

Ceramic Composites: Integrated Materials and Mechanics Curriculum

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The research in ceramic matrix composites (CMCs) 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 US 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 ORNL, on CMCs into the interdisciplinary undergraduate and graduate level curricula of Materials and Mechanics at UT.

Implementation of New Curriculum

The two courses on CMCs have been developed by the co-principal investigators (Co-PIs), Liaw and Yu, and approved by (a) Materials Science and Engineering (MSE) and Mechanical and Aerospace Engineering and Engineering Science (MAES) Departments, (b) College of Engineering (CoE), and (c) Undergraduate and Graduate Councils at UT. The newly developed undergraduate course - MSE 429/ES (Engineering Science) 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 credit hours with one design credit hour for the undergraduate course. The undergraduate course (MSE 429/ES 429) is offered every Spring semester and is a pre-requisite for the graduate course (MSE 528/ES 528), which is provided every Fall semester. Both courses may serve as technical electives for all engineering majors at UT. The titles and descriptions of these two new courses have been published in the 1997 and 1998 editions of UT undergraduate and graduate catalogs.

The two courses were taught by the UT professors and ORNL scientists. Specifically, the curriculum covers lectures, demonstrations, and hands-on experimentation on the mechanics, design, fabrication, characterization, and applications of CMCs. The courses involve two novel approaches: (a) the integration of materials science and mechanics, and (b) the collaboration between a university - UT - and a national laboratory - ORNL. The following summary outlines some of the features of the two courses.

	ES/MSE 528	MSE/ES 429
No. of 75-minute class meetings:	29	29
No. of meetings conducted by UT professors:	19	21
No. of meetings conducted by ORNL scientists:	10	8
No. of participating UT faculty members:	3	3
No. of participating ORNL scientists:	7	5
No. of ORNL lab tours	3	1
No. of homework assignments:	7	7
No. of projects (written reports and oral presentations required):	1	1
No. of exams:	3	3

Instructional Modules

Instead of using traditional instructional equipment, such as blackboards, chalk, transparencies, slides, etc., the Co-PIs have taught the two courses using state-of-the-art technology. In particular, the lectures have been conducted in the UT Distance Learning Center's Telecommunication classroom. All of the lectures have been videotaped in the Telecommunication classroom. Therefore, the students on other UT campuses, the UT evening school and all institutions having agreements with UT can enroll in the classes. For instance, two students from the Tennessee Space Institute and one student from Oak Ridge, Tennessee have taken the graduate course using the videotapes through the Distance Learning Center and the Evening school, respectively.

Experiments of materials processing, specifically, chemical vapor infiltration and gelcasting techniques, have been videotaped for instructional purposes. Furthermore, the videotapes have experienced further post-production improvements, such as sound effects. In addition, mechanical characterization methods including fatigue and flexure tests at both room and elevated temperatures have been videotaped. These videotapes help the students to be well-prepared before going to the laboratory and save costs for repeated demonstrations.

A SONIX ultrasonics system has been purchased and set up at UT. This system contains state-of-the-art scanning arrangements and a water tank. Moreover, the unit is computer-controlled with elaborate software for ultrasonic wave analyses. Lab demonstrations are planned for the graduate course that will be lectured in Spring '98. Furthermore, lab projects using the unit will be designed.

Internet-Based Educational Technology

In recent years, modern computer technologies, including hypertext techniques together with multimedia resources (namely, hypermedia), open a new avenue to effective learning and teaching. For example, when students read on-line hypertext documents, they can click key subjects or key words for computer-activated cross references that contain detailed information about the topic the students just selected. This technology enables the students to quickly access the desired information rather than thumbing through several journals, conference proceedings, and/or reports on their desks. The selected information may be implemented on Internet by instructors and other professionals. This format of instructional presentation further provides a wider variety of the types of information that can be presented (for instance, multimedia and/or interactive delivery). In addition, it offers a permanent record of the lecture/discussion that can be retrieved/reviewed by the student as well as instructors for further clarification and modification. The innovative WWW-based educational delivery may stimulate students' interests, enhance the effectiveness of students' learning, and aid in the dissemination of the developed courseware to a very broad audience.

