Ceramic Matrix Composites: A Combined Mechanics-Materials Science Educational Program

N. Yu, P. K. Liaw
Department of Mechanical and Aerospace Engineering and Engineering Science/
Department of Materials Science and Engineering
The University of Tennessee, Knoxville, TN 37996, U.S.A.

Introduction

The development of ceramic matrix composites (CMCs) is of industrial and national importance. For example, continuous fiber-reinforced CMCs, which have been successfully fabricated at the Oak Ridge National Laboratory (ORNL) and several industrial companies, are being recognized as necessary for high-temperature structural applications. The pertinent applications include aerospace structural and machinery components, and energy-related facilities, such as heat exchangers, combustors, hot gas filters and boiler components, and first walls and high heat flux surfaces in fusion reactors. The technology for the fabrication, characterization, modeling, design, and application of CMCs is of crucial importance for improving U.S. industrial competitiveness in the worldwide market.

Monolithic ceramics exhibit high performance in severe service environments, but their applications are greatly curtailed by their excessive brittleness. Techniques to remedy the brittleness of ceramics are the subjects of intensive research. One such method is to reinforce the monolithic ceramics with ceramic fibers, particles, or whiskers to increase the toughness and to avoid catastrophic failure. Ceramic matrix composites have emerged as one of the most promising engineering materials for today's industry in view of their enhanced fracture toughness, chemical inertness, excellent specific strength and stiffness in aggressive environments.

A combined effort is being initiated at the Mechanical and Aerospace Engineering and Engineering Science (MAES) Department and Materials Science and Engineering (MSE) Department at the University of Tennessee (UT) to integrate UT's and ORNL's long-standing research advances on the *mechanics* and *materials science* of CMCs into *interdisciplinary* undergraduate and graduate level curricula at UT. A number of distinguished UT faculty members and renowned ORNL scientists have been actively participating in this NSF-funded program. In addition, strong administrative commitment to the implementation of the newly developed program has been made by UT and ORNL administrators, in the form of matching equipment funds, cost sharing, graduate assistantship, personnel time, space, facilities, etc. Furthermore, state-of-the-art instructional modules, such as on-line hypermedia lecture notes, are being developed for quality teaching and effective learning.

Curriculum Development

Our vision is to provide students with an interdisciplinary curriculum with an emphasis on hands-on training and overall knowledge of CMCs, along with communication skills and teamwork. The students have the unique opportunity of receiving the combined *mechanics* and *materials science* training on CMCs under the guidance of experienced and knowledgeable UT and ORNL instructors. Moreover, the students are exposed to the *complete* and *state-of-the-art* facilities at ORNL and UT, and the integration of important research advances on broad aspects of CMCs. The newly developed undergraduate and graduate curricula on

CMCs are cross-listed under both MAES and MSE departments in the College of Engineering at UT, and have three (3) credit hours with one (1) design credit hour for the undergraduate course. The undergraduate course is offered every Fall semester and serves as a pre-requisite of the graduate course, which is offered every Spring semester.

The following areas in CMCs are discussed in an integrated manner and in the form of demonstration and/or *hands-on group projects* in both undergraduate and graduate courses: fabrication, mechanics, characterization, testing, design, and application. The students analyze the interactions between these important materials science and mechanics aspects of CMCs in a well-coordinated manner. Thus, they realize that the performance of materials is related to the microstructure, which, in turn, is also related to the processing. Therefore, an interactive approach to microstructural characterization, thermo-mechanical evaluation, and mechanics modeling provides an effective means for the design and manufacture of advanced materials, as shown in Figure 1. The newly developed curricula are constructed to do exactly that. For example, a group of two students, ideally one from MAES department and the other from MSE department, will design the microstructure of laminated CMCs and predict the material properties (e.g., tension behavior) using the classical laminated plate theory, and will tour ORNL for the demonstration of the fabrication of CMCs with their designed microstructure, and will then perform thermo-mechanical evaluations along with microstructural characterizations, for the verification of predicted material properties. The students will subsequently discuss the discrepancy between experimental results and theoretical predictions and therefore, establish the principles for further improvement in the materials design for specific needs (e.g., optimal tensile properties). Written reports and oral presentation are required for the group projects so that written and oral communication skills are emphasized.

