12. MATERIALS CROSS-CUTTING R&D

A. Technical Cost Modeling

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Contractor: Oak Ridge National Laboratory (ORNL)
Contract No.: DE-AC05-00OR22725

Objectives

- Address the economic viability of new and existing lightweight materials technologies.
- Develop technical cost models to estimate the cost of lightweight materials technologies.

Approach

- Address the economic viability of lightweight materials technologies supported by the Lightweighting Materials (LM).
- Use cost modeling to estimate specific technology improvements and major cost drivers that are detrimental to the economic viability of these new technologies.
- Derive cost estimates based on a fair representation of the technical and economic parameters of each process step.
- Provide technical cost models and/or evaluations of the “realism” of cost projections of lightweight materials projects under consideration for LM funding.
- Examine technical cost models of lightweight materials technologies that include (but are not limited to) aluminum (Al) sheet; carbon-fiber precursor and precursor processing methods; fiber-reinforced polymer composites; and methods of producing primary Al, magnesium (Mg), and titanium (Ti) and Mg alloys with adequate high-temperature properties for powertrain applications.

Accomplishments

- An update of primary Mg production-cost estimates for automotive applications was completed. One of the two journal articles submitted based on the last fiscal year (FY) report on the cost-benefit evaluation of the Phase II LM projects funded during the FY 2000-2004 period was accepted for publication in Research Evaluation. Life-cycle inventory data collection for several Mg manufacturing technologies was completed and a paper was published on the preliminary, comparative life-cycle assessment of a lightweight automotive part.

Future Direction

- Complete the life-cycle analysis task for the multinational Mg Front End Research and Development (MFERD) project (see 6.C). A life-cycle assessment of carbon-fiber polymer composites will also be initiated.
- Complete a cost assessment of the proposed LM future vehicle weight reduction goal of 50% by the year 2011, starting with 25 % in 2008.
- Continue individual project-level cost modeling to identify specific technology improvements and major cost drivers that are detrimental to the economic viability of these technologies.

Primary Mg Production Cost Assessment Update

This activity updated earlier, FY 2002 work which focused on primary Mg production cost estimates to provide a sound forecast of the long-term competitiveness of Mg in automotive applications. Competing Mg production technologies are considered in this assessment, with particular emphasis on the long-term viability of the inexpensive supplies using Chinese production technology. Also considered in the comparative production-cost analysis are two yet-to-be-commercialized production processes. Production-cost estimates of competing technologies are disaggregated by major cost categories using the most recent information available from the literature. At first, the recent price trend and the weight-savings potential of competing materials are considered to determine what the primary Mg production costs need to be for Mg to be a viable material/technology option now and in the coming decade. A discussion of the future viability of Mg use in automotive applications based on the potential sources of Mg for the U.S. market, the recent supply trend, production-cost estimates, and potential demand has also been covered in this assessment.

Five primary Mg production processes are considered in this assessment:
- Conventional western electrolytic reduction
- Western Pidgeon (thermal reduction)
- Chinese Pidgeon (thermal reduction)
- Carbothermic, and
- Solid oxygen-ion conducting membrane (SOM) technology developed by Boston University.

The SOM technology, which is still at the laboratory-scale, is electrochemical in nature. A current is passed through a flux containing Mg oxide in a stainless steel crucible, which works as a cathode.

Figure 1 shows an operating cost range of \$0.52–\$0.87/lb and total production cost range of \$0.62–\$1.41/lb for the five production processes considered here. Major contributors to cost-effectiveness of the conventional Mg production processes lie in capital and raw material costs for electrolytic and thermal reduction processes, respectively. The lower cost of materials under the electrolytic reduction is due to credits taken for by-products produced. Fluctuations in the market price of raw materials would have greater impact on the total cost of thermal-reduction processes. Numerous processing steps for raw minerals contribute significantly to the higher conventional electrolytic production cost. Because of financial constraints, electrolytic plant expansions are unlikely, although expansion could reduce per-unit overhead costs. Capital costs continue to cause significant financing problems for proposed new electrolytic production capacity in Western economies. The projected Mg cost estimate is consistent with the Mg price projection of \$1.27/lb made by North Pacific Alloys for the technical and economic viability of a proposed 150,000 tonnes/year Mg extraction plant from Mg silicates.

