Educational Impact of the NSF State/Industry/University Cooperative Research Center on Low-Cost, High-Speed Polymer Composites Processing at Michigan State University

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Abstract *- The National Science Foundation (NSF) State of Michigan/Industry/University Cooperative Research Center on Low-Cost, High-Speed Polymer Composites Processing at Michigan State University (MSU) is in its seventh year of operation. The objectives of the Center are the design, development and deployment of technology to reduce the cost of polymer composites processing by a) developing new high speed processing technologies, b) reducing costs of components, and c) reducing the time to implement new composite designs and processes using knowledge-based systems. To meet these objectives, the center has established 1) a basic "core" research program in the five selected thrust areas, 2) a "core" technology transfer program, 3) "non-core" research and development programs, and 4) interactions with small and large companies. The major benefits of this program are to 1) integrate into and increase the use of polymer composites in Michigan and near-by states, 2) expedite the deployment of new polymer composites processing technology nationwide and 3) increase the number of engineers with education specific to polymer composites processing. Researchers at Michigan State University are conducting this multidisciplinary program in collaboration with colleagues at the University of Delaware, and the University of Michigan. Significant accomplishments have been made in fundamental research, education and technology transfer in the areas of novel processing, liquid molding, thermoplastics processing, intelligent modeling of processes for design and manufacturing, and interphases and joining.*

The Center has become well known and respected for its work in composites processing based on the productivity of the faculty and student participants in the Center, and with substantive input from industrial participants. The graduate students who are involved in the Center play an integral role in the research and at the same time are being educated in a non-traditional manner. Students conduct research and take regular courses for their degrees; however, they are also involved with their advisors and industrial monitors as part of the Center's research team. They not only receive feedback from their advisors on the content and quality of the research but from the industrial monitors on its direction and pace. Because of the role of industry in sponsoring and selecting research projects, students also develop economic, marketing and manufacturing skills as part of their training.

The Center has actively pursued the development and delivery of educational materials in the field of polymer composites processing. Courses in polymer composites processing have been developed and are regularly offered. A hands-on workshop for industry has been developed and offered in which lecture and laboratory are combined using Center facilities. Two new initiatives started at the Center, the General Electric/General Motors National Institute of Standards & Technology - Advanced Technology Program on Thermoplastic Engineering Design and the Technology Reinvestment Project (TRP) - Manufacturing Education and Training (MET) Program in Composite Materials for the Department of Defense and Durable Goods Industries contribute significantly to the integration and synergy of education and research at the Center. Within these initiatives engineering design manuals, video modules, teaching laboratories, and computer software tutorials are being developed.

Using Computer Technology to Support Education

Two ongoing projects are developing a web-based tutorial for liquid molding and an Intelligent Tutoring System (ITS) shell utilizing the Generic Task approach to problem solving. The tutorial covers the domain of molding technologies, including resin transfer molding, injection molding, compression molding, and reaction injection molding. The intended users include industry professionals, university students, and others. The tutorial includes several methods of navigation, and makes use of various media types. The second project involves the development of an ITS shell which is generated automatically from existing knowledge-based problem solvers. Our focus in this second project is to develop a family of ITS shells for the class of Generic Task (GT) problem solvers. The goal is to develop an ITS architecture that can interact with any GT-based problem solver, and produce an effective tutorial covering the domain knowledge represented in the problem solver.

In industry, the need to educate employees about a specific subject matter is often a recurring requirement. The process is often both expensive and time-consuming. There is a need for better methods of providing education and training, in industry as well as in academia. One possible solution to this problem, which holds great future potential, is the idea of web-based tutorials. A tutorial that is deliverable through the Internet can be used by many users simultaneously at different locations. In addition, it allows students to browse through the material in their own order preference and to progress through the material at their individual pace. Overall, web tutorials are a very cost-effective method for the education and training of people in the manufacturing industry as well as in other environments.

The tutorial content is organized as chapters, each of which is divided into sections and subsections. Several navigation techniques are provided to allow users to access the information in the manner most suitable to their needs. Users have the option of navigating directly to the specific information required or reading through the tutorial sequentially in a step-by-step manner. To make the learning process more effective, the tutorial utilizes various media forms to present the information to the user.

