various process conditions (i.e. pure injection, injection-compression, and hand-pour compression) with fiber preforms made by different fiber rovings and binder concentrations. We will also correlate in situ measurements (i.e. pressure in the mold and compression speed) with void content and composite properties, in order to develop on-line process control strategies.

## Shrinkage Control of Unsaturated Polyester Resins Cured at Low Temperature

by Xia Cao (Lee)

The shrinkage control mechanism of UP (unsaturated polyester) resins with several commercial LPAs (low profile additives) cured at low temperatures was established from an integrated rheology-morphology-dilatometry-surface characterization study (see CAPCE Report T-98-01). Based on experimental results, we are exploring methods to improve shrinkage control in low temperature processes. One method modifies commercial LPAs by adjusting their compatibility with resins and curing agents. Encouraging but limited success has been found so far. The second method adds multifunctional secondary monomers. Preliminary results showed significant reduction of resin shrinkage at low temperatures. We are also evaluating other commercially available LPAs through collaboration with CAPCE members. ■