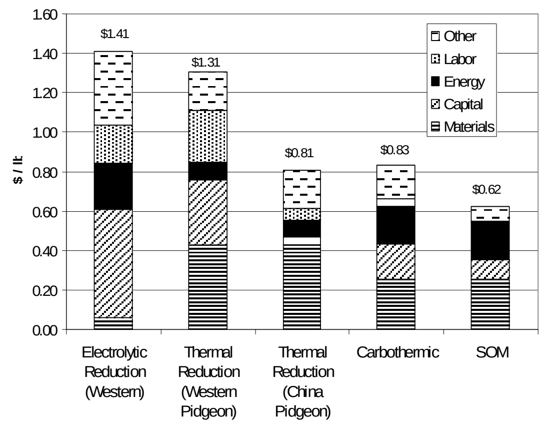

Figure 1. Production cost of major primary Mg production technologies.

The estimated total Chinese Mg production cost is around $0.81/lb—consistent with the Chinese free-market Mg price observed during the past few years. This cost is significantly lower than the estimated Mg production cost of $1.41/lb and $1.31/lb for the Western electrolytic and thermal producers, respectively. China's significantly lower capital and labor costs and its position as the world's biggest producer of ferrosilicon help it to maintain its role as the low-price world Mg supplier. It appears that, in past years, Chinese producers have fully recovered their production costs. With Chinese business becoming increasingly motivated by profits and with Chinese producers having attained significant market share, the Chinese Mg market price has increased and may remain high in the future. In fact, Mg prices in China increased steadily in 2006 after the export rebate on all Mg products was reduced to 5% from 13% at the end of 2005. By the end of the second quarter of 2007, free-market Chinese Mg has increased to $1.18-$1.23/lb range. Energy price increases would affect Chinese Mg production plants less than Western producers that use energy-intensive electrolytic reduction. It is anticipated that any new process could compete with the cheap Chinese Pidgeon process if it could produce Mg with operating costs in the $0.50-$0.75 per pound range.

Two yet-to-be-commercialized Mg production processes could be competitive with the low-cost Chinese Pidgeon production technology. Total estimated Mg production costs for these processes--the carbothermic and SOM processes--are $0.83/lb and $0.50/lb, respectively. The total Mg production cost using the rapid plasma-quench carbothermic process has been reported by Donaldson and Cordes to be $0.72/lb, without consideration of any labor cost associated with production. Both production technologies would have similar raw material costs that would be lower than material costs for the conventional Pidgeon process. As a simpler production technology with lower capital-cost requirements, less processing of the raw material, and lower labor costs, SOM production cost equals about one-third of the conventional electrolytic production cost.

Life-Cycle Analysis of MFERD (See 6.C)

This project is a Canada-China-USA collaborative research and development effort which was kicked-off during the second quarter of FY 2007 as one of the ten enabling technology development tasks to analyze the energy consumption and greenhouse gases effect of Mg production, i.e., CO_2 emissions in primary Mg production (electrolytic process, traditional and improved Pidgeon processes) and SF_6/SO_2 other emissions in Mg casting, wrought-alloy processing as well as recycling. A total life-cycle analysis including vehicle-use and the end-of-life stages will be considered to capture the benefits of light-weighting automobiles such as fuel-economy improvements and associated emission reductions. Environmental performance of the advanced Mg-based front end design of a Cadillac CTS will be compared against the conventional steel-based design. A work plan has been developed jointly in which the US contribution to this task would be in providing: 1) life-cycle inventory data for the baseline conventional steel vehicle; 2) life-cycle inventory data for major Mg part fabrication technologies (e.g., casting, extrusion, and sheet forming, etc.) and for North America electrolytic primary Mg production process; and 3) energy and estimates for the use phase. To date, the preliminary life-cycle analysis framework has been developed using the commercial software SimaPro, and the framework has been populated with some readily-available, public-data databases. In addition, the methodology including data has been developed to estimate energy and emissions at the use life-cycle stage. Preliminary results using the framework have also been presented at an international conference. Life-cycle inventory data collection for the following Mg production technologies have either been completed or underway from the US side by using a questionnaire developed:

