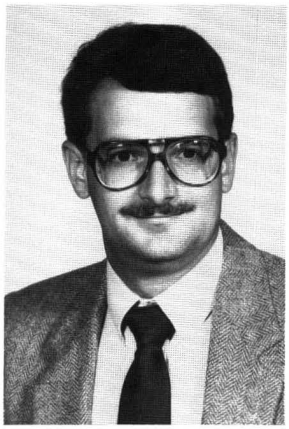
Research on . . .

ADVANCED ENGINEERING FIBERS

DAN D. EDIE, MICHAEL G. DUNHAM
Clemson University
Clemson, SC 29634-0909

A NEW GENERATION of composite materials is revolutionizing today's aircraft and automotive industries [1]. In applications ranging from the globe-circling Voyager aircraft to truck drive shafts, composites are demonstrating properties which are superior to traditional materials. In aircraft applications where weight, strength, and stiffness are critical, many structural components are now made using graphite/epoxy composites. Looking ahead, approximately half of the structural weight of the Air Force's advanced tactical fighter will be composite materials. Composites of glass and carbon fibers surrounded by epoxy and polyester are being increasingly utilized in automobile structure applications. Although U.S. auto production in 1986 fell 3.7% from the 1985 level, composites shipments to the industry rose 3.0%, reaching 585 million pounds [2]. The high-temperature strength and stability of fiber reinforced ceramics offer the promise of more fuel efficient engines in tomorrow's automobiles. In the future, plastics, metals and ceramics reinforced with graphite, glass, aramid, and other fibers will replace much of the metal in aircraft and automobile structures.



Dan D. Edie is professor of chemical engineering and co-director of the Advanced Engineering Fibers Laboratory at Clemson University. He received his BS degree from Ohio University and his PhD degree from the University of Virginia. Before joining Clemson he was employed by NASA and the Celanese Corporation. His research interests include rheology, polymer processing, high-performance fibers and composite materials. **(L)**

Michael G. Dunham, a PhD student in chemical engineering at Clemson University, received his BS degree from Clemson in 1980. Prior to returning to pursue an advanced degree, he served in a variety of technical and supervisory positions with the DuPont Company. In his research he is using mathematical modeling to study the stabilization and carbonization of carbon fibers. **(R)**

In a composite, a structure of fibers provides strength and stiffness, and these fibers are held together by a matrix material. The result is that the properties of a composite material can be exactly tailored to fit the structure. For example, if one end of the structure is under a higher load, more fibers (or higher strength fibers) can be added to that end of the composite structural member.

A composite for use at moderate temperatures normally consists of high-strength carbon or polymeric fibers encased in a plastic matrix. Higher temperature applications may require either carbon or ceramic fibers to be embedded in a metal, ceramic, or carbon matrix. The fiber and matrix are carefully selected to provide the best composite properties for the particular application.

CHEMICAL ENGINEERING'S ROLE

Composite materials represent a major growth market for the chemical industry. In the future, chemical companies, rather than metal producers, will be the major raw material suppliers for the automotive and aircraft industries. Even commercial building and highway construction may utilize significant amounts of composite materials. Since the processing, development, and production of polymers has been an important part of chemical engineering for the last thirty years, research into the new high-strength fibers and matrix polymers is a natural extension. New research and development challenges in the fibers area include

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- **Continually upgrading manufacturing processes for the fibers to improve properties and to reduce cost. Chemical engineers in industrial research have recently developed new processes to produce the precursors for many types of ceramic, carbon, and graphite fibers.**
- **A number of new high-performance fibers have been developed which are made from polymers as complex as polybenzimidizole and as simple as polyethylene. Chemical engineers must develop and design processes to produce these fibers on an economic commercial basis.**

The polymer matrix materials are undergoing dramatic improvements. New polymers designed for improved toughness, temperature stability, and melt processability are being developed by a number of firms. Chemical engineers will be principally responsible for developing the processes used to produce and utilize these polymers.

Another major role for chemical engineers involves the fabrication of the composites themselves. Today, most advanced composites are made by manually laying up layers of matrix coated fibers or by winding the fibers into the desired shape. These expensive, labor-intensive processes limit end uses to very high value-in-use applications. The application of chemical engineering principles to the development of automated processes for these fibers, such as weaving, braiding, or the production of non-woven fabrics, will dramatically lower the cost of these materials. These automated processes require that future reinforcing fibers be less brittle and have improved finish coatings. Other processes such as thermoforming, injection molding, and pultrusion are also being explored by chemical engineers in order to automate composite manufacturing.

CLEMSON'S ADVANCED ENGINEERING FIBERS LABORATORY

To address these challenges, Clemson established the Advanced Engineered Fibers Laboratory in August of 1986. The laboratory's purpose is to provide national leadership and expertise in developing the processing equipment and advanced fibers necessary for the chemical, fiber, and textile industries to enter the composite materials market. Since the problems encountered are often too complex to be solved by a single academic program, the contribution of each of the fields involved in the laboratory is critical. Researchers in chemical engineering, textile science, polymer chemistry, mechanical engineering, and ceramic engineering all interact in laboratory research projects. The laboratory also offers technical and educational support to the fiber, textile, and composite materials industries.

