Final Technical Report
(September 2005-August 2012)

Upgrading the Center for Lightweighting Automotive Materials and Processing – a GATE Center of Excellence at the University of Michigan-Dearborn

DOE Award Reference No. : DE-FG26-05NT42621

Submitted by

Prof. P. K. Mallick
Center for Lightweighting Automotive Materials and Processing
University of Michigan-Dearborn
Dearborn, MI 48128

November 2012

"*Disclaimer*: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

TABLE OF CONTENTS

1. INTRODUCTION……...3

2. EDUCATION…… 4

3. FACULTY……..10

4. RESEARCH……11

5. STUDENTS…….. 11

6. LABORATORY FACILITIES……11

7. MATERIALS DATABASE……11

8. INTERACTION AND COLLABORATION WITH INDUSTRY……...12

9. CONCLUSIONS……..17

APPENDIX

PUBLICATIONS OF CLAMP FACULTY (2005-2012) ……..18

1. INTRODUCTION

The Center for Lightweighting Materials and Processing (CLAMP) was established in September 1998 with a grant from the Department of Energy's Graduate Automotive Technology Education (GATE) program. The center received the second round of GATE grant in 2005 under the title "Upgrading the Center for Lightweighting Automotive Materials and Processing". Using the two grants, the Center has successfully created 10 graduate level courses on lightweight automotive materials, integrated them into master's and PhD programs in Automotive Systems Engineering, and offered them regularly to the graduate students in the program. In addition, the Center has created a web-based lightweight automotive materials database, conducted research on lightweight automotive materials and organized seminars/symposia on lightweight automotive materials for both academia and industry. The faculty involved with the Center has conducted research on a variety of topics related to design, testing, characterization and processing of lightweight materials for automotive applications and have received numerous research grants from automotive companies and government agencies to support their research. The materials considered included advanced steels, light alloys (aluminum, magnesium and titanium) and fiber reinforced polymer composites. In some of these research projects, CLAMP faculty have collaborated with industry partners and students have used the research facilities at industry locations.

The specific objectives of the project during the current funding period (2005 – 2012) were as follows:

(1) develop new graduate courses and incorporate them in the automotive systems engineering curriculum

(2) improve and update two existing courses on automotive materials and processing

(3) upgrade the laboratory facilities used by graduate students to conduct research

(4) expand the Lightweight Automotive Materials Database to include additional materials, design case studies and make it more accessible to outside users

(5) provide support to graduate students for conducting research on lightweight automotive materials and structures

(6) provide industry/university interaction through a graduate certificate program on automotive materials and technology idea exchange through focused seminars and symposia on automotive materials.

2. EDUCATION

The College of Engineering and Computer Science at the University of Michigan-Dearborn offers a 30-credit-hour interdisciplinary master's program in Automotive Systems Engineering and a 50-credit hour interdisciplinary PhD program in Automotive Systems Engineering. The master's program was started in 1996 to provide students with strong, automotive related engineering knowledge and systems-thinking skills. The PhD program in Automotive Systems Engineering was started in 2009 to meet the need of engineers who intend to follow a career of technical specialists and serve as technical leaders, innovators and research mentors in the automotive industry.

The curriculum of the master's program provides breadth through four core courses and depth through four concentration courses (Table 1). In addition, each student must complete a 6-credit hour capstone project or thesis to complete the program. Through the courses and project/thesis, students in the program gain a considerable amount of design and analysis experience on advanced automotive technologies. The PhD program requires 24 credit hours of coursework and 26 credit hours of dissertation.

Both master's and PhD programs contain a concentration area in Automotive Materials. The lightweight automotive materials curriculum developed under GATE funding during the first cycle of funding (1998 – 2005) and expanded during the second cycle of funding (2005 – 2012) was integrated into the master's and PhD programs. Students in both programs have the opportunity to either select Automotive Materials as their concentration area or take one or more elective courses to learn about the automotive materials technology.

Students specializing in the automotive materials concentration in the master's program have the opportunity to take up to 12 credit hours of elective concentration courses on automotive materials and a 6 credit hour course for capstone design project or master's thesis (Table 1). The other 12 credit hours include two required core courses (one of which is AE 587, Automotive Manufacturing Processes) and two elective core courses (one of which can be

AE 581, Materials Selection in Automotive Design). Students specializing in the automotive materials concentration in the PhD program have the opportunity of taking 12-15 credit hours of courses on automotive materials and related topics, at least two of which must be 600-level courses. They must also complete a 26 credit hours dissertation of original research on topics related automotive materials.

Four new courses were developed and taught during the current funding period (2005 -2012). In addition, two other existing courses were modified with new case studies and examples. They were Materials Selection in Automotive Design (AE 581) and Design and Manufacturing Considerations for Lightweight Automotive Materials (AE 586).

(1) Design and Analysis for Crashworthiness (AE 650) (Instructor: Prof. H. T. Kang)

The course aims to provide knowledge on vehicle crash mechanics, structural design to improve crashworthiness and crash energy management. Finite element techniques for vehicle crash analysis are also covered.

(2) Design and Manufacturing and for Environment (AE 588) (Instructor: Prof. G. Reyes-Villanueva)

This course is focused on the effects of product design and manufacturing on the environment, with special emphasis on automobiles. The fundamental principles of life cycle engineering are introduced. The importance of environmental improvement is considered. Design and material selection for recycling, reuse and disposal are illustrated. Furthermore, it covers the elementary relationships between design and manufacturing for the development of future environmentally friendly vehicles.

(3) Advanced Steels for Automotive Applications (AE 590E) (Instructor: Prof. P. K. Mallick)

Steel is the major material of construction of automobiles. Recent advancements in steel technology have made steel one of the materials of choice for lightweight automobiles. This course is designed to teach the metallurgy, material properties, design and manufacturing characteristics of advanced sheet steels. It starts with a basic review of steel technology and then discusses the recent advancements in both material and manufacturing process developments in the steel industry. It also illustrates the

application of advanced steels in constructing lightweight vehicles. This course was developed with funding from the American Iron and Steel Institute (AISI).

(4) Automotive Assembly Systems (AE 590) (Instructor: Prof. E. Orady)

This course addresses the unique issues and challenges faced in the assembly of an automobile in view of the variety of materials used in its construction. The course starts with a discussion on the key characteristics of a good assembly and differences in material characteristics that contribute to the dimension and tolerance problems. It then covers the variety of joining processes used, such spot welding for steel, self-piercing riveting for aluminum alloys and adhesive bonding for composites. It also discusses the assembly system design, design for assembly and modular assembly.