- Chinese Mg-alloy production (AE44, AJ62, AM50, AM60, AZ91)
- Western die casting (AM50, AM60, AZ91)
- Chinese die casting (AE44, AJ62, AM50, AM60, AZ91)
- High-vacuum die casting
- Secondary Mg production
- Conventional sheet forming (AZ31)
- Twin-roll casting
- Extrusion

Conclusions

The potential for Mg use in automotive applications looks promising because the prices of competing lightweight materials are trending upward and the lower-price Chinese Mg remains in good supply and is priced commensurate with its production cost. It is difficult to say how long the strong demand pressure on lightweight materials other than Mg will continue. It is estimated that the Chinese Mg production cost is around $0.80/lb, but higher raw material costs, reduced tax incentives for exports of raw materials, a booming Chinese economy, currency revaluation, and environmental compliance costs may increase the cost of Chinese-produced Mg as seen during 2007. Anticipated inexpensive supplies from the non-Western economies are likely to remove cost from the list of major barriers to wide-range use of Mg in automotive applications. The lack of available financing for the huge capital investment required to expand existing electrolytic plant capacity or add new electrolytic capacity is a barrier to more cost-effective Mg production in the West, even though these higher-capacity plants could offer lower overhead costs. New, cost-effective Mg supply sources appear to be limited, and it is unlikely that some of the yet-to-be-commercialized technologies considered here will come online, although they do hold significant promise to be competitive with the low-cost Chinese Pidgeon process. At the 2006 U.S. price of $1.13/lb, Mg was competitive with Al and galvanized steel sheet for automotive applications. However, since the beginning of 2007, Mg supplies have been tight with major supplies limited to China, Russia, and Israel, resulting in the U.S. western spot price range of $1.64-$1.69/lb – reaching for the first time above the conventional Western Mg production costs of $1.41/lb and $1.31/lb for electrolytic and thermal reduction, respectively. This recent Mg price increase reduces its cost-effectiveness compared to Al and galvanized steel sheet. Currently, anti-dumping duties help Western producers recover their operating costs only. If prices adjust to better reflect full Western production costs as seen during 2007, Mg substitution will become less attractive.

The life-cycle analysis framework, including a majority of the life-cycle inventory data collection for Mg manufacturing technologies, has been completed for the life-cycle analysis of mg front-end research and development. With the availability of Mg front end design, life-cycle analysis will be completed during the coming fiscal year.

Presentations/Publications/Patents

"Preliminary Comparative Life Cycle Assessment of an Automotive Part :Steel, Mg Alloys, Al Alloys, Advanced High Strength Steel**,"** presented at the 3rd International Conference on Light Metals Technology - LMT2007 in Saint-Sauveur, Québec, Canada from September 24-26, 2007.

B. Intermediate-Rate Crush Response of Crash Energy Management Structures

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Contractor: ORNL
Contract No.: DE-AC05-00OR22725

Objective

- Develop a unique characterization facility for controlled, progressive-crush experiments at intermediate rates of automotive materials (polymer composites, high-strength steels, and aluminum (Al)) and structures.
- Study the deformation and failure mechanisms of automotive materials subjected to crush forces as a function of impact velocity.
- Obtain specific energy absorption (SEA) and strain data and correlate with deformation and failure mechanisms to describe the unknown transitional effects from quasi-static to high loading rates for polymer composites.
- Characterize the strain-rate effects for metallic materials and components.
- Provide access to unique test capabilities to university, industry, and government users for collaborative research.