MSU's tutorial is organized into six major chapters: General Liquid Molding, Resin Transfer Molding, Injection Molding, Reaction Injection Molding, Compression Molding, and New Technologies and Special Applications. Each of these chapters is organized into major sections, each of which may have one or more subsections.

The current organization of material produces a tree-like structure. This makes it easy to get to major topic areas from the start of the tutorial. This will be useful for users interested in a subject area (for example, Compression Molding). Many users, however, may wish to make a linear progression through areas of the tutorial. In order to allow this, each page of the tutorial has a button that takes the user to the next page in the sequence.

To facilitate efficient navigation, each page also has a menu bar at the top. The menu bar contains buttons that allow users to jump to four points in the tutorial based on their current location. The buttons allow the user to jump to the top of the tutorial, the current chapter index, the current section index, and a navigational guide (discussed below). This allows a user to easily jump forward or backward if they find themselves already familiar with the current topic area or need to find their way back to an area they want to review.

The navigational guide, always available from the menu bar, allows the user to more easily find information. The guide has four main parts: a glossary, a topical index, a list of equations, and a table of contents. The glossary contains many of the terms used in the tutorial and their definitions. The topical index contains a list of the various topics covered in the tutorial with links to the places that topic is discussed. The list of equations provides a list of all equations covered in the tutorial and links to their locations in the tutorial. The table of contents shows the hierarchy of the tutorial to allow a user to easily find an item or topic or to get a general idea of a chapter's content.

The table of contents can also become a persistent part of the interface at the user's discretion. In this mode, the table of contents becomes a vertical frame on the left side of the screen. A persistent table of contents was made part of the interface for users who like to see where they have been and what is ahead. It is also convenient for users who prefer to skip around a lot such as more knowledgeable users who are reading the tutorial for specific information.

Other computer software being developed at the Center is an "Intelligent Tutoring System" (ITS) shell to be used to automatically generate tutorials in the area of molding technology from knowledge contained in current problem solvers developed in our group. ITS shells with modular designs and well-defined intercommunication strategies can be effectively reused. Our focus is to develop a family of ITS shells for the class of Generic Task (GT) problem solvers. The GT approach to large-grained knowledge-based problem solving (Chandrasekaran, 1986) is one of the oldest of the task specific approaches to knowledge-based systems. The assumption of the GT approach is that there are basic "tasks"-problem solving strategies and corresponding knowledge representation templates - from which complex problem solving may be decomposed. Our goal is to develop an ITS architecture that can interact with any GT-based problem solver, and produce an effective tutorial covering the domain knowledge represented in the problem solver. The backing intuition of this work is that GT problem solvers are strongly committed to both a semantically meaningful knowledge representation method, and to a structured inferencing strategy. By leveraging this strong structure, automated generation of tutorial overlays is enabled.

In our group we have extensive experience in developing knowledge-based problem solvers in the composites area (e.g., Lenz et al, 1994; and Moy et al, 1994). These problem solvers have involved extensive knowledge acquisition from the area of polymer composites. In particular, we have developed a number of problem solvers that operate in the domains of material system design and fabrication technology selection for polymer composites. Our goal in developing the tutorial overlays is to allow the accumulated knowledge that exists in our problem solvers to be available for tutorial purposes. Moreover, as new problem solvers are developed, we will be able to automatically generate tutorials for the new domains covered. It is anticipated that this capability will prove to be very useful especially for industry specific systems.

As a testbed for our ITS project in molding technology, we are working on the development of an ITS in the domain of composite material design and fabrication in conjunction with the Composite Materials and Structures Center (CMSC) at MSU, and the Center for Composite Materials (CCM) at the University of Delaware (UDEL).