The other courses taught regularly in the automotive materials area are as follows:

(1) Materials Selection In Automotive Design (AE 581) (Instructor: Prof. P. K. Mallick)

This course develops an understanding of the properties of modern engineering materials and explains the role of materials selection process in product design, development and manufacturing. Materials selection, design problems and case studies involving automotive and other commercial products are discussed. The role of environmental regulations, social pressure and customer wants on the selection of alternate materials is discussed.

(2) Lightweight Automotive Alloys (AE 584) (Instructor: Prof. G.T. Kridli)

This course introduces structure-processing-property relationships in lightweight automotive alloys that are candidate for automotive applications, such as aluminum, magnesium and titanium. Metal matrix composites and intermetallic materials are also discussed. Emphasis is given on the processing and design of these materials in future automotive applications.

(3) Automotive Composites (ME 587) (Instructor: Prof. P. K. Mallick)

The emphasis in this course is on materials and manufacturing of automotive composites, such as SMC, SRIM and RTM. In addition to the properties and applications of these materials, this course covers the processing, design considerations, test methods

and quality issues. The use of continuous fiber composites in automotive applications, such as leaf springs, drive shafts and energy absorbing structures, is also discussed.

(4) Ceramics for Automotive Applications (AE 585) (Instructor: Prof. P. K. Mallick)

This course presents physical, thermal and mechanical properties of structural ceramics, ceramic coatings and ceramic matrix composites. Design and processing issues for these materials are emphasized. Automotive applications of ceramics are discussed. Thermoelectric and other propulsion materials are also discussed.

(5) Design and Manufacturing Considerations for Lightweight Automotive Materials (AE 586) (Instructor: Prof. P. K. Mallick)

This course addresses the design and manufacturing issues for various structural materials considered for lightweight automobiles through case studies and design projects. Design issues include stiffness, fatigue, noise and vibration, dent resistance, crush resistance, etc., whereas manufacturing considerations include formability, moldability, dimensional tolerance, etc. Methods of producing lightweight automotive structures are discussed.

(6) Corrosion and Environmental Degradation of Materials (ME 590) (Instructor: Prof. P. Mohanty)

This course introduces students to the fundamentals of corrosion in metals and degradation behavior of metals, polymers and composites. Monitoring and life prediction techniques are covered. Preventive measures, such as proper material selection and design, protective coatings, surface treatments, inhibitors, are covered. Case studies are used to illustrate how preventive techniques are applied, when they should be used and how various techniques can be integrated to solve complex problems.

In addition to the above graduate level courses in the Automotive Systems Engineering program, students have the option of selecting a variety of graduate courses on materials, manufacturing and design from mechanical, industrial and manufacturing systems, and electrical and computer engineering departments. These courses are listed below:

(1) Advanced Engineering Materials (ME 580)

(2) Mechanical Behavior of Polymers (ME 584)

(3) Materials Considerations in Manufacturing (ME 586)

(4) Composite Materials (ME 589)

(5) Automotive Manufacturing Processes (AE 587)

(6) Injection Molding (ME 582)

(7) Fracture and Fatigue Considerations in Design (ME 558)

(8) Energy Storage (ESE 502)

TABLE 1: Curriculum of Master of Science in Engineering in Automotive Systems Engineering

Required Core: (Six Credit Hours)

AE 500 The Automobile – An Integrated System
AE 587 Automotive Manufacturing Processes

Elective Core: (Six Credit Hours – select any two courses from this group)

AE 502 Modeling of Automotive Systems
AE 505 Digital Systems and Microprocessors
AE 510 Vehicle Electronics I
AE 541 Introduction to Automotive Dynamics
AE 545 Vehicle Ergonomics
AE 547 Automotive Powertrains I
AE 581 Materials Selection in Automotive Design*
AE 583 Project Management and Concurrent Engineering
AE 596 Internal Combustion Engines I

Concentrations: (12 Credit Hours – select four courses from this group)

Electrical and Computer Engineering

ECE 515 Vehicle Electronics II
ECE 531 Intelligent Vehicle Systems
ECE 532 Automotive Sensors and Actuators
ECE 533 Active Automotive Safety Systems
ECE 536 All Weather Automotive Vision
ECE 5462 Electrical Controls for Electric Vehicles
ECE 565 Digital Control Systems

Industrial and Manufacturing Engineering

IMSE 513 Robust Design
IMSE 538 Intelligent Manufacturing Systems
IMSE 561 Total Quality Management
IMSE 593 Vehicle Package Engineering
AE 590 Automotive Assembly Systems**

Mechanical Engineering

ME 537 Automotive Air Conditioning Systems
ME 543 Vehicle Dynamics
ME 545 Acoustics and Noise Control
ME 548 Automotive Powertrains II
ME 597 Internal Combustion Engines II
ME 598 Automotive Emissions
AE 550 Design of Automotive Body and Chassis Systems
AE 650 Design and Analysis for Crashworthiness**

Automotive Materials

AE 584 Lightweight Automotive Alloys*
AE 585 Ceramics for Automotive Applications*
AE 586 Design and Manufacturing with Lightweight Automotive Materials *
AE 588 Design and Manufacturing for Environment**
AE 590E Advanced Steels for Automotive Applications**
ME 583 Mechanical Behavior of Materials
ME 584 Mechanical Behavior of Polymers
ME 587 Automotive Composites*
ME 590 Corrosion and Environmental Degradation of Materials*

Capstone Project or Thesis: (Six Credit Hours)

Note: Courses marked with asterisk were developed during the first GATE funding period (1998-2005). Courses marked with two asterisks were developed during the current GATE funding period (2005-2012)>.

FACULTY

The key faculty members participating in CLAMP's activity are:

(1) Dr. P. K. Mallick, Professor, Department of Mechanical Engineering

Dr. P. K. Mallick serves as the Center's director and was the PI of the current project.. His research interests include mechanical properties and environmental degradation of automotive materials, processing-property-design relationships, composite manufacturing processes and joining of automotive materials

(2) Dr. Ghassan T. Kridli, Associate Professor, Department of Industrial and Manufacturing System Engineering

Dr. Kridli's research interests include forming of lightweight alloys, including hydroforming, warm forming and superplastic forming.