Approach

- Develop a unique, high-force (500-kN), high-velocity (8-m/s), servo-hydraulic machine to conduct progressive-crush experiments on structural components at intermediate rates.
- Use high-speed imaging to observe and document deformation and damage mechanism during the crush event.
- Conduct strain measurements at discrete locations and explore full-field measurements of strains and curvatures.
- Coordinate polymer composites investigations with the Automotive Composites Consortium (ACC) Energy Management Group (EMWG). (See 8.I).
- Coordinate steel investigations with the Automotive/Steel Partnership (A/SP).

Accomplishments

- Completed preliminary octagonal tube tests in support of the A/SP project. (See 5.G.)
- Completed diagnostic tests on a high-rate (18-meter/second) test machine to better understand inertia effects in the test data.
- Updated the high-rate data-acquisition program to include strain gages and extensometers, and improved interface.
- Completed User Project with Quickstep Technologies.
- Completed User Project with L&L Products.
- Completed User Project with Army Corps of Engineers, Engineering Research and Development Center.
- Completed scoping tests on high-rate tensile coupons for General Motors (GM)/ACC User Project.

Future Direction

- Explore techniques for full-field measurements of strains and curvatures.
- Explore techniques for local strain measurements on the 18-meter/second test machine.
- Complete octagonal tube tests in support of the A/SP project.
- Complete base-metal strain-rate characterization tests.
- Complete User Project with the ACC.
- Complete second User Project with L&L Products.
- Complete second User Project with Army Corps of Engineers

Introduction

Progressive crush is an important mechanism by which the kinetic energy of a traveling automobile is dissipated in a collision to protect the safety of occupants. Unfortunately, the mechanisms governing the progressive-crush response of some emerging automotive materials are not well understood. Additionally, many of these materials are known to exhibit responses that are sensitive to rate of loading.

Understanding the influence of impact velocity on the crush response of materials and structures is critically important for crashworthiness modeling inasmuch as collisions occur at a range of velocities. Additionally, from a structural standpoint, the deformation (or strain) rate is generally not unique from either a spatial or temporal standpoint. Consequently, it is important to quantify the behavior of materials at various strain rates.

Test Machine for Automotive Crashworthiness (TMAC)

Typically, standard test machines are employed for experiments at quasi-static rates, whereas drop towers or impact sleds are the convention for dynamic rates. These two approaches bound a regime within which data, for experiments at constant impact velocity, are not available by conventional experimental practice. This regime is termed herein the intermediate-rate regime and is defined by impact velocities ranging from 1 m/s to 5 m/s. Investigation of rate effects within this regime requires experimental equipment that can supply a large force with constant velocity within these rates.

Using a drop tower or sled at intermediate rates, although technically possible, is problematic due to the prohibitively large mass required to maintain constant velocity during the crush. Consequently, ORNL and the ACC collaborated to define specifications for a unique experimental apparatus that mitigates the shortcomings of existing equipment. MTS Systems Corporation designed and built the servo-hydraulic test machine, referred to as the TMAC. TMAC is uniquely capable of conducting controlled, progressive-crush tests at constant velocity in the intermediate velocity range (i.e., less than 5 m/s) because of the large energy available at those rates and the sophisticated simulation and control software that permits velocity uniformity to within 10%.

The new experimental facility will be used to understand the crush behavior between the static and dynamic (8-m/s) conditions. The original installation of the TMAC, shown in Figure 1, was at the National Transportation Research Center (NTRC) Knoxville, Tennessee. Since then, TMAC has been relocated to ORNL.

Figure 1. Installation of TMAC in the NTRC composite's lab.

Status

Since the last reporting period, activities have focused on supporting users, developing and promoting user interactions, improving data acquisition, and expanding test capability for higher-rate coupon tests.

