Ceramic Matrix Composites: Combined Materials and Mechanics Curricula

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INTRODUCTION

The research in ceramic-matrix composites is of industrial and national importance. For example, continuous fiber reinforced ceramic composites (CFCCs) have been successfully fabricated by chemical vapor infiltration techniques at the Oak Ridge National Laboratory (ORNL) and industrial companies, such as DuPont, 3M/Delta G, B. F. Goodrich, Amercom, Refractory Composites and B. P. Chemicals Ltd. The CFCCs are being recognized as necessary for high-temperature structural applications. The pertinent applications include heat exchangers, combustors, hot gas filters and boiler components in power generation systems, and first walls and high heat flux surfaces in fusion reactors. The technology for fabrication, characterization, modeling, design, and applications of ceramic composites is of crucial importance for improving U.S. industrial competitiveness in the worldwide market.

A three-year project on "Ceramic Matrix Composites - A Combined Research-Curriculum Development (CRCD) Program" has been supported by the National Science Foundation to integrate the long-standing research advances, achieved by the University of Tennessee (UT), Knoxville, and the Oak Ridge National Laboratory (ORNL), on ceramic-matrix composites (CMCs) into the interdisciplinary undergraduate and graduate level curricula of Materials and Mechanics at UT.

PROJECT COMPONENTS

Research

Significant high-quality and innovative research progress covering a broad class of technologically important areas of CMCs, including fabrication, characterization, modeling and design, has been accomplished at ORNL as well as at UT since early 80's[1-39]. The research advances of CMCs are ready for being integrated into curriculum development. The continued research efforts are currently being supported by the Department of Energy [Fossil and Fusion Energy Materials Programs and Continuous Fiber Ceramic Composites (CFCC) Program] as well as Air Force Office of Scientific Research. The UT/ORNL research accomplishments[1-39] center around the following three pertinent and inter-related areas of CMCs:

Materials Fabrication and Processing

Using the conventional CMC fabrication techniques, such as hot-pressing, fiber damage may result from the high temperatures and pressures. Significant progress has been made regarding the fabrication of CMCs using the forced chemical vapor infiltration (FCVI) technique at ORNL, which has overcome the problems of fiber-damage, slow diffusion and restricted permeability.[1-

3] The FCVI processes have been successfully simulated by finite-volume modeling for optimum processing conditions.[4-9] Moreover, the time to fabricate ceramic composites with acceptable density has been significantly shortened, which greatly reduces the fabrication cost for industrial applications.[5-9]

Materials Characterization

A significant amount of research advances has been made regarding the understanding of thermomechanical behavior of CMCs, including tensile, compressive, shear, fracture, fatigue, and creep properties at UT and ORNL[1-39]. Moreover, nondestructive evaluation has been conducted to determine the composites' elastic, thermal, and physical properties.[18,19] Mechanistic understanding regarding the damage and failure mechanisms of CMCs has been provided. In addition, interface problems have been investigated to study the effect of coating thickness on fracture behavior[20,24,25,30,31] and to search for oxidation-resistant coating.[21] Significant progress has been made concerning the understanding of the influence of fiber fabric orientation on fracture and fatigue behavior of CFCCs.[11,14,15] Microstructural characterization of CMCs using the latest technology, such as atomic force microscopy (AFM)[32], and high-resolution transmission electron microscopy (TEM),[33] and dedicated interfacial fiber microprobe,[24,25] has been conducted before and after the application of thermomechanical loading to assist in the mechanistic understanding of the microstructural evolution in the composites.

Mechanics Modeling

It is well known that the microstructure plays a key role in the thermomechanical and damage behavior of CMCs. The clear delineation of the microstructure-property interactions provides guidelines for the manufacture and design of CMCs tailored for specific technological applications. Significant advances have been made regarding the prediction of the effects of microcracks and/or microvoids on the elastic properties and stiffness degradation of CMCs using micromechanics models, which account for the constituents' properties, distribution, size and shape.[10, 12, 13, 18, 19, 30-39] In addition, the damage evolution, such as transverse matrix crack propagation and creation, interfacial and interlaminar slipping, and fiber breakage, in CMCs has been quantified and predicted using developed models.[37-39] Moreover, interface mechanics has been used to model the fiber push-in and push-out behavior of CMCs in light of the application of the newly developed nanoindentation techniques.[29-31]

<u>Curriculum Development</u>

The vision and rationale for the proposed program hinge on the following questions: Can the students in most of the educational institutions get access to the complete facilities and equipment of materials fabrication, characterization, and theoretical modeling? Do they have chances to witness how materials are fabricated, or even to fabricate specimens themselves, followed by microstructural characterization, such as optical, scanning and transmission electron microscopy, or even AFM, and thermomechanical testing, such as tensile, flexural, or even creep evaluation, further followed by mechanics analyses, and therefore, having an overall understanding of technologically important engineering materials, such as CMCs? Moreover, can they design structural components using CMCs? The answers to the above questions are probably not affirmative at most educational institutions.