(3) Dr. Elsayed Orady, Professor, Department of Industrial and Manufacturing Systems Engineering

Dr. Orady's research interests include materials processing (especially machining), dimensional measurements, assembly systems, computer-aided manufacturing and robotics.

(4) Dr. Pravansu Mohanty, Professor, Department of Mechanical Engineering

Dr. Mohanty's research interests include spray forming, laser forming, additive manufacturing, nano-structured metals, metal casting and corrosion of materials.

(5) Dr. German Reyes-Villanueva, Associate Professor, Department of Mechanical Engineering

Dr. Reyes-Villanueva's research interests include manufacturing of composite-metal hybrid systems, formability of composite-metal hybrid systems and fracture behavior of nano-reinforced thermoplastic composites.

(6) Dr. Hong Tae Kang, Associate Professor, Department of Mechanical Engineering

Dr. Kang's research interests include fatigue of various materials and their joints including electrical resistance spot weld, gas metal arc weld, and self-piercing riveted

joint for advanced high strength steels, aluminum alloys, and magnesium alloys. He is also working on thermo-mechanical fatigue of cast aluminum alloys and finite element analysis of automotive structures.

3. RESEARCH

Faculty and graduate students working in the Center have conducted a variety of research projects. A list of these projects is given in Table 2. Several of these projects were supported by GATE funding. There were also several external and internal research grants, which provided additional funding for supporting research on advanced automotive materials, manufacturing and joining. A list of CLAMP faculty publications (books, book chapters, journal articles and conference papers) is given in the Appendix.

4. STUDENTS

A list of students participating in CLAMP research and their project titles is given in Table 3. The students were either in the master's program or doctoral program at the university. Partial or full assistantships were provided to at least two students each year for the duration of this project. There were also four undergraduate students who did independent research under the supervision of CLAMP faculty. Two of the undergraduate students were from India and one from South Korea.

5. LABORATORY FACILITIES

Laboratory facilities in the automotive materials area include equipment and instrumentation for mechanical property measurements, materials processing and microstructure examination (Table 4). The laboratory equipment, either upgraded or purchased during the project period, are: (1) upgrading the MTS testing machine with Telstar IIS Controller, (2) upgrading the corrosion laboratory with miscellaneous laboratory equipment, such as a pH meter, ultrasonic cleaner bath, etc. and (3) purchasing the Mettler-Toledo Dynamic Mechanical Analyzer.

6. MATERIALS DATABASE

Upgrading the materials database included the creation of a new web page for CLAMP (www.engin.umd.umich.edu/research/gate/) and linking it to the materials database. The

materials database was originally developed in the first cycle of funding (1998-2005) and included both material property charts and archival information on publications related to automotive materials. The upgrading was completed in the first year of the project current period.

7. INTERACTION AND COLLABORATION WITH INDUSTRY

The CLAMP faculty had several collaborations with the automotive companies and their suppliers. These collaborations were in the form of research funding, summer internships and consulting work. Faculty members also formed research partnerships with the local automotive companies. For example, the research project titled "Adhesive Joining of Magnesium Alloys", which was funded by USAMP, was partially conducted at Ford Motor Co., under the joint supervision of a technical specialist and a CLAMP faculty. A graduate course titled "Advanced Steels for Automotive Applications" was developed with funding from American Iron and Steel Institute (AISI). There was close coordination between AISI and the CLAMP faculty who developed the course.

A graduate certificate program on Automotive Materials was created for engineers and managers from industry who wish to acquire knowledge on structural materials and manufacturing processes related to automotive applications. To receive the certificate, the student must complete four graduate courses in the Automotive Materials area out of the six approved courses. These courses are Materials Selection in Automotive Design (AE 581), Lightweight Automotive Alloys (AE 584), Ceramics for Automotive Applications (AE 585), Design and Manufacturing with Lightweight Automotive Materials (AE 586), Mechanical Behavior of Polymers (ME 584) and Automotive Composites (AE 587).

CLAMP has also organized and held two international conferences, two workshops and one symposium during the project period (Table 5). These events were attended by industry engineers and managers, faculty and students as well as government scientists.

TABLE 2: Research at the Center for Lightweighting Automotive Materials and Processing (CLAMP) (2005-2012)

Titles of Research Projects	Faculty	Sponsor
Effect of Surface Treatment on Adhesive Joining of Magnesium Alloys	P.K. Mallick	USAMP
Evaluation of Titanium for Vehicle Fuel Economy and Performance Improvement	P. K. Mallick	PNNL
Fatigue Performance of Fusion Welded Joints in Sheet Steels	H.T. Kang	Auto/Steel Partnership
Variability Study of Spot Weld Specimens for Advanced and Traditional High Strength Steels	H.T. Kang	Auto/Steel Partnership
Investigation of Forming Effect on Fatigue Strength of Dual Phase and TRIP Sheet Steels	H.T. Kang	Center for Engineering Education and Practice
Development of Coupled Thermo-Mechanical Finite Element Analysis Tools for Simulating Warm Forming Processes	G. T. Kridli	Ford Motor Co.
Development of CAE Tools and Design Guidelines for the Implementation of FAST (Ford Advanced Superplastic Forming Technology)	G. T. Kridli	Ford Motor Co.
Development of a Test Method for Determining Hydroformability of Aluminum Alloys	G.T. Kridli/ P. K. Mallick	CLAMP (GATE)
Development of Aluminum Frame for a Fuel Cell Scooter	H. T. Kang	Asian Pacific Fuel Cell Technologies
Development of Spot Friction Welding between Mg-Mg, Mg-Al and Mg-Nylon	H.T. Kang and P.K. Mallick	CLAMP (GATE)
Development of Thermoplastic Matrix Composites for Structural Automotive Applications	P. K. Mallick and G. Reyes-Villanueva	CLAMP (GATE)
Study on the Crush Resistance of Composite Plates	G. Reyes-Villanueva and P. K. Mallick	CLAMP (GATE)
Numerical Process Simulation of Self-Piercing Rivet Joint for Magnesium Alloys	H.T. Kang	Faculty Research Grants, University of Michigan-Dearborn
Numerical Simulation for Spot Friction Welding Process of Magnesium Alloys	H.T. Kang	The University of Michigan-Ann Arbor
Investigating the Superplastic Behavior of Twin-Roll Cast Magnesium Alloys for Effective Use in Automotive Applications	G.T. Kridli	Qatar National Research Fund
Development of Composite Sandwich Panels with Corrugated Core for Automotive Body Applications	P.K. Mallick	CLAMP (GATE)
Biaxial Fatigue of Glass and Carbon Fiber Composites	P.K. Mallick	CLAMP (GATE)
Investigation of Thermo-Mechanical Fatigue Characteristics for Cast Aluminum (AL319-T7)	H.T. Kang	Chrysler LLC.