Interactions with potential users have taken place with Rutgers, Massachusetts Institute of Technology, SAE High Strain Rate Plastics Consortium, GM, Ford, Imperial College (London, England), Washington University, University of Utah, and L&L Products. Also, discussions continued with the University of South Carolina and Correlated Solutions towards developing a full-field, dynamic-strain measurement using digital image-correlation techniques.

In addition to promoting user programs, continued support was provided to the development of a crashworthiness chapter for the military's composite design guide, CMH-17 (formerly MIL-HDBK-17), and the start of a technical division on the Dynamic Response of Materials within the Society for Experimental Mechanics.

Project Support Activities

Tube tests were completed on TMAC in support of the A/S-P Strain Rate Characterization project (see 5.G). These tubes had an octagonal shape with spot welds down the edges of the tube. Preliminary tests were run to determine the initial folding pattern and appropriate triggering mechanism. These tests were successful and the rest of the tubes needed to complete the test matrix were machined and instrumented. Tests are planned for fiscal year (FY) 2008. In addition to the tube tests, coupon-level strain-rate characterization tests are planned on different high-strength base metals. Dynamic-testing issues associated with these tests are currently being addressed through diagnostic testing.

User Programs

A user project was completed for Quickstep Technologies. Aaron Brighton, Dale Brosius and Ben Ludtka from Quickstep visited ORNL to carry out prismatic-tube crush tests on TMAC. A total of 72 crush tests were run over a range of impact speeds of 0.25, 0.5, 0.75, 1, 2 and 4 m/s. The tubular test specimens were all produced using an Al male mandrel connected to the Quickstep machine. The Quickstep machine utilizes a heat-transfer fluid to provide the required heat to cure the resin system in fiber-reinforced composites. Two material systems were investigated. The first consisted of a Toray G83C quick-cure resin prepreg with a T700 fiber in a 2x2 twill weave. The G83C resin requires 3 minutes of curing time at temperature with the Quickstep process. The other material system consisted of a St Gobain product called Twintex which is a glass-commingled polypropylene thermoplastic composite. The Twintex is a thermoplastic-matrix material and requires about 30 seconds to cure at temperature. All of the tubes contained four layers of material layered in a "Swiss roll" formation around the mandrel that was then shrink taped. All specimens were machined square at the ends and had a 45-degree chamfer machined in one end. Specimens were approx 240-mm long with a 60-mm inner diameter. Tests were conducted using just the 45-degree chamfer as an initiator and then both the 45-degree chamfer plus a 2.5-mm radius plug as initiator. Testing was 100% successful with no lost specimens, video or data. Figure 2 shows one of the failed specimens being held by one of the Quickstep representatives.

Figure 2. Failed Quickstep tube.

The second user project completed was an exploratory one for L&L Products. L&L products manufactures reinforced, composite/steel box-beam structural components that are integrated into key locations in vehicles to improve vehicle crashworthiness. TMAC can conduct tests at rates higher than normally available from other test methods and can supply the needed structure-performance data necessary for evaluating their product. To help L&L Products define their test plan, 14 exploratory bend-crush tests were conducted to explore the suitability of their custom, three-point bend-test fixture and verify the suitability of the test for collecting the desired high-rate data. Figure 3 shows the test set-up and Figure 4 shows some of the failed specimens. All tests were successful and future testing is scheduled this fall to complete their test matrix consisting of over 100 specimens at various rates up to 8 m/sec. This was the first non-axial crush testing to be preformed on TMAC and was successful in demonstrating its use for studying side impact.

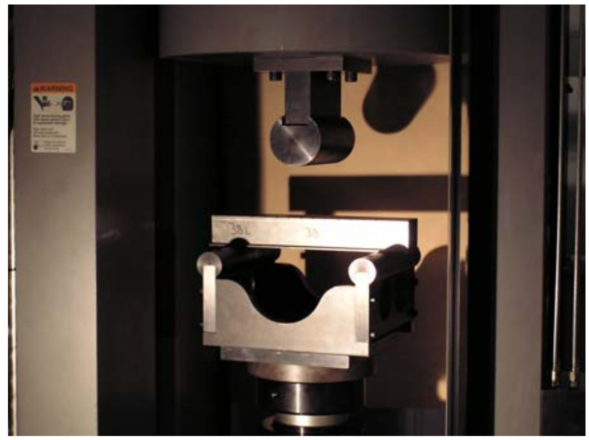

Figure 3. Three-point bend-test set-up on TMAC.