Specifically, we are working with two GT problem solvers, both of which are utilized in the design phases of composites. The first system, COFATE (Moy et al., 1994) is a composite fabrication technology selector. The input for the problem solver consists of characteristics of the target application, as well as economic considerations. The output is a recommended set of fabrication technologies, which should be used to build the application. The second problem solver, COMADE (Lenz et al., 1994) is a composite material designer. The inputs to the system are characteristics of the target application. Output from the system is a set of designs satisfying these requirements. Composites are more flexible than corresponding metals because there is a very wide range of choices for the various components of a composite. This problem solver designs a composite material by finding satisfying choices for each of these components.

Tutorials developed for these two problem-solving systems will serve to teach users the domain of the knowledge embedded in the problem solving systems. These tutorials will assume that the users have a working knowledge of composite material design and fabrication and will aim to familiarize them with the process employed by the systems.

Teaching Laboratory for Molding Polymer Composites

Several new experiments have been developed at both Michigan State University (MSU) and University of Delaware (UDEL) under a joint program between the two universities, for a teaching laboratory on molding polymers and polymer composites. One experiment developed at MSU involves compression molding of sheet molding compound plaques under a variety of processing conditions and then inspecting the molded samples under an optical microscope. An experiment on design of cure cycles for resin transfer molded thick section composite has been developed at UDEL. The objective of these experiments is to provide a design experience and to illustrate important relationships between processing and performance of these materials. Students conducting these experiments gain valuable insight into the interdisciplinary work involved in designing processes for polymer composites.

The objective of this laboratory development program is to illustrate design issues in fabrication of composites and the connection between processing and performance via microstructure of the finished component. The broader objective is to integrate the latest developments in low-cost manufacturing of polymer composites into the undergraduate engineering and continuing education programs at MSU and UDEL.

These objectives have been achieved by developing a variety of courseware such as videotapes, computer based tutorials with interactive process simulations, and manufacturing design software that emphasize the connections among characterization, processing, performance and design for manufacturing in the context of composite materials. These tools have been supplemented in the laboratory at MSU with equipment such as an instrumented press, an optical microscope with image processing software, an injection molding machine suitable for making filled plastic components and a mechanical test frame on which students can conduct destructive mechanical testing of coupons they manufacture as a part of two experiments.

Compression Molding of Sheet Molding Compound (SMC)

This experiment is conducted in a senior level chemical engineering laboratory ChE 472 at MSU. This course is taken by forty to fifty seniors per year. Plaques of glass fiber reinforced vinyl ester (SMC) are molded in an instrumented press. Students are required to study the effect of varying initial charge area and charge location on the variability of microstructure and mechanical properties. The goal of this experiment is to illustrate the effect of process parameters on the microstructure of compression molded plaques. Students verify the effects of varying initial charge area, in addition to the effects of other processing conditions such as temperature and closing speed. To begin with, the students vary the initial charge area and its location in the mold; this procedure helps the students to eliminate short shots and non-uniform filling of the mold. The students are encouraged to perform a separate experiment in which compression stroke is controlled. This results in short shots that give valuable information on the flow pattern during the compression molding process.

Using optical microscopy and attached image grabbing and analysis software, students measure fiber lengths and fiber orientations with respect to the dominant flow direction in the center of the plaque. Students determine two micro-structural parameters -- one representing planar fiber orientation distributions and another being the effective aspect ratio of fiber bundles. These micro-structural parameters allow students to estimate the thermo-elastic properties of the composite plaque using a PC based software tool which they can compare with the measured properties after carrying out mechanical testing of the finished product.

The students then proceed with mechanical property tests and inspection of the microstructure in two distinct regions: the initial charge area and areas filled later. The effect of processing on the microstructure and mechanical properties is brought out and students are prompted to quantitatively compare the planar fiber orientation present in the SMC after compression in two distinct regions (areas) of the molded plaques. This part of the exercise illustrates the variability of orientation from region to region based on processing conditions. The impact of this exercise on the senior undergraduate students is to make them think about the flow process right away while planning the experiment and subsequently while analyzing the process.