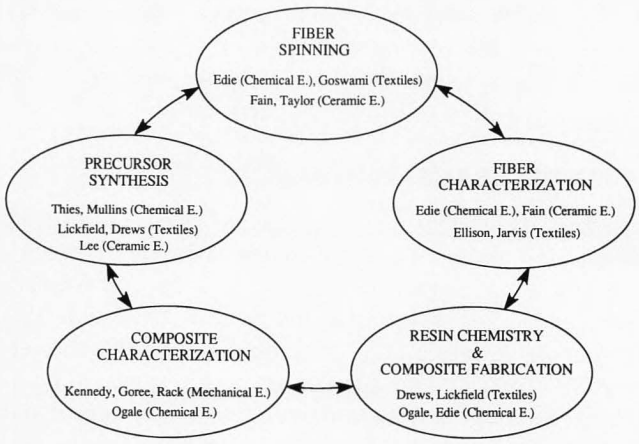

FIGURE 1. Advanced Engineering Fibers Laboratory areas of emphasis. Faculty from four academic departments participate in this unique research effort.

Many universities study composite materials. However, this research effort has typically focused on the analysis, fabrication, and mechanical evaluation of the composite. Clemson's Advanced Engineering Fibers Laboratory is unique in that its efforts are directed toward the high performance fibers and matrix polymers so critical to composite materials. Research on these fibers, the matrix polymers, and their fabrication into textile structures using automated equipment is being coordinated by the laboratory. The laboratory conducts research in six primary emphasis areas

- **The chemistry of engineering fiber precursors**
- **Fiber formation and processing**
- **Characterization of engineering fibers**
- **Fabrication of three-dimensional textile structures**
- **Composite material characterization**
- **Process economics and information transfer.**

Figure 1 lists the faculty who are participating in

ongoing laboratory projects. It also indicates the interrelationship of the various research areas. For example, improvements in fiber formation processes require an understanding of precursor chemistry, an ability to characterize the resulting fibers, the fabrication and testing of the fibers in composites, and the assessment of the process economics. This gives the laboratory the unique ability to study high performance fibers from the chemical precursors through their application in composite structures.

CURRENT ChE RESEARCH PROJECTS

The Department of Chemical Engineering at Clemson has had an active and well-funded research program in polymer processing and fiber formation for years. The establishment of the Advanced Engineering Fibers Laboratory has augmented this effort and provided an increase in both internal and external funding for this important area of chemical and materials research. Numerous research projects are

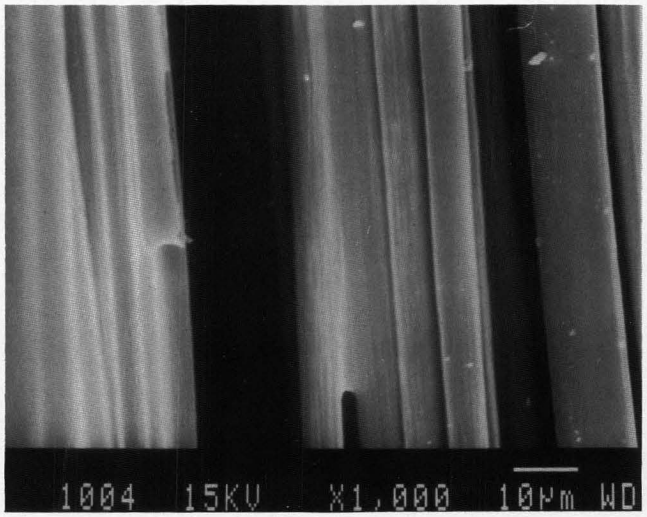

FIGURE 2. An electron microscope photograph of carbon fibers coated with LaRC thermoplastic polyimide. The electrical resistance of the carbon fiber is employed to melt the thermoplastic matrix material.

underway in the laboratory and the following are brief descriptions of several typical studies being carried out by chemical engineering graduate students.

Coating of Carbon Fibers with Thermoplastic Polymers. A novel process for coating carbon fibers with thermoplastic matrix materials is being developed. A polymer powder is applied to the carbon fiber and then melted by utilizing the electrical resistance of the carbon fiber itself [3]. An electrical potential is applied across a length of the fiber. This heats the fiber to a temperature higher than the melting point of the thermoplastic matrix and results in flow of the polymer throughout the fiber bundle. This technique is currently being used to apply new high-temperature matrix polymers such as LaRC thermoplastic polyimide (developed by NASA) and polyetheretherketone (developed by ICI) to carbon fibers. These tough matrix polymers have been specifically developed for aircraft applications. The polymer coating allows the brittle fibers to be readily woven or braided into a fabric which can be thermoformed into a composite material. Figure 2 shows an electron microscope photograph of a bundle of carbon fibers coated with LaRC thermoplastic polyimide using this technique.