Table 3: Students Participating in CLAMP Research and their Project Titles

Student	Project Title
Garun Agarwal (MSE)	Study of Flow and Compressibility in the Development of Thermoplastic Matrix Composite Prepreg by Film Stacking Technique
Lavish Agarwal (MSE)	Spot Friction Welding of Mg-Mg, Al-Al and Mg-Al Alloys
Shardul Bhambure (MSE)	Stress Analysis of Adhesive Joints with Magnesium Substrates
Brandon Fell (MSE)	Elliptic Composite Springs for Vehicle Suspensions
Ananth Kamath (MSE)	Preliminary Investigation into Flaring as a Test for Tube Hydroformability
Raghuram Mandapati (MSE)	Fatigue Performance of Gas Metal Arc Welded Joints in Advanced Steels
Sahuraj Mane (MSE)	Crush Behavior of Thin Composite and Aluminum Plates
Anand Pandy (MSE)	Simulation of Heat Transfer during Processing of Thermoplastic Matrix Composites
Cody Ragone (MSE)	Development of a Thermoplastic Prepreg Manufacturing Process by Continuous Resin Infusion
Brent Rajaniemi (MSE)	Effects of Crush Initiators on the Crush Behavior and Energy Absorption of Aluminum, Composite and Hybrid Round Tubes
Shivanand Sankaran (MSE)	Fatigue Properties of Injection Molded Short Glass Fiber Reinforced Polyamide-6,6
Siddharth Valluri (MSE)	Tensile and Fatigue Performance Evaluation of Two Lightweight Fiber-Reinforced Composites for Automotive Applications
Wenchao Wang (MSE)	Adhesive Joining of Magnesium Alloys
Senthil Arul (D.Eng.)	Experimental Analysis of Spot Friction Welding of 6111-T4 Aluminum Alloy
Rajesh Kumar Boorle (Ph.D.)	Bending and Vibration Response Characteristics of Composite Sandwich Structures with Corrugated Core Construction
Raghuram Mandpati (Ph.D.)	Study of Biaxial Fatigue of Fiber Reinforced Composites under Normal and Shear Loads
Frank Morelli (Undergraduate)	Crush Resistance of Polycarbonate Tubes
Pranab Sen Choudhury (Undergraduate)	Effect of Biodiesel on the Tensile Properties of Nylon 6
Bishal Mazumdar (Undergraduate)	Effect of Silane Coupling Agent on the Tensile and Flexural Properties of E-glass Fiber Reinforce Nylon-6 Prepregs and Laminates
Soon Kim (Undergraduate)	The Influence of Injection Molding Conditions and Moisture-absorption on the Flexural Properties of a short E-glass fiber/Polyamide-6,6 Composites

TABLE 4: Laboratory Facilities in Automotive Materials and Processing Research

Laboratory	Major Equipment	Major Function
Materials Testing Laboratory	Three MTS Servohydraulic Testing Machines with Environmental Chamber and High Temperature Testing Facility	Tension/Compression/Bending Fatigue Tests
	Instron Testing Machine	Quasi-static Tension/Compression/ Bending/Shear Tests
	Dynatup Drop Weight Testing Machine	Low Energy Impact Tests
	Plate Bending Fatigue Machine	Fatigue Testing in Bending Mode
	Fast Fourier Transform Vibration Testing	Resonant Frequency and Damping Factor
	ARAMIS Strain Measuring System	3-D Strain Measurement in Quasi-static and Dynamic Tests
	Mettler-Toledo Dynamic Mechanical Analyzer	Dynamic Testing of Polymers, Elastomers and Adhesives
Plastics and Composites Processing Laboratory	Injection Molding Machine	Injection Molding of Thermoplastics
	Hydraulic Press with Heated Platens	Compression Molding and Press Forming
	Filament Winding Machine	Filament Winding of Tubes
	Ovens	Heating/Curing
Metals Forming Laboratory	Interlaken Servohydraulic Forming Press	Formability Tests, Hydroforming Experiments
	Two-Roll Mill	Sheet Rolling
Optical Microscopy and Metallography Laboratory	Leica Optical Microscope with Insight Image Analysis Software	Optical Microscopy with Image Processing
	Clark Microhardness Tester	Knoop and Vickers Microhardness Measurement
	Cutting, Mounting Polishing Equipment	Metallographic Specimen Preparation
	Leica Stereo Microscope	Optical Microscopy
Electron Microscopy Laboratory	Scanning Electron Microscope (Hitachi S-2600N)	Fracture Surface Observation
	Transmission Electron Microscope (Hitachi-7000)	Metallographic Observation
	Scanning Probe Microscope, (Quesant-3000)	
Corrosion Laboratory	Camry Potentiostat	Corrosion Rate Measurement
	Solartron and Biologic Multichannel System	
Metrology Laboratory	Brown and Sharpe and Sheffield Coordinate Measurement Machines (CMM), Surface Roughness Tester, Toolmaker's Microscope	Dimensional Measurements

TABLE 5: Symposia, Workshops and Conferences organized/co-organized by CLAMP (2005-2012)

Title	Year
First Canada-China-USA Workshop on Magnesium	October 17-19, 2005
21st Annual Technical Conference of the American Society for Composites	September 17-20, 2006
12th US-Japan Conference on Composite Materials	September 21-22, 2006
Workshop on Fuel Cells: Materials and Manufacturing Issues	June 20, 2007
Symposium on Materials for Lightweight Vehicles	December 8, 2009

CONCLUSIONS

The goal of the proposal was to improve, expand and update the interdisciplinary graduate studies program and research on lightweight automotive materials initiated at the Center for Lightweighting Automotive Materials and Processing (CLAMP) in 1998 using the first cycle of GATE funding. The Center has developed significant experience in educating graduate engineering students in lightweight automotive materials and manufacturing processes, and preparing them for designing future generation vehicles that would be lightweight, structurally safe and fuel-efficient. The students in this program are either working professionals in the automotive industry or have joined the automotive industry after graduation. The education they have received at the Center has helped them incorporate and promote advanced automotive materials technologies for the design and manufacturing of automobiles and automobile parts, and therefore can be considered the best way to overcome the advanced automotive technology implementation barrier.