In the CRCD program, the students at UT, however, have the unique opportunity of receiving the combined materials and mechanics training on CMCs under experienced instructors. Moreover, they will be exposed to the state-of-the-art facilities at ORNL and UT, and the research advances of the four important areas of fabrication, characterization, modeling, and design of CMCs. The undergraduate and graduate courses on CMCs will be cross-listed under both MSE and ESM departments in the College of Engineering at UT, and will have three (3) credit hours with one-and-a-half (1.5) design credit in the undergraduate course. The undergraduate course will be offered every Fall and will be a pre-requisite of the graduate course, which will be offered every Spring semester. Drs. Liaw and Yu have conducted and attended all of the class meetings and labs.

Upper Level Undergraduate Course

At the undergraduate level, fundamental and overall knowledge about CMCs along with hands-on training will be the emphasis. Students who enroll in this class have been exposed to an introduction to the characteristics of ceramics, fibers, interfaces and CMCs. The following five inter-related topics will then be extensively discussed. (1) Macromechanics: Stress and strength analyses of laminae and laminates will be taught. Existing interactive computer codes will be available to students. (2) Fabrication: Demos on FCVI as well as conventional powder, sol-gel and microwave processing techniques will be given. (3) Microstructural Characterization: Projects on how to determine important physical properties, such as the density, fiber volume fraction and porosity of the fabricated CMCs, will be assigned to students. Students will use optical and scanning electron microscopy to characterize the microstructures of the fabricated specimens. (4) Mechanical Behavior: Fundamentals of mechanical behavior of CMCs will be systematically presented. (5) Design and Applications: The design of CMCs with good mechanical properties has been conducted based on macromechanical analyses. A summary of the advantages and limitations of CMCs have been addressed.

Introductory Graduate Course

The aforementioned five areas of mechanics, fabrication, microstructural characterization, mechanical behavior, and design and applications have formed the main body of the proposed graduate course. However, at the graduate level, an in-depth understanding of recent research advances along with hands-on training is the emphasis. (1) Micromechanics: Elastic properties and damage evolution including interfacial debonding of CMCs will be discussed. (2) Fabrication: Students have learned about the FCVI processes and visit the facility at ORNL. (3) Microstructural Characterization: Projects on SEM analysis of fabricated CMCs have been assigned to students. (4) Thermomechanical Behavior: Recent advances in the mechanistic understanding and theoretical modeling of CMCs have been systematically taught. Demos on fiber push-in and push-out tests using nanoindentation techniques will be conducted. (5) Design and Applications: Projects on the design of CMCs, based on micromechanics models, have been carried out by the students.

Implementation of New Curriculum

A sequence of two courses on ceramic matrix composites (CMCs) have been proposed by the authors, and eventually approved by MSE and MAES Departments, College of Engineering (CoE), Undergraduate and Graduate Councils at UT. The newly developed undergraduate course - MSE 429/ES 429: *Introduction to Ceramic Matrix Composites* - and graduate course - MSE 528/ES 528: *Ceramic Matrix Composites: Materials and Mechanics* - are cross-listed under both

MSE and MAES departments in CoE at UT, and have three (3) credit hours with one (1) design credit hour for the undergraduate course. The undergraduate course (MSE 429/ES 429) is offered every Fall semester and is a pre-requisite of the graduate course (MSE 528/ES 528), which is offered every Spring semester. Both courses may serve as technical electives for all engineering majors at UT. The titles and description of these two new courses have been published in the latest editions of UT undergraduate and graduate catalogs.

Since the project was not funded until September 1, 1995, and the Fall semester of '95 already started in late August, 1995, at UT, the graduate course was *not* offered during the first year of the project. However, the undergraduate course was offered in Spring '96 under *MSE 496 Special Topics in Materials Science and Engineering* and *ES 494 Special Engineering Science Topics*.

Participants

The Co-principal investigators (Co-PIs) of the proposed program are Professor **Peter K. Liaw**, Ivan Racheff Chair of Excellence, MSE department, and Dr. **N. Yu**, assistant professor of ESM department, UT. Dr. Liaw's research and teaching expertise centers around the fatigue, fracture, fiber coating, and thermomechanical behavior of CMCs. Dr. Yu's research and teaching interests are focused on the micromechanics of elastic properties, nonlinear behavior, and damage of CMCs. Both Drs. Liaw and Yu are responsible for the curriculum development and liaison with ORNL. Furthermore, they have been effectively working together to conduct a synergistic investigation of materials and mechanics of CMCs,[10,12,13,18,19] which has been integrated into the proposed materials/mechanics curricula.

The projects, including hand-on experimentation, demos, and design will be assisted by the following ORNL scientists: Drs. **Theodore M. Besmann**, **Mattison K. Ferber**, **Ashok Choudhury** and **Paul F. Becher**. Furthermore, the projects involve four graduate teaching assistants and undergraduate students for specimen preparation, equipment setup, demo, grading, etc.