The novelty of the approach is that this experiment is designed to reveal the dependence of part performance on processing conditions through the intermediate step of micro-structural inspection. Initially, students carry out compression molding by varying charge area. Optical microscopy reveals more fiber alignment in the dominant flow direction as the initial charge area is reduced. Students are expected to explain this observation by noting the fact that lesser initial charge area results in more flow during compression which directly increases flow induced alignment of fiber bundles in SMC. If the processing temperature is increased beyond the suggested value, students find that the plaque exhibits dark patches on the surface that degrade the cosmetic appearance of the finished product. Students are required to explain this defect generation logically, based on their understanding of resin cure kinetics, the exothermic nature of the reaction and possible evaporation of styrene.

Design of RTM Cure Cycles for Thick Section Composites

This experiment is conducted in a senior level chemical engineering laboratory, CHEG 445, at UDEL. The experiment is the outgrowth of research conducted within the Center for Composite Materials and is a significant departure from the format of other experiments conducted in CHEG 445 --the design section is an integral component as well as the focus of the experiment.

The resin transfer molding (RTM) process is used to fabricate a composite material. Dry reinforcing fibers are impregnated by a low viscosity thermosetting resin, which, upon curing, provides integrity to the assembly. The process begins by placing the dry fiber sheets into the mold cavity. Once the fibers are placed and the mold is closed, the resin is injected into the mold. This is achieved by applying pressure (via compressed air) to the surface of a resin reservoir, which forces the resin into the mold and through the fiber preform. Once the mold is completely filled, the curing cycle of resin can begin.

Prior to engaging in the laboratory work, the students are required to develop a design for a cure cycle through extensive use of computer software made available on the World Wide Web. The design of the cure cycle involves properly selecting the temperature cycle to allow complete, uniform, controlled cure while completing the cure process in as short a period of time as possible to reduce the cost of producing the part. A major problem encountered in curing thick section laminates is the control of the reaction exotherm and heat transfer in order to achieve uniform cure and minimum residual stresses. The problem is aggravated by the poor and non-isotropic thermal conductivity of the assembly. A cure simulation computer program and literature values for in-put parameters are used to predict temperature and extent of reaction profiles through the thickness of the composite plate for various temperature cycles of the heat press. A preliminary cure cycle is selected which minimizes the peak temperature observed in the center of the composite, ensures composite cures inside/out once the gel point is reached, and maintains a curing time less than 1.5 hours. The sensitivity of the above criteria will be investigated with respect to variations in key in-put parameters.

The laboratory's focus is on evaluation of the performance of the proposed cure cycle by (a) fabrication of a composite plate, (b) monitoring of the temperature distributions within the plate during cure, and (c) post-inspection of the cured plate for voids, de-laminations, and variations in fiber volume fraction. The data collected in the laboratory is used to verify the design or provide information for improving it. The execution of this experiment requires the students to synthesize their knowledge of reaction kinetics, heat transfer, and fluid mechanics.

The simulation of the cure process is available to students on the World Wide Web, and includes sections for: (1) frequently asked questions, (2) constitutive equations, and (3) examples of simulation runs.

Liquid and Injection Molding Video Instruction Modules

Four video modules have been produced to cover, at a high level, the interactions between processing, design and performance of composites made by resin transfer molding and injection molding. The video modules are used in conjunction with workshops and classroom instruction.

The first two videos focus on liquid molding. The instructional Objectives of Liquid Molding Module I are to 1) explain two stages in the manufacture of composites by liquid molding, preforming and mold filling, 2) to show how preform architecture governs the cost and the performance (or strength) of the composite part, 3) to demonstrate what is the effect of preform architecture on resin permeation which controls the mold filling operation, and 4) to explain anisotropic permeability. This module also discusses the implications of anisotropic permeation and non-homogeneous preforms for mold filling operation and explains design choices for controlling dry spots and voids in the molded part. This volume concludes at the mold filling stage. The second Liquid Molding Module deals with critical issues involved in the cure stage beginning with resin selection, cure kinetics, effects of coupling agents on the mechanical properties of the finished component and mold design for heat transfer during non-isothermal cure.