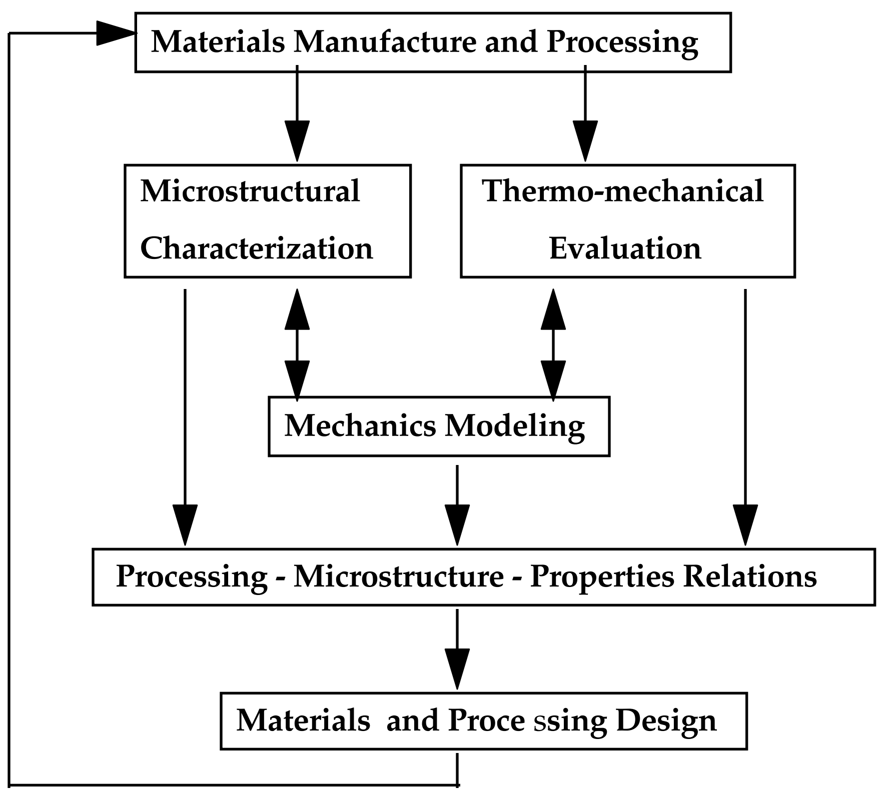

Figure 1. An integrated *mechanics and materials science* approach to the development of advanced CMCs.

At the undergraduate level, *fundamental* and *overall* knowledge of CMCs along with *hands-on* training are emphasized. However, at the graduate level, an *in-depth* understanding and the *integration* of recent research advances on CMCs along with *hands-on* training will be the emphases.

Instructional Modules

Effective instructional modules using advanced multimedia educational tools are being developed in this NSF-funded program. For example, instead of traditional instructional equipment, such as blackboards and chalk, a data/video color projection panel with an enhanced illumination projector is used in the classroom. Therefore, every item that can be presented on the screen of a computer monitor, including text, 3-D graphics, color pictures, computer simulation, animation, video clips, etc., can be projected onto a large screen with full motion and rich sound.

Experimentation of materials processing, microstructural characterization, and thermo-mechanical testing is videotaped for instructional purposes. The videotapes, which help the students to be well-prepared before going to the laboratory and save costs for repeated demonstrations, are presented not only in the classroom but also in a hypermedia form on the Internet (see below). Furthermore, the videotaped experimentation, along with lectures, will be televised through UT Distance Learning Center's network. Therefore, the students and professionals in the evening school, other UT campuses, and all the institutions that have agreements with UT, are able to enroll in these MAES and MSE curricula.

On-line lecture notes are implemented, with the aid of the Center for Computer Integrated Engineering and TeleMedia Service Group of UT, using hypertext techniques incorporated with multimedia resources, i.e., *hypermedia*. Therefore, when students read the on-line documents, they can click key subjects or key words for computer-activated cross references, which are implemented by the authors and contain detailed information about the topic the students just selected, rather than thumbing through several open volumes on their desks. The information may be in the form of text, 3-D graphics, color animation with rich sound, or even video clips. Moreover, the learning process can be interactive. For example, students may do on-line exercises at the end of each topic and be answered promptly. The hypermedia lecture notes are in development at http://www.engr.utk.edu/~cmc.