The WWW-based courseware includes on-line hypertext documents with audio/video effects, computer animation, and interactive modules. The courseware, located at <http://www.engr.utk.edu/~cmc>, consists of (a) syllabus, (b) instructors' handout in the form of text, color three-dimensional figures, and color pictures, (c) animation/simulation, (d) short video clips with audio effects, (e) interactive homework/exercises with audio effects, and (f) on-line teaching evaluation forms.

In traditional instructional presentations, schematic diagrams are drawn on blackboards. Furthermore, samples and micrographs are circulated among students in the classroom. The present WWW-based courseware, on the other hand, includes three-dimensional figures and color pictures that provide unambiguous explanation and are easy to be retrieved. Computer animation/simulation further helps illustrate continuously changing phenomena. For instance, the damage evolution in fiber-reinforced CMCs subjected to uniaxial tension may be well illustrated by the animation located in the section of Introduction/Mechanics/Mechanical Behavior of CMCs of the present WWW-based courseware.

As mentioned before, experimentation of materials processing (chemical vapor infiltration and gelcasting technologies) and characterization (monotonic and cyclic flexural tests at room and high temperatures) have been videotaped for instructional purpose. The videotapes have been not only edited into several short clips for the inclusion into the WWW-based course but also presented in the classroom. Moreover, the learning process can be interactive. On-line homework has been implemented in such a manner that students' work is graded promptly for immediate feedback. Furthermore, the students can create their own exercises by changing input data. The common gateway interface (CGI) scripts implemented are able to compute the correct answers in response to different input data. Audio effects, such as applause or car crash, respond to students' correct or incorrect inputs to quizzes, which makes the learning process interesting.

It is noted that our Web-based courseware is accessible to all students and professionals having Internet access to WWW and is registered with several top search engines on WWW. The present WWW-based courseware has been accessed approximately 100 times per month. The authors have started to receive e-mails of inquiry on CMCs from almost everywhere in the world. The dissemination of the results of the present curriculum development efforts will be further widespread in the light of the extensive and increasing attention and access to WWW.

Integration of Research into Education

All of the ORNL scientists participating in the present CRCD project are leading researchers in various technical areas of CMCs. Consequently, they are able to present well-accepted and state-of-the-art research results relevant to the current curriculum. The ORNL scientists as well as UT faculty members give lectures on topics of their expertise, while the two Co-PIs of the present CRCD project serve as coordinators and give introductions and overviews to ensure that individual topics are presented in a coordinated, rather than fragmented, manner. The Co-PIs also incorporate their graduate assistants' research work, such as microstructural characterization, mechanical testing, and computational analyses of CMCs, into the lectures, instructional videotapes, and the courseware developed on Internet. Currently, four Ph.D. students are supported by the present program. Example publications of students' research are listed in Refs. 1-28.

Evaluations and Assessment

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 our

Department, CoE, and the University. On the other hand, to improve the effectiveness of teaching in a prompt manner, an on-line teaching evaluation form has been implemented on our WWW-based courseware. The form includes specific questions regarding the textbooks, lectures, assignments, and other aspects of the curriculum. Sufficient space is also available for students' general comments. Students can fill out the on-line teaching evaluation form anonymously and submit it electronically whenever and as often as they want. Our students have rated our curriculum as an excellent one and expressed their interest in taking more classes from us in the future.

Three senior experts in engineering research/education and applications have been separately invited to UT to assess our CRCD-sponsored curriculum. They are Professor Z. Suo of Princeton University, Mr. Don Sidwell of Lockheed Martin Skunk Works Division in Palmdale, California, and Mr. Morris Johnson, a manager at UCB Chemicals, a Belgium-based company in Smyrna, Georgia. Each of them has spent one day at UT to listen to our briefing on the motivation and implementation of the curriculum, to examine the instructional modules developed, and to provide Co-PIs with their suggestions. All of them highly rated the present CRCD project.

Dissemination

The contribution of the project to the area of research and education on CMCs has been presented in the form of books, technical papers, and presentations in journals and professional conferences. During the three years of the project, 4 edited books, and more than 50 articles and 85 technical presentations have acknowledged NSF CRCD's support of the present project. Example publications acknowledging NSF CRCD's support of the present project are shown in Refs. 1-48.