APPENDIX

PUBLICATIONS BY CLAMP FACULTY (2005-2012)

Books and Book Chapters

Mallick. P.K., *Fiber Reinforced Composites: Materials, Manufacturing and Design*, 3rd edition, CRC Press, Inc., N.Y., 2008

Mallick. P.K. (ed.), *Materials, Design and Manufacturing for Lightweight Vehicles*, editor and author of four chapters in the book, Woodhead Publishing Ltd., Cambridge, UK, 2010.

Kridli, G.T., Friedman, P.A., and Boileau, J.M., *"*Manufacturing Processes for Lightweight Alloys", *Materials, Design and Manufacturing for Lightweight Vehicles*, (editor: P.K. Mallick), Woodhead Publishing Ltd., Cambridge, UK, p. 235-274, 2010.

Lee,Y.-L, Barkey, M.E., and Kang, H., *"Metal Fatigue Analysis Handbook: Practical Problem-Solving Techniques for Computer-Aided Engineering"*, Butterworth-Heinemann, London, UK, 2011.

Mallick, P.K, "Testing the Fatigue Strength of Fibers used in Fiber Reinforced Composites using Fiber Bundle Tests," invited chapter author in *Creep and Fatigue in Polymer Matrix Composites* (editor. R.M. Guedes), Woodhead Publishing Ltd., Cambridge, UK, 2011.

Mallick, P.K., "Testing of Fatigue Strength of Fibers used in Fiber-Reinforced Composites using Fiber Bundle Tests", invited chapter author in the book *Creep and Fatigue in Polymer Matrix Composites*, (editor: R.M. Guedes), Woodhead Publishing Ltd., Cambridge, UK. 2011.

Mallick, P.K., *"*Advanced Materials for Automotive Applications: An Overview", invited chapter author in the book *Advanced Materials in Automotive Engineering* (editor: J. Rowe), Woodhead Publishing Ltd., Cambridge U.K., p.5-26, 2012.

Mallick, P. K., "Failure of Polymer matrix Composites (PMCs) in Automotive and Transportation Applications", invited chapter author in *Failure Mechanisms in Polymer Matrix Composites* (editors: P. Robinson, E. Greenhalgh and S. Pinho), Woodhead Publishing Ltd., Cambridge U.K., p.368-390, 2012.

Journal and Conference Articles

1. G. Reyes-Villanueva and S. Gupta, "Formability Analysis of Thermoplastic Fiber-Metal Laminates", Proc. 20th Annual Technical Conference, American Society for Composites, Philadelphia, PA, 2005.
2. C. Dandekar, E. Orady and P. K. Mallick, "Drilling Characteristics of an E-glass Fabric Reinforced Polypropylene Composite", Proc. 21st Annual Technical Conference, American Society for Composites, Dearborn, MI, September 2006.
3. F. Pervin, Y. Zhou, S. Jeelani and P. K. Mallick, "Improvement in Mechanical Properties of Carbon Nanofiber Filled Carbon-Epoxy Composite", Proc. 21st Annual

Technical Conference, American Society for Composites, Dearborn, MI, September 2006.

4. G. Reyes-Villanueva and S. Gupta, "Interfacial Fracture Properties of Environmentally Friendly Hybrid Systems", Journal of Materials Sci., 41, *18*, 2006.
5. G. Reyes-Villanueva and S. Gupta, "Interfacial Fracture in Environmentally Friendly Thermoplastic Composite-Metal Laminates," 2006 SAE World Congress, Detroit, MI, 2006-01-0117, 2006.
6. G. Reyes-Villanueva, H. Kang, R. Singh and S. Gupta, "Formability Analysis of Thermoplastic Lightweight Fiber-Metal Laminates," 2006 SAE World Congress, Detroit, MI, 2006-01-0118, 2006.
7. G. Reyes-Villanueva, "Failure mechanisms in FML Reinforced Aluminum Foam Sandwich Structures", Proc. 2006 SAMPE Symposium and Exhibition, Long Beach, CA, 2006.
8. Kang H. and Reyes-Villanueva G., "Fatigue Response of Lightweight Thermoplastic Fiber-Metal Laminates", Proc. 9th International Fatigue Congress, Atlanta, GA, 2006.
9. Reyes-Villanueva G. and S. Gupta, "Interfacial Fracture Properties of Thermoplastic Composite-Metal Hybrid Laminates Based on Automotive Grade Steels", Proc. 21st Annual Technical Conference, American Society for Composites, Dearborn, MI, 2006.
10. Bonnen, J. J., Kang, H. T., Amaya, M. A., Iyengar, R. M., Yan, B., Link, T. M., Agrawal, H. N., Walp, M. S., Khosravaneh, A. K., and Shih, M., "Fatigue of Advanced High Strength Steel Spot Welds," SAE Paper No. 2006-01-0978, SAE World Congress, Detroit, 2006.
11. Kang, H. T. and Reyes-Villanueva G., "Fatigue Prediction of Lightweight Thermoplastic Fiber-Metal laminates", Journal of Testing and Evaluation, 35, 3, 2007.
12. Reyes-Villanueva G. and Kang H.T., "Mechanical Behavior of Lightweight Thermoplastic Fiber-Metal laminates", Journal of Materials Processing Technology, Vol. 186, pp. 284-290, 2007.
13. Reyes G., Farha E., Lotfi N., Al-Mutar A., Rasheed A., "Mechanical Response of Composite Reinforced Aluminum Foam Sandwich Structures for Automotive Structures", SAE Paper No. 2007-01-17222007 SAE World Congress, Detroit, MI, 2007
14. Gupta S. and Reyes G., "Fracture Properties of Thermoplastic Hybrid Laminates Based on Automotive Grade Steel", Proceedings of the SAMPE 2007 Symposium and Exhibition, Baltimore, PA, 2007.
15. Le, Quochung, Kang, H., Khosrovaneh, A., Sa, C.Y. and Yan, B., "Prestrain Effect on Fatigue of DP600 Sheet Steel," SAE Paper No. 2007-01-0995, SAE World Congress, Detroit, 2007.
16. Balakrishnan, K., Kang, H. and Mallick, P.K., "Joining Aluminum with Nylon Using Frictional Heat," SAE Paper No. 2007-01-1701, SAE World Congress, Detroit, 2007.