Other invited lecturers include Dr. **Thomas. T. Meek** (fabrication, UT), Prof. **C. R. Brooks** (microstructural characterization, UT), Dr. **C. H. Hsueh** (interface mechanics, ORNL), and Mr. **David P. Stinton** (fabrication and applications, ORNL).

INSTRUCTIONAL MODULES

Instead of traditional instructional equipment, such as blackboards, chalk, transparencies, slides, etc., a multimedia projector has been used in the classroom. Thus, every item that can be presented on the screen of a computer monitor, including text, 3-D graphics, color pictures, and even video clips, can be projected onto a large screen with full motion and rich sound

Experiments of materials processing, specifically, chemical vapor infiltration and gelcasting techniques, have been videotaped for instructional purposes. The videotapes help the students to be well-prepared before going to the laboratory and save costs for repeated demonstrations. The two videotapes currently need further postproduction improvement, such as sound effects.

On-line class notes have been implemented using hypertext techniques incorporated with multimedia resources, i.e., *hypermedia*. At this moment, only the notes for undergraduate course, MSE 429/ES 429: *Introduction to Ceramic Matrix Composites*, which was taught in

Spring '95, are available at http://www.engr.utk.edu/~cmc. The notes for the graduate course, MSE 528/ES 528: *Ceramic Matrix Composites: Materials and Mechanics*, which is to be offered in Fall '96, are still in preparation.

EVALUATIONS AND ASSESSMENT

A student evaluation of the present curriculum is conducted by UT twice every semester. The questions on the mid-semester evaluation, performed by the UT Learning Research Center, cover a broad aspect of teaching activities. The results of the mid-semester evaluation are summarized and forwarded to the Co-PIs promptly for their use in the modification and improvement of the current course offering. Note that in Spring '96, the students gave the undergraduate course a quite positive evaluation on almost all aspects of the curriculum.

The Campus Teaching Evaluation Program (CTEP) is conducted by the UT Office of Academic Affairs at the end of each semester. The results of CTEP are used to improve future offerings of the proposed course and are not made available to the Co-PIs until the students have received their grades. The results of the evaluation are also compared with the average performance of the Department(s), CoE, and the University.

SUMMARY AND CONCLUSIONS

(1) A significant amount of research endeavor, including fabrication, characterization, modeling and design of CMCs, which are of industrial and national importance, has been completed at both UT and ORNL for the past many years[1-39]. It is the time to incorporate the completed research advances into upper-level undergraduate and introductory graduate curricula at UT. The continued research efforts on CMCs are currently sponsored by DoE and AFOSR.

(2) Students who enroll in the proposed courses have been exposed to the *complete* and *state-of-the-art* facilities and equipment at ORNL and UT. Furthermore, students interact with scientists and engineers who are knowledgeable and have extensive research and hands-on experience on CMCs.

(3) The proposed undergraduate course emphasizes the basic concepts, overall knowledge, and hands-on skills of fabrication, and microstructural and mechanical characterization of CMCs, as well as fundamental theories of mechanics of CMCs. Co-PIs' previous experience has shown that at the undergraduate level, fundamental and overall knowledge and hands-on training are what students need and what they will appreciate in the future. After taking the undergraduate class, the students are expected to be able to conduct important characterization of CMCs, followed by a mechanistic understanding. On the other hand, the proposed graduate course emphasizes in-depth knowledge of the processing, thermomechanical behavior, and micromechanics models of CMCs. In addition, the class is well-designed in the sense that all important characteristics of CMCs, including materials processing, characterization, damage evolution, interface, micromechanics, design and applications will be systematically presented and discussed.

(4) The program is *interdisciplinary* so that students are exposed to not only *materials* science but also *mechanics* and *design* of CMCs. That is, the students will be expected to be able to characterize the technologically important engineering materials and analyze their response. They will also be able to predict the materials' behavior and verify it experimentally.

(5) Instructional modules, such as textbooks, video tapes, slides or CD-ROMs, will be developed and available for future UT students as well as students and professionals in other institutions.

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The proposed program has been conducted at the UT and ORNL under the supervision of Dr. Peter K. Liaw, Professor and Ivan Racheff Chair of Excellence, Department of Materials Science and Engineering (MSE), and Dr. N. Yu, Assistant Professor at the Department of Engineering Science and Mechanics (ESM) at UT, assisted by Dr. Theodore M. Besmann, head of the ceramic surface systems group, Dr. Mattison K. Ferber, head of the mechanical properties user center in the high temperature laboratory and Dr. Paul F. Becher, head of the mechanical characterization and analysis group at ORNL, and three graduate teaching assistants and several selective undergraduate students. In addition, a number of UT faculty members and ORNL scientists, who have extensive research experience on CMCs, will be actively participating in the proposed program.