Future Work

- (a) The Co-PIs will continue to offer the two courses developed under NSF CRCD support. The courses will be provided through distance education. The collaboration with ORNL will continue as well.
- (b) More videotapes for microstructural characterization and nondestructive evaluation of CMCs will be produced with the aid of the UT Telemedia Services Group.
- (c) The WWW-based courseware will be improved to include more multimedia and interactive features.
- (d) Students' communication skills will be emphasized in the upcoming course offerings. Students are asked to (1) write short memos as well as long reports and (2) make short and long presentations for their project work. Their reports and presentations will be reviewed and discussed for further improvement.

Summary and Conclusions

Ceramic-matrix composites (CMCs) are wear-resistant, hard, of high-strength and modulus, and lightweight in elevated-temperature and aggressive environments in comparison with many other conventional engineering materials. The technology for the fabrication, characterization, modeling, design, and applications of CMCs is of vital importance for improving U.S. industrial competitiveness in the worldwide market.

In cooperation with the near-by world-renowned Oak Ridge National Laboratory, the present courses have been developed to integrate the *materials science* and *mechanics* of CMCs into *interdisciplinary* undergraduate and graduate level curricula. In particular, multimedia and interactive WWW-based courseware has been developed, and therefore, has provided effective

learning resources for interested students and professionals. On-line lecture notes are implemented using hypertext techniques incorporated with multimedia resources, i.e., hypermedia.

The success of such an integrated interdisciplinary curriculum and combined university and national laboratory efforts offers a showcase for other departments in the College of Engineering of the University of Tennessee and even other universities in the US for similar curriculum development. Well-trained engineering students, who are future engineers in industry or faculty members in academia, will be well-prepared for the competitive world market of the design and applications of advanced materials, such as ceramic matrix composites, and will make their significant contributions to the industry and the nation.

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References

- [1] M. A. Borst, W. Y. Lee, Y. Zhang and P. K. Liaw, "Preparation and Characterization of Chemically Vapor Deposited ZrO₂ Coating on Nickel and Ceramic Fiber Substrates," J. of American Ceramic Society, 80[6], 1591-1594 (1997).
- [2] N. Miriyala, P. K. Liaw, C. J. McHargue, L. L. Snead and J. A. Morrison, "The Monotonic and Fatigue Behavior of A Nicalon/Alumina Composite at Ambient and Elevated Temperatures," American Ceramic Society Meeting, Ceramic Eng. Sci. Proc., 18[3], 747-756 (1997).
- [3] W. Zhao, P. K. Liaw and N. Yu, "Effects of Lamina Stacking Sequence on the In-Plane Elastic Stress Distribution of a Plain-Weave Nicalon Fiber-Reinforced SiC Laminated Composite with a Lay-up of [0/30/60]," American Ceramic Society Meeting, Ceramic Eng. Sci. Proc., 18[3], 401-408 (1997).
- [4] W. Zhao, P. K. Liaw and D. C. Joy, "Microstructural Characterization of a 2-D Woven Nicalon/SiC Ceramic Composite by Scanning Electron Microscopy Line-Scan Technique," American Ceramic Society Meeting, Ceramic Eng. Sci. Proc., 18[3], 295-302 (1997).
- [5] J. G. Kim, P. K. Liaw, D. K. Hsu and D. J. McGuire, "Nondestructive Evaluation of Continuous Nicalon Fiber Reinforced SiC Composites," American Ceramic Society Meeting, Ceramic Eng. Sci. Proc., 18[4], 287-296 (1997).