17. Kang, H. T. and Li, N., "Microstructure and Mechanical Properties of Magnesium Alloy AM60 and its Cast Processing Conditions," TMS 2007, 136th Annual Meeting & Exhibition, Orlando, February, 2007.

18. Kang, H.T., Mohan Iyenga, R. and Bonnen, J., "Variability of Fatigue Strength of Spot Welded Specimens for Advanced and Traditional High Strength Steels," Materials Science and Technology 2007, Detroit, September, 2007.

19. Kang, H. T., "Fatigue Prediction of Spot Welded Joints Using Equivalent Structural Stress," Materials & Design, Vol. 28, pp. 837-843, 2007.

20. Bonnen, J., Agrawal, H. N., Amaya, M. A., Kang, H. T., Khosravaneh, A. K., Link, Todd M., Mohan Iyengar, R., Shih, M., Walp, M., Scott, M. and Yan, B., "Fatigue of Advanced High Strength Steel Spot Welds," SAE Transactions Journal of Materials & Manufacturing, pp.726-744, 2007.

21. Reyes-Villanueva, G. and Kang, H., "Mechanical Behavior of Lightweight Thermoplastic Fiber-Metal Laminates", Journal of Materials Processing Technology, Vol. 186, pp. 284-290, 2007.

22. Kang, H. T., Dong, P., and Hong, J., "Fatigue Analysis of Spot Welds using a Mesh-Insensitive Structural Stress Approach", International Journal of Fatigue, Vol. 29, pp. 1546-1553, 2007.

23. Kang, H. and Reyes-Villanueva, G., "Fatigue Test and Prediction of Lightweight Thermoplastic Fiber-Metal Laminates", Journal of Testing and Evaluation, Vol. 35, pp. 266-271, 2007.

24. Yoon, D., Shen, J., Ohou, E. and Orady, E., "Simulating Multi-Axis Machining Using NURBS and Quaternions", J. Computer-Aided Design & Applications, Vol.4, No. 1-4, pp 49-56, 2007.

25. Dandekar, C., Orady, E. and Mallick, P. K., "Drilling Characteristics of an E-glass Fabric Reinforced Polypropylene and an Aluminum Alloy: A Comparative Study", J. Manufacturing Science and Engineering, ASME Trans., Vol. 129, No.6, pp. 1080-1087, 2007.

26. Park, J. M. and Kang, H.T., "Prediction of Fatigue Life for Spot Welds using Back-Propagation Neural Networks", Materials & Design, Vol. 28, pp. 2577-2584, 2007.

27. Kang, H.T., Lee, Y-L, Chen, J. and Fan, D., "A Thermo-Mechanical Fatigue Damage Model for Variable Temperature and Loading Amplitude Conditions", International Journal of Fatigue, Vol. 29, pp. 1797-1802, 2007.

28. Zhou, Y., Pervin, F., Jeelani, S. and Mallick, P.K., "Improvement in Mechanical Properties of Carbon Fabric-Epoxy Composite using Carbon Nanofibers", J. Materials Processing Technology, Vol. 198, pp. 445-453, 2008.

29. Arul, S.G., Miller, S.F., Kruger, Pan, T.-Y., Mallick, P.K. and Shih, A.J., "Experimental Study of Joint Performance in Spot Friction Welding of 6111-T4 Aluminum Alloy", Science and Technology of Welding and Joining, Vol. 13, pp. 629-637, 2008.

30. Kang, H.T and Ostrom, T., "Mechanical Behavior of Cast and Forged Magnesium Alloys and their Microstructures," Materials Engineering and Science A, Vol. 490, pp. 52-56, 2008.
31. Shi, Z., Mallick, P.K. and McCune, R.C., "Characterization of Film Formation on Magnesium Alloys due to Corrosion in Engine Coolants", SAE Paper No. 2008-01-1155, 2008 World Congress, Society of Automotive Engineers, Detroit, MI, April, 2008.
32. Agarwal, L., Mallick, P.K. and Kang, H.T., "Spot Friction Welding of Mg-Mg, Al-Al and Mg-Al Alloys", SAE Paper No. 2008-01-0144, 2008 World Congress, Society of Automotive Engineers, Detroit, MI, April, 2008.
33. Mohan Iyenger, R. Amaya, M., Bonnen, J., Citrin, K., Kang, H.T., Laxman, S. Khosrovaneh, A.K. and Schillaci, N., "Influence of Geometric Parameters and their Variability on Fatigue Resistance of Spot-Weld Joints", SAE Paper No. 2008-01-0698, 2008 World Congress, Society of Automotive Engineers, Detroit, MI, April, 2008.
34. Reyes-Villanueva, G. and Kang, H.T., "Non-Contact Full Field Strain Analysis of Engineering Materials: Lightweight Multifunctional Aluminum Foam Sandwich Structures and Spot-Welded High Strength Steels", Proceedings of 2008 NSF Engineering Research and Innovation Conference, Knoxville, TN, January, 2008.
35. Giefer, B. and Mallick, P.K., "Effect of Processing Parameters on the Strength of Resin Infused Polyamide-6 Impregnated Glass Fabric Composite", 23rd Annual Tech. Conference, American Soc. for Composites, Memphis, TN, September, 2008.
36. Ragone, C. and Mallick, P.K., "Development of a Thermoplastic Prepreg Manufacturing Process by Continuous Resin Infusion", SAMPE Fall Conference, Memphis, TN, September, 2008.
37. Kang, H.T., Lee, Y.-L., Sun, X.J., "Effects of Residual Stress and Heat Treatment on Fatigue Strength of Weldments", Materials Science and Engineering: A, Vol. 497, Issue 1-2, pp. 37-43, 2008.
38. Ho, S., Lee, Y.-L., Kang, H.T. and Wang, C.J., "Optimization of a Crankshaft Rolling Process for Durability", International Journal of Fatigue, Vol. 31, pp. 799-808, 2009.
39. Le, Q., Kang, H.T., Kridli, G.T, Khosrovaneh, A.K. and Yan, B., "Effect of Pre-strain Paths on the Mechanical Behavior of Dual Phase Sheet Steel", International Journal of Fatigue, Vol. 31, pp. 607-615, 2009.
40. Reyes, G. and Gupta, S., "Manufacturing and Mechanical Properties of Thermoplastic Hybrid Laminates based on DP500 Steel", Composites, Part A, Vol. 40, No. 2, pp. 176-189, 2009.
41. Mane, S.T., Reyes, G. and Mallick, P.K., "Crush Behavior of Thin Composite Plates", Proc. 24th Annual Technical Conference, American Society for Composites, Newark, DE, September, 2009.