The third and fourth videos are titled, "Design for Manufacture of Injection Molded Parts" and "Microstructure and Performance of Injection Molded Parts." The instructional objectives of these modules on injection molding are to illustrate the interaction among part design, mold design and part performance in an injection molded part with the help of specific case studies. The main thrust of the first module is mold design, processing conditions and dimensional stability. The second module concentrates on process-induced microstructure and its influence on part performance.

Thermoplastic Engineering Design Manuals

Manufacturing industries, ranging from automotive to appliance to industrial equipment, design and introduce thousands of new thermoplastic parts every year. The ability to effectively design and manufacture these parts requires a large body of knowledge defined as "design know-how." This design know-how represents the interdisciplinary understanding of material properties, design methods, manufacturing processing, assembly and recycling considerations; however, the interactions between material properties, processing conditions and part geometry are not well understood, and this lack of adequate design know-how results in lengthy, expensive development cycles for thermoplastic parts. Developing these parts requires several cycles of analysis, design, molding trials, and redesign to correct problems in the original design. This trial-and-error or "make it/break it" cycle adds both cost and time to the overall product development cycle. In addition to the lengthy and expensive product design cycle, the lack of comprehensive thermoplastic design information has resulted in poor designs with unanticipated failures and inefficient designs and use of material.

As part of a 4-year program sponsored by General Electric, General Motors, and the National Institute of Standards & Technology, the Thermoplastic Engineering Design (TED) Venture, engineering based thermoplastic design methodologies have been developed for use as an educational tool for a broad spectrum of industries. The initial phases of the program were devoted to developing a scientific understanding of the relationship between processing, part geometry, material microstructure and part performance. The second phase of the TED program was to incorporate this understanding into a base of design knowledge and techniques that can be used to design thermoplastic parts "right the first time." The third aspect of the program is education and technology transfer to a wide range of manufacturers and future engineers.

MSU is helping create an educational tool in the form of design manuals. The manuals have been put on CD-ROM. There are ten manuals concentrating on seven key issues for injection molded thermoplastic parts: assembly, basic structural analysis, creep and stress relaxation, dimensional stability, fatigue, impact, and stiffness and strength. Additionally, there are manuals on design for injection molding, hot tool welding, and vibration welding. These manuals are used in conjunction with workshop presentations to train current and future engineers.

Polymer and Polymer Composites Science and Engineering Courses Offered at Michigan State University

Michigan State University currently offers twenty three courses relating to composites which are taught by sixteen faculty members from several different departments in the College of Engineering, Natural Science, and Agriculture including Chemical Engineering (CHE), Chemistry (CEM), Materials Science and Mechanics (MSM), Mechanical Engineering (ME), and Packaging (PKG). There is currently work being done to create a degree program in Polymer and Polymer Composites Science and Engineering. Undergraduate and graduate courses are listed and described in the following tables.

UNDERGRADUATE COURSES
(all courses are 3 semester credits)

CHE 371	Chemical Engineering Materials Structure, properties, and performance of classes of materials emphasizing polymeric materials.
PKG 320	Plastic and Glass Packaging Physical and chemical properties of plastic and glass and their relationship to selection, design, manufacture, performance and evaluation of packages made from these materials.
MSM 380	Polymeric Materials Polymers and engineering plastics. Chemical, physical and mechanical properties. Environmental effects on polymers. Manufacturing processes. Coatings.
BME 424	Biomaterials and Biocompatability Materials science of human implants. Design requirements imposed by the body's milieu and the need to protect the body.
MSM 444	Introduction to Composite Materials Constituents and interfacial bonding. Manufacturing techniques. Microstructure and micromechanics. Theory of anisotropy. Classical laminate theory. Material characterization. Failure damage. Composite structure design.
CHE 472	Composite Materials Processing Manufacturing processes for thermoset and thermoplastic matrix composites. Mechanical and thermal evaluation of composites. Rheology and molding of fiber-filled materials.
MSM 483	Environmental Effects on Materials Electrochemical processes and kinetics. Metallic corrosion and protection. Degradation of ceramics, polymers and composites.