Conclusion

Advanced aerospace applications require structural materials and components that exhibit high strength and stiffness, low density, and acceptable toughness in high-temperature and corrosive environments. Ceramic-matrix composites are excellent candidates for these applications. In essence, CMCs, including carbon/carbon composites, are the only ones that generally have any strength left above 900_C. In particular, CMCs find numerous applications in the U.S. space shuttles, High Speed Civil Transport (HSCT) program, Advanced Tactical Fighters (ATFs), many existing fighters, missiles, etc. Among the non-aerospace applications of CMCs, engine components in severe environments, cutting and forming tools, wear-resistant parts in machinery, nozzles and exhaust ducts, valve seals and bearings, heat-exchanger tubes, etc. are the prime areas.

The research on CMCs has long been identified as one of the strengths of both UT and ORNL. A significant amount of research endeavor, covering the fabrication, characterization, modeling, and design of CMCs, has been conducted at both UT and ORNL for many years. The participating UT faculty members and ORNL scientists have extensive research experience on CMCs. They are highly *qualified* for and are willing to interact with undergraduate and graduate students in the areas of their expertise. Furthermore, the students are exposed to the *complete* and *state-of-the-art* facilities and equipment at ORNL and UT.

The boundary between *materials science* and *mechanics* should be removed. The newly developed curricula are *interdisciplinary* so that the elements of manufacture/processing, characterization of structure and composition, mechanical evaluation, and mechanics modeling, and compositional and microstructural designs are studied in a systematic and integrated manner, rather than being treated separately. The newly developed undergraduate course emphasizes the *basic concepts*, *overall knowledge*, and *hands-on skills* of fabrication, microstructural characterization, mechanical testing, and *fundamental* mechanics principles and *design* of CMCs. The experience has shown that at the undergraduate level, fundamental and overall knowledge, along with hands-on training, is what students need and what they will appreciate in the future. On the other hand, the graduate course demands in-depth knowledge of recent research advances and a full understanding of the interactions among processing, thermo-mechanical behavior, microstructure, micromechanics, design, and application of CMCs.

In summary, the curricula are well-designed in such a manner that all important *mechanics* and *materials science* aspects of CMCs will be integrated and systematically presented and discussed. It is anticipated that the students, after being trained by the present program, will (1) have a clear understanding about how composites, especially CMCs, are fabricated and processed; (2) be able to determine the important physical properties, and to characterize the thermo-mechanical and fracture behavior as well as microstructural evolution of CMCs; (3) have the capabilities of predicting and explaining the material behavior based on mechanics analyses; and (4) be able to perform basic compositional and microstructural designs of advanced CMCs. Even if the students' future careers are not focused on CMC-related fields, they will have the capability and strategy of approaching mechanics and materials problems in a systematic manner.

Numerous multimedia techniques, together with computers, are utilized in the present program. They include videotapes, on-line lecture notes with audio/video effects under world wide web (WWW), computer simulation, and state-of-the-art presentation tools. The multimedia effects will stimulate students' interests, add the dimensions of instructors' knowledge transfer, enhance the effectiveness of students' learning, and disseminate the developed curricula to an extremely broad extent.

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Biographical Information

Dr. N. YU is an Assistant Professor in the Department of Mechanical and Aerospace Engineering and Engineering Science at UT. He received his Ph.D. in Engineering Science (Applied Mechanics) from the University of California, San Diego, in 1992. Dr. YU has seventeen publications and twenty four presentations on micromechanics of ceramic, metallic and smart piezoelectric composite materials.

Professor P. K. LIAW received his Ph.D. from Northwestern University in 1980. He then worked at Westinghouse Research and Development Center for twelve years. Currently he holds the position of Ivan Racheff Chair of Excellence in the Materials Science and Engineering Department at UT and has more than one hundred eighty publications covering fabrication, characterization, and modeling of advanced materials.