42. Sankaran, S. and Mallick, P. K., "Fatigue Properties of Injection Molded 33% E-glass Fiber Reinforced Polyamide-6,6", 9th Annual SPE Automotive Composites Conference, Troy, MI, September, 2009.

43. Mallick, P.K. and Ragone, J.C., "The Effect of Process Parameters on the Quality of Resin Infused Thermoplastic Matrix Prepregs", 17th International Conference on Composite Materials, Edinburgh, Scotland, July, 2009.

44. Mallick, P.K. and Agarwal, L., "Fatigue of Spot Friction Welded Joints in Mg-Mg, Al-Al and Al-Mg Alloys", SAE Technical Paper 2009-01-0024, 2009 SAE World Congress, Soc. of Automotive Engineers, Detroit, MI, April, 2009.

45. Lazarz, K., McCune, R.C., Wang, W. and Mallick, P.K., "Effect of Surface Pretreatment on Adhesive Bonding and Corrosion Resistance of AM60B, AZ31-H24 and AM30 Magnesium", SAE Technical Paper 2009-01-0037, 2009 SAE World Congress, Soc. of Automotive Engineers, Detroit, MI, April, 2009.

46. Bhise, V.D., Mallick, P.K. and Sarma, V.H., "Determining Perceptual Characterization of Automotive Interior Materials", SAE Technical Paper 2009-01-0017, 2009 SAE World Congress, Soc. of Automotive Engineers, Detroit, MI, April, 2009.

47. Shi, Z., Mallick, P.K. and McCune, R.C., "Study of Cathodic Metal Transfer to Magnesium Surfaces in Aqueous Environments and Engine Coolant Formulations by Surface Analytic Methods", 2009 Magnesium Technology, TMS Conference, San Francisco, February 2009.

48. Mao, J., Shen, J., Reyes, G., and Chow, C.L., "A Multi-Resolution Transformation Rule of Material Defects," International Conference on Nanoscience & Technology, China NANO, Beijing, China, September 1-3, 2009.

49. Shen, J., Mao, J., Reyes, G., and Chow, C.L., "A Multi-resolution Transformation Rule of Material Defects", International Journal of Damage Mechanics, Vol. 18, pp. 739-758, 2009.

50. Bonnen, J.J., Mandapati, R., Kang, H.T., Mohan Iyengar, R., Khosrovaneh, A.K., Amaya, M.A., Citrin, C., and Shih, H.C., "Durability of Advanced High Strength Steel Gas Metal Arc Welds" , SAE International Journal of Materials Manufacturing, Vol. 2, No. 1, pp.155-171, 2009.

51. Reyes, G. and Sharma, U., "Analysis of Woven Glass Fiber Reinforced Thermoplastic Composites under Varying Strain Rates," Proceedings of SPE Automotive Composites Conference and Exhibition, Detroit, MI, September 15-16, 2009.

52. Sankaran, S. and Mallick, P.K., "Fatigue Properties of Injection Molded 33% E-glass Fiber Reinforced Polyamide 6.6," Society of Plastics Engineers-Automotive Composites Conference and Exhibits, Troy, MI, September 2009.

53. Reyes, G. and Rangaraj, S., "Interfacial Fracture Properties of Carbon Foam / PEEK Sandwich Structures", Proceedings of SAMPE 2009 Fall Technical Conference, Wichita, KS, October 19-22, 2009.

54. Reyes, G. and Sharma, U., "Effect of Loading Rate on the Mechanical Behavior of Woven Thermoplastic Composites", Proceedings of SAMPE 2009 Fall Technical Conference, Wichita, KS, October 19-22, 2009.

55. Lei, Z., Kang, H.T., and Reyes, G., "Full Field Strain Measurement of Resistant Spot Welds Using 3D Image Correlation Systems," Experimental Mechanics, Vol. 50, No. 7, pp. 111-116, 2010.

56. Kang, H.T., Accorsi, I., Patel, B., and Pakalnins, E., "Fatigue Performance of Resistance Spot Welds in Three Sheet Stack-ups", Procedia Engineering , Vol. 2, Issue 1, pp. 129-138, 2010.

57. Sistla, P. and Kang, H.T., "Twist Beam Suspension Design and Analysis for Vehicle Handling and Rollover Behavior", SAE 2010 World Congress, Paper No. 2010-01-0085, Detroit, MI, April 13-15, 2010.

58. Garware, M., Kridli, G.T., and Mallick, P.K., "Tensile and Fatigue Behavior of Friction-Stir Welded Tailor-Welded Blank of Aluminum Alloy 5754," Journal of Materials Engineering and Performance, January 14, 2010.

59. Shi, Z., Mallick, P.K., McCune, R.C., Simko, S., and Naab, F., "A Study of Corrosion Film Growth on Pure Magnesium and a Creep Resistant Magnesium Alloy in an Automotive Engine Coolant", 2010 Magnesium Technology, 139th TMS Annual Meeting, Seattle, WA, February 2010.

60. Hociota, D.I. and Mallick, P.K., "A Parametric Design and Formability Study of Boron Steel Bumper Beams", 2010 SAE World Congress, Paper No. 2010-01-0433, Detroit, MI, April 2010.

61. Sarma, V.H., Bhise, V.D., and Mallick, P.K., "Effect of Material Type, Surface Roughness Compressibility, Shape, Gender, Age, and Sense Modality on Perception of Automotive Interior Materials," 2010 SAE World Congress, Paper No. 2010-01-0682, Detroit, MI, April 2010.

62. Awad, M., Orady, E. and Dandekar, C., "Drilling Process Robust Optimization for 6061 Aluminum Using Desirability functions", ALHOSN J. of Engineering and Applied Sciences, Vol. 3, No. 1, pp. 75-85, July 2010.