- [6] N. Miriyala, P. K. Liaw, C. J. McHargue and L. L. Snead, "The Monotonic and Fatigue Behavior of a Nicalon/Alumina Composite at Ambient and Elevated Temperatures," Ceram. Eng. Sci. Proc., 18[3], 747-756 (1997).
- [7] H. Jeong, D. K. Hsu and P. K. Liaw, "Anisotropic Conductivities of Multiphase Particulate Metal-Matrix Composites," Composites Science and Technology, 58, 65-76 (1998).
- [8] J. H. Zhu, P. K. Liaw, J. M. Corum, J. G. R. Hansen and J. Cornie, "Damage Mechanisms in a Cast Ductile Iron and a Al₂O₃p/Al Composite," Metallurgical and Materials Transactions, 29A, 2855-2862 (1998).
- [9] J. H. Zhu, P. K. Liaw and C. T. Liu, "Effect of Electron Concentration on the Phase Stability of Nb-Cr₂-Based Laves Phase Alloys," Materials Science and Engineering, A239-240, 260-264 (1997).
- [10] W. Zhao, P. K. Liaw, N. Yu, E. R. Kupp, D. P. Stinton and T. M. Besmann, "Computation of the Lamina Stacking Sequence Effect on the Elastic Moduli of a Plain-Weave Nicalon Fiber Reinforced SiC Laminated Composite with a Lay-up of [0/30/60]," J. of Nuclear Materials, Vol. 253, 10-19 (1998).
- [11] N. Miriyala, P. K. Liaw, C. J. McHargue and L. L. Snead, "The Mechanical Behavior of A Nicalon/SiC Composite at Ambient Temperature and 1000°C," J. of Nuclear Materials, Vol. 253, 1-9 (1998).
- [12] W. Y. Lee, Y. Zhang, I. G. Wright, B. A. Pint and P. K. Liaw, "Effects of Sulfur Impurity on the Scale Adhesion Behavior of a Desulfurized Ni-based Superalloy Aluminized by Chemical Vapor Deposition," Metallurgical and Materials Transactions A, Vol. 29A, 833 (1998).
- [13] P. K. Liaw, "Understanding Fatigue Failure in Structural Materials," J. of Metals, Vol. 49, No. 7, 42 (1997).
- [14] N. Miriyala and P. K. Liaw, "CFCC (Continuous-Fiber-Reinforced Ceramic Matrix Composites) Fatigue: A Literature Review," J. of Metals, Vol. 49, No. 7, 59-66, 82 (1997).
- [15] L. Garimella, P. K. Liaw and D. L. Klarstrom, "Fatigue Behavior in Nickel-Based Superalloys: A Literature Review," J. of Metals, Vol. 49, No. 7, 67-71 (1997).
- [16] R. K. Holman and P. K. Liaw, "Methodologies for Predicting Fatigue Life," J. of Metals, Vol. 49, No. 7, 46-52 (1997).
- [17] N. Miriyala and P. K. Liaw, "Specimen Size Effects on the Flexural Strength of CFCCs," American Ceramic Society Meeting, Ceramic Engineering and Science, Vol. 19 (1998).
- [18] W. Zhao, P. K. Liaw and N. Yu, "Computer-Aided Prediction of the First Matrix Cracking Stress for a Plain-Weave Nicalon/SiC Composite with Lay-ups of [0/20/60] and [0/40/60]," Ceramic Engineering and Science, Vol. 19, 3 (1998).
- [19] W. Zhao, P. K. Liaw and N. Yu, "Computer-Aided Prediction of the Effective Moduli for a Plain-Weave Nicalon/SiC Composite with Lay-ups of [0/20/60] and [0/40/60]," Ceramic Engineering and Science, Vol. 19 (1998).