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Modeling of Heat and Mass Transfer in Carbon Fiber Manufacturing. Two of the most important steps in the manufacture of carbon fibers are stabilization and carbonization of the precursor fibers. Each of these steps involves high temperature and exothermic reactions which produce gaseous products. In order to better understand these processes and predict optimum conditions, an effort is underway to model these two process steps. The equations of heat and mass transfer are applied to each process step and solved simultaneously with equations describing the reaction kinetics. In order to accurately describe the reacting system, it is also necessary to determine several physical constants such as diffusivities and thermal conductivities as well as heat and mass transfer coefficients. Current work is directed toward understanding the reaction kinetics and measuring these constants and coefficients by a variety of experimental methods.

Non-Circular Carbon Fibers. Chemical and ceramic engineers at Clemson have developed a process for the production of non-circular carbon fibers by melt spinning mesophase pitch. The shape of the fibers has been found to dramatically affect the properties of the resulting composites [4, 5]. The goal of the current research is to improve the toughness of the fibers and resulting composites and to better understand the novel fracture mechanisms of non-circu-

lar fibers. Tougher fibers are needed if composite fabrication is to be automated to produce the inexpensive composite materials required for automotive applications. Figure 3 is an electron microscope photograph of a C-shaped fiber produced in this research.

Aging Characteristics of High Temperature Thermoplastic Composites. One of the most important trends in composites is toward tough, high temperature thermoplastics to replace the thermosetting polymers currently used as matrix materials. The proper design of composite materials which use these new thermoplastics will require more than the limited physical data presently available. Clemson chemical engineers are studying the effect of aging on composites of high temperature thermoplastics such as PEEK (polyetheretherketone) and carbon fibers through dynamic testing on a Rheometrics spectrometer. The loss modulus, a measure of the composite's ability to absorb energy, goes through a minimum at a certain frequency of the applied load. The effect of time, temperature, and composite processing history on this minimum are being studied. It is expected that this work will describe the high temperature limits of the material and provide important physical data to the composites industry.

THE LABORATORY'S ROLE IN EDUCATING CHEMICAL ENGINEERS

The laboratory offers no courses or degree programs. Instead, it complements the existing degree programs. The laboratory provides a mechanism for students and faculty to interact with other engineering and scientific disciplines. This is of increasing importance as chemical engineers enter new areas such as composite materials where polymer processing, fiber physics and mechanics, as well as chemical engineering principles, must be applied to solve process problems.

This interdisciplinary environment has long been used by companies for research, design, and process assistance. Normally, a variety of engineering and scientific fields are represented on industrial research and design teams. The laboratory exposes chemical engineers to a similar environment and permits the synergism which can be achieved as students and faculty with different backgrounds and skills work together to solve a problem.

The laboratory also provides a mechanism for sharing experimental facilities among four departments which are located in five buildings on the Clemson campus. This is important as equipment becomes more expensive and requires more expertise to operate. It provides chemical engineering students the opportunity to become familiar with processes as diverse as fiber spinning, composite characterization, and polymer spectroanalysis.

SUMMARY

Clemson's Advanced Engineering Fibers Laboratory provides a unique interdisciplinary environment for the study of high performance fibers and matrix polymers from their precursor chemicals to their final application in composites. The interaction provided by the laboratory provides chemical engineers with an opportunity to explore other engineering and scientific approaches in solving problems. At the same time, the laboratory itself benefits from the traditional ability of chemical engineers to solve problems by utilizing ideas obtained from a number of sources.

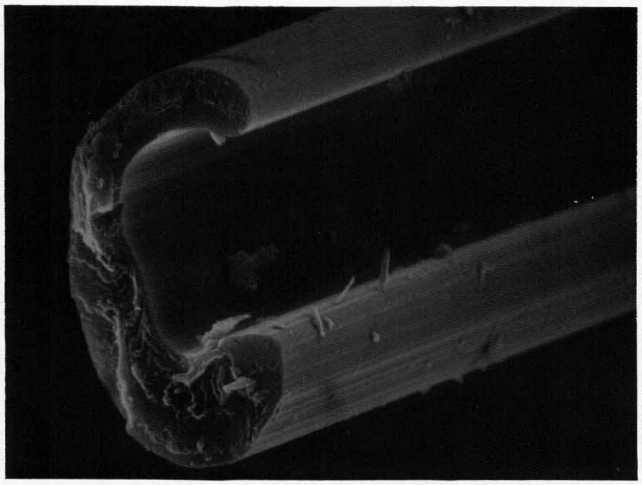

FIGURE 3. A C-shaped carbon fiber produced by melt spinning mesophase pitch. Non-circular fibers can offer improved physical properties and toughness.

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