GRADUATE COURSES
(all courses are 3 semester credits)

MSM 814	Mechanics of Composite Materials A student may earn a maximum of 6 credits in all enrollments for this course. Topics vary each semester. Topics such as fiber-reinforced composite materials or laminated composite structures.
MSM 814A	Fiber-reinforced Composite Materials Application of anisotropic elasticity theory to fiber-reinforced composite materials. Effects of inhomogeneity. Failure analysis. Effective properties.
MSM 814B	Laminated Composite Structures Fundamentals of anisotropic elasticity, applications to laminated composite structures, unique states of deformation, stress, vibration and buckling not encountered in isotropic, homogeneous constructions.
PKG 815	Permeability and Shelf Life Relationship between the storage life of packaged food and pharmaceutical products and the gas, moisture, and organic vapor permeability of packages in various environments.
PKG 817	Instrumental for Analysis of Packaging Materials Spectrophotometric, chromatographic, thermal and other methods of analysis applied to packaging. Material identification and characterization. Migration and permeation measurements.
PKG 825	Polymeric Packaging Materials Physical and chemical properties of polymeric materials and structures commonly used in packaging. Relationships of properties to performance.
CHE 871 & MSM 871	Material Surfaces and Interfaces Physical and chemical nature of solid surfaces and their interaction with gases, liquids, and other solids. Characterization of surfaces and solid-solid interfaces. Relation of surface and interfacial structure to engineering phenomena.
ME 873	Design-for-Manufacture Strategies for Composite Materials Modeling of fiberous composite materials. Processing techniques for thermoplastics and thermosets. Design-for-Manufacture (DFM) strategies.

GRADUATE COURSES - continued
(all courses are 3 semester credits)

PKG 875	Stability and Recyclability of Packaging Materials Interactions between packaging materials and their environments including corrosion degradation, stabilization, and recycling. Impacts of packaging disposal.
MSM 876	Advanced Polymeric Materials Advanced topics in polymers structure and properties. Thermoplastics, thermosets, polyblends and elastomers. Processing techniques. Deformation and mechanical properties. Thermal, optical, and chemical properties. Composites.
MSM 918	Thermoelasticity and Viscoelasticity Thermomechanics of solids. Theory of thermoelasticity. Boundary value problems in thermoelasticity. Linear and nonlinear viscoelasticity. Model representation. Boltzmann superposition. Correspondence principle.
CHE 972	Viscoelasticity and Flow of Polymeric Materials Time dependent and steady flow properties of polymeric materials related to molecular and structural parameters. Examples of polymeric blends and composites with the thermoplastic and thermoset components.
CHE 973	Advanced Polymer Reaction Engineering Principles of chain polymerization and network forming reactions. Emulsions and suspension polymerization versus graft reactions on bulk polymers. Reactor design. Morphology in polymer alloys, effects of mixing on polymer reactions.
CEM 956	Introduction to Polymer Chemistry An introductory course in polymer science that covers the synthesis, characterization and properties of polymers. Target audience: Senior undergraduates, and graduate students with no prior polymer background. (currently offered in the spring semester in odd-numbered years.)
CEM 956	Polymer Synthesis A survey of modern synthetic routes to polymers, including important industrial polymerizations and new routes to polymers. Among the topics discussed are polymer formation by step and chain growth mechanisms, ring opening polymerization, metal catalyzed polymerization and copolymerization. Target audience: graduate students in chemistry and chemical engineering. (currently offered during the fall semester in even-numbered years.)
CEM 956	Polymers for High Technology A new course that examines the applications of polymers in "High-Tech" applications. Topics include polymers for photolithography, polymer applications in linear and nonlinear optics, thermally stable polymers, liquid crystalline polymers, electrical and ionic conduction in polymers, and other current research topics taken from the current literature.

Summary

These new tools and methods being developed at MSU are being used to improve the education of future engineers, as well as, keep current engineers working in industry up to date in their field. In addition to the development of educational materials, the Center has provided a base of support for its students. There are approximately 20 undergraduate and 80 graduate students currently involved with research projects at the Center. This hands on research experience has provided them with an academically enriched experience in the environment of the Center. Through research at the Center, MSU is continually striving to find better ways to educate and train the workforce of today and tomorrow.

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