- [20] N. Miriyala, P. K. Liaw, C. J. McHargue, A. Selvarathinam and L. L. Snead, "The Effect of Fabric Orientation on the Flexural Behavior of CFCCs: Experiment and Theory," the 100th Annual American Ceramic Society Meeting, Cincinnati, Ohio, May 3-6, 1998, Ceramic Transactions (in press).
- [21] N. Miriyala, P. K. Liaw, C. J. McHargue and L. L. Snead, "Fatigue Behavior of Continuous Fiber-Reinforced Ceramic-Matrix Composites (CFCCs) at Ambient and Elevated Temperatures," Invited Paper, Prof. Paul Paris Symposium, the TMS/ASM Materials Week, Indianapolis, Indiana, September 14-18, 1997.
- [22] E. Y. Shen, C. R. Brooks, P. K. Liaw, J. Kim, D. L. Klarstrom and J. Y. Huang, "Fatigue Behavior of a Commercial Co-26 Cr-Ni (wt.%) Base Alloy (ULTIMET)," Prof. Paul Paris Symposium, the TMS/ASM Materials Week, Indianapolis, Indiana, September 14-18, 1997, W. O. Soboyejo and T. S. Srivatsan, eds., TMS, 313-326 (1997).
- [23] W. Zhao, P. K. Liaw, and N. Yu, "The Reliability of Evaluating the Mechanical Performance of Continuous Fiber-Reinforced Ceramic Composites by Flexural Testing," International Conference on "Maintenance and Reliability," pp. 6-1 to 6-15 (1997).
- [24] P. K. Liaw, J. Kim, N. Miriyala, D. K. Hsu, N. Yu, D. J. McGuire and W. A. Simpson, Jr., "Nondestructive Evaluation of Woven Fabric Reinforced Ceramic Composites," Symposium on "Nondestructive Evaluation of Ceramics," C. Schilling, J. N. Gray, R. Gerhardt and T. Watkins, eds., Ceramic Transactions, Vol. 89, 121-135 (1998).
- [25] D. C. Worley II, P. K. Liaw, R. S. Benson, W. A. Simpson, Jr. and J. Corum, "Nondestructive Testing Techniques Used to Evaluate Progressive Damage of a Swirl Mat Composite," Proceedings International Composites Expo '97, Section 5A, 1-8 (1997).
- [26] M. E. Fine and P. K. Liaw, "Commentary on the Paris Equation," Prof. Paul Paris Symposium, the TMS/ASM Materials Week, Indianapolis, Indiana, September 14-18, 1997.
- [27] W. Zhao, P. K. Liaw, D. C. Joy and C. R. Brooks, "Effects of Oxidation, Porosity and Fabric Stacking Sequence on Flexural Strength of a SiC/SiC Ceramic Composite," Processing and Properties of Advanced Materials: Modeling, Design and Properties, B. Q. Li, eds., the Minerals, Metals, and Materials Society, 283-294 (1998).
- [28] W. Zhao, P. K. Liaw, and N. Yu, "Computer Modeling of the Fabric Stacking Sequence Effects on Mechanical Properties of a Plain-Weave SiC/SiC Ceramic Composite," Proceedings on "Processing and Properties of Advanced Materials: Modeling, Design and Properties," B. Q. Li, eds., the Minerals, Metals, and Materials Society, 149-160 (1998).
- [29] M. Huang, L. Liang and P. K. Liaw, "A Review of Acoustic Emission in Fatigue and Fracture Research of Materials," the Chinese-American Academic and Professional Association in Southeastern United States, Atlanta, Georgia, July 3-5, 1998 (Invited).
- [30] M. Huang, L. Jiang, P. K. Liaw, C. R. Brooks, R. Seeley and D. L. Klarstrom, "Using Acoustic Emission in Fatigue and Fracture Materials Research," J. of Metals, Vol. 50, No. 11, JOM-e, <http://www.tms.org/pubs/journals/JOM/9811/Huang> (1998).
- [31] J. Kim and P. K. Liaw, "The Nondestructive Evaluation of Advanced Ceramics and Ceramic-Matrix Composites," J. of Metals, Vol. 50, No. 11, JOM-e, <http://www.tms.org/pubs/journals/JOM/9811/Kim> (1998).