63. Reyes, G., and Sharma, U., "Modeling and Damage Repair of Woven Thermoplastic Composites Subjected to Low Velocity Impact," Composite Structures, Vol. 92, pp. 523-531, 2010.

64. Reyes, G. "Mechanical Behavior of Thermoplastic FML Reinforced Sandwich Panels Using an Aluminum Foam Core: Experiments and Modeling", Journal of Sandwich Structures and Materials, Vol. 12, pp. 81-96, 2010.

65. Li, B. and Kang, H., "Temperature Distribution during Friction Stir Spot Welding of Magnesium Alloys," Journal of Testing and Evaluation, Vol. 39, No. 1, pp. 16-24, 2011.

66. Lee, Y.-L., Polehna, D., and Kang, H., "Fatigue Damage Severity Calculation for Vibration Tests," Journal of Testing and Evaluation, Vol. 38, No. 6, pp. 707-716, 2010.

67. Fell, B. and Mallick, P.K., "Stiffness and Fatigue Behavior of Composite Elliptic Springs", Proc. 25th Annual Tech. Confer., American Society for Composites, Dayton, OH, September, 2010.

68. Valluri, S., Sankaran, S., and Mallick P.K., "Tensile and Fatigue Performance of a Self-Reinforced Polypropylene," Society of Plastics Engineers-Automotive Composites Conference and Exhibition, Troy, MI, September, 2010.

69. Bhise, V. and Mallick, P.K., "Relationship between Subjective and Objective Surface Characteristics of Automotive Interior Materials," SPE Automotive TPO Global Conference, Sterling Heights, MI, October 3-6, 2010.

70. Shulze, R. and Mallick, P.K., "How the University of Michigan-Dearborn Prepares Engineering Graduates for Careers in Automotive Systems Engineering," *SAE* Convergence, SAE Technical Paper No. 2010-01-2327, Detroit, MI, November, 2010.

71. Mohan Ram, S. and Kang, H., "Investigation of Hole Expansion Characteristics of DP600 with Testing and Modeling," 2010 ASME Internal Mechanical Engineering Congress and Exposition, Paper No.: IMECE 2010-39455, Vancouver, British Colombia, Canada, November 12-18, 2010.

72. Ng, J., Kridli, G., Luckey, S.G. and Friedman, P.A., "Development and Validation of an Analytical Seal Bead Design Model for Automotive Superplastic Forming," SAE International Journal of Materials and Manufacturing, Vol. 3, pp. 682-690, 2010.

73. Kim, W., Kwon, J., Kang, H., Koo, G., and Kim, T., "Development of Advanced Fatigue Evaluation Methodology for Monitoring Major Components in Nuclear Power Plant," ASTM 2010 Pressure Vessels and Piping Division/K-PVP Conference, Paper No. PVP2010-25585, Bellevue, WA, July 18-22, 2011.

74. Kang, H., Khosrovaneh, A.K., Link, T., Bonnen, J.J., Amaya, M.A., and Shih, H.-C., "The Effect of Welding Dimensional Variability on the Fatigue Life of Gas Metal Arc Welded Joints", SAE Paper No. 2011-01-0196, SAE World Congress, Detroit, 2011.

75. Kang, H., Khosrovaneh, A.K., Amaya, M.A., Bonnen, J.J., Shih, H.-C., Mane, S., and Link, T., "Application of Fatigue Life Prediction Methods for GMAW Joints in Vehicle Structures and Frames," SAE Paper No. 2011-01-0192, SAE World Congress, Detroit, 2011.

76. Ng, J., Luckey, S.G., Kridli, G. and Friedman, P.A., "Validation of a Modified Material Model for use with Shell Elements to Accurately Predict the Thickness Distribution in Superplastic Forming of Sheet Metal," Journal of Materials Processing Technology, Vol. 211, pp 1386-1394, 2011.

77. Zhou, Y. and Mallick, P.K., "Fatigue Performance of Injection-Molded Short E-glass Fiber Reinforced Polyamide 6,6. II. Effects of Melt Temperature and Hold Pressure," Polymer Composites, Vol. 32, pp. 268-276, 2011.

78. Mallick, P.K., "Crush Behavior of Aluminum, Composite and Aluminum/Composite Hybrid Tubes under Quasi-Static Loading," International Conference on Composites for 21st Century, Bangalore, India, January, 2011.

79. Bhambure, S. and Mallick, P.K. "Analysis of Single Lap Adhesive Joints Between Magnesium and Other Structural Automotive Materials", SAE Paper No. 2011-01-0076, SAE World Congress, Society of Automotive Engineers, Detroit, 2011.

80. Reyes, G. and Rangaraj, S., "Fracture Properties of High Performance Carbon Foam Sandwich Structures", Composites Part A, Vol. 42, pp. 1-7, 2011.

81. Vincent, A., Bhise, V. and Mallick, P.K., "Seat Comfort as a Function of Occupant Characteristics and Pressure Measurements at the Occupant-Seat Interface", SAE Technical Paper No. 2012-01-0071, 2012 SAE World Congress, Society of Automotive Engineers, Detroit, MI, April 2012

82. Sen Choudhury, P. and Mallick, P. K., "Effect of Bio-Diesel on the Tensile Properties of Nylon-6", SAE Technical Paper No. 2012-01-0752, 2012 SAE World Congress, Society of Automotive Engineers, Detroit, MI, April 2012

83. Bhambure, S. and Mallick, P.K., "Effect of Temperature Variation on Stresses in Adhesive Joints between Magnesium and Steel", SAE Technical Paper No. 2012-01-0771, 2012 SAE World Congress, Society of Automotive Engineers, Detroit, MI, April 2012

84. Zhou, Y., Hosur, M., Jeelani, S. and Mallick, P.K., "Fabrication and Characterization of Carbon Fiber Reinforced Clay/Epoxy Composite", J. Materials Science, Vol. 47, No. 12, p. 5002-5012, 2012

85. Boorle, R. K. and Mallick, P. K., "Global Bending Response of Composite Sandwich Structures with Corrugated Core using Potential Energy Approach", 27th Annual Tech. Conference, American Soc. for Composites, Arlington, TX, October 2012

86. Mandapati, R. and Mallick, P. K., "Development of a Biaxial Fatigue Test for Laminated Composite Plates under Normal and Shear Loadings", 27th Annual Tech. Conference, American Soc. for Composites, Arlington, TX, October 2012