- [32] N. Yu and P. K. Liaw, "Ceramic-Matrix Composites: An Integrated Interdisciplinary Curriculum," J. of Engineering Education, 539-544, 1998 Supplement (1998).
- [33] P. K. Liaw, "Continuous Fiber Reinforced Ceramic Composites," J. of the Chinese Institute of Engineers, Vol. 21, No. 6, 701-718 (1998).
- [34] N. Yu and P. K. Liaw, "Ceramic-matrix Composites: Web-based Courseware and More," the 1998 ASEE Annual Conference and Exposition, Seattle, WA, June 28 - July 1, 1998.
- [35] N. Yu and P. K. Liaw, "Ceramic-matrix Composites," <http://www.engr.utk.edu/~cmc>.
- [36] "Nondestructive Evaluation and Materials Properties (III)," P. K. Liaw, O. Buck, R. J. Arsenault and R. E. Green, Jr., eds., the Minerals, Metals and Materials Society (TMS), Warrendale, PA, 1997.
- [37] "Design and Reliability of Solders and Solder Interconnects," R. K. Mahidhara, D. R. Frear, S. M. L. Sastry, K. L. Murty, P. K. Liaw and W. L. Winterbottom, eds., the Minerals, Metals and Materials Society (TMS), 1997.
- [38] P. K. Liaw, A. Saxena and J. Schaefer, "Creep Crack Growth Behavior of Steam Pipe Steels: Effects of Inclusion Content and Primary Creep," Engineering Fracture Mechanics, 57, 105-130 (1997).
- [39] C. Y. Yang, P. K. Liaw, and S. S. Palusamy, "S-N Curve for Crack Initiation and Prediction of Fatigue Crack Nucleus Size," ASTM 27th National Symposium on "Fatigue and Fracture Mechanics" (in press).
- [40] W. M. Matlin, T. M. Besmann and P. K. Liaw, "Optimization of Bundle Infiltration in the Forced Chemical Vapor Infiltration (FCVI) Process," Symposium on "Ceramic Matrix Composites-Advanced High-Temperature Structural Materials", R. A. Lowden, M. K. Ferber, J. R. Hellmann, K. K. Chawla, S. G. DiPietro, eds., Materials Research Society, Vol. 365, 309-315 (1995).
- [41] P. K. Liaw, D. K. Hsu, N. Yu, N. Miriyala, V. Saini and H. Jeong, "Measurement and Prediction of Composite Stiffness Moduli," Symposium on "High Performance Composites: Commonalty of Phenomena", K. K. Chawla, P. K. Liaw, and S. G. Fishman, eds., the Minerals, Metals and Materials Society (TMS), Warrendale, PA, pp. 377-395 (1994).
- [42] N. Chawla, P. K. Liaw, E. Lara-Curzio, R. A. Lowden and M. K. Ferber, "Effect of Fiber Fabric Orientation on the Monotonic and Fatigue Behavior of a Continuous Fiber Ceramic Composite," Symposium on "High Performance Composites", K. K. Chawla, P. K. Liaw, and S. G. Fishman, eds., the Minerals, Metals and Materials Society (TMS), Warrendale, PA, pp. 291-304 (1994).
- [43] P. K. Liaw, D. K. Hsu, N. Yu, N. Miriyala, V. Saini and H. Jeong, "Modulus Investigation of Metal and Ceramic Matrix Composites: Experiment and Theory," Acta Metallurgica. et Materialia, 44 [5], 2101-2113 (1996).
- [44] P. K. Liaw, N. Yu, Hsu, D. K., Miriyala, N., V. Saini, L. L. Snead, C. J. McHargue and R. A. Lowden, "Moduli Determination of Continuous Fiber Ceramic Composites (CFCCs)," Journal of Nuclear Materials, 219, 93-100 (1995).
- [45] P. K. Liaw, "Book Review on Ceramic Matrix Composites by K. K. Chawla," MRS Bulletin, XIX, p. 78 (1994).

- [46] D. K. Hsu, P. K. Liaw, N. Yu, V. Saini, N. Miriyala, L. L. Snead, R. A. Lowden and C. J. McHargue, "Nondestructive Characterization of Woven Fabric Ceramic Composites," Symposium on "Ceramic Matrix Composites-Advanced High-Temperature Structural Materials," R. A. Lowden, M. K. Ferber, J. R. Hellmann, K. K. Chawla, S. G. DiPietro, eds., Materials Research Society, Vol. 365, 203-208 (1995).
- [47] J. H. Miller, R. A. Lowden and P. K. Liaw, "Fiber Coatings and the Fracture Behavior of a Continuous Fiber Ceramic Composite," Symposium on "Ceramic Matrix Composites-Advanced High-Temperature Structural Materials," R. A. Lowden, M. K. Ferber, J. R. Hellmann, K. K. Chawla, S. G. DiPietro, eds., Materials Research Society, Vol. 365, 403-410 (1995).
- [48] S. Shanmugham, D. P. Stinton, F. Rebillat, A. Bleier, E. Lara-Curzio, T. M. Besmann and P. K. Liaw, "Oxidation-Resistant Interfacial Coatings for Continuous Fiber Ceramic Composites," S. Shanmugham, D. P. Stinton, F. Rebillat, A. Bleier, T. M. Besmann, E. Lara-Curzio and P. K. Liaw, Ceramic Eng. Sci. Proc., 16[4], 389-399 (1995).

Biography

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