Figure 4. Failed L&L Products specimens.

The third user project completed was for the Army Corps of Engineers, Engineering Research and Development Center. The research objective for this proposal was to investigate the effects of strain-rate and heat-of-deformation and their significance on the energy-absorption process during dynamic progressive-crush deformation. Ductile, metal-alloy structures that rely on controlled, progressive plastic deformation of material along specific paths or "traveling foldlines" in the geometry can achieve extremely high energy-absorption capability and have significant potential to provide advanced levels of impact and blast-load protection. However, the material response is very complex because, at a particular location in a foldline where most of the energy is absorbed by severe, localized plastic deformation, the material undergoes transient, nonlinear, multiaxial stress/strain history paths in the low-to-high strain-rate range and load magnitudes and energy-absorption capability is influenced by inertia, strain rate, temperature and heat-of-deformation. Currently, there are few data or little understanding of the resulting material response under dynamic, progressive-deformation conditions and both are critical for developing accurate, predictive, computational material models and for obtaining advanced material solutions for protective structures applications.

The experimental approach for the proposed work consisted of performing dynamic axial crush testing on thin-wall, steel box components for a constant geometry (cross-section: 50 mm x 50 mm by 1.40 to 1.65-mm thickness (2 in x 2 in x 0.055-in to 0.065-in thickness) and length of 30.5 cm (12 in)) and four steel materials: A36 structural steel, A513 mechanical steel, 316SS stainless steel and 304SS stainless steel. The tube specimens had groove collapse initiators and were quasi-statically precrushed. For the dynamic tests on TMAC, the tube specimen ends were constrained by end caps. All tests were performed at the constant velocity of 6 meters/second. This was the first user project on TMAC to try incorporating a high-speed infrared camera to capture the heat generated during high-speed deformations in metals. Temperature contours were successfully captured during the test, but calibration of the results needs further investigation.

The GM/ACC user project is to conduct high-rate coupon tests on carbon-fiber braided material. This same material has been used extensively in other ACC projects for tube-crush studies. The data to be generated from these tests are in support of a rate-sensitive material model developed by Stanford University for predicting the crush behavior of carbon-fiber tubes. Preliminary scoping tests were conducted on the high-rate coupon test machine (this equipment is described in the next section). The coupons used for these tests were machined from unidirectional, braided plaques. The test plan consists of 25°, 45°, and 65° off-axis coupons tested at 5 different strain rates (0.01, 0.1, 1.0, 10.0, and 100/second). The preliminary tests were completed to determine load- and strain-measuring requirements and any corresponding data-acquisition modifications. It was determined that updates to the data-acquisition hardware were needed to increase scan rates and that strain gages were the preferred method for measuring strain. The hardware was updated and all specimens were returned to GM to instrument with strain gages. Completion of the test matrix is planned for the first quarter of FY 2008.

High-Rate Coupon Test Machine

To complement the TMAC capability, a high-rate coupon test machine was designed, fabricated by MTS, and installed at ORNL. Where TMAC provides the capability for a large-force (500 kN static), structural-level test, this machine was designed to conduct low-force (40 kN static), coupon-sized tests under primarily tensile loads. A typical size coupon would be a dog-bone strip where the gage section is 15 mm wide with a thickness of 3 mm. This type of test is ideal for generating rate-sensitive stress-strain curves in development of basic material constitutive laws. The machine has a maximum crosshead speed of 18 meters/second with a 400-mm total stroke capacity. The actually working stroke is reduced to 175 mm when installing a slack adapter to allow for the actuator to get up to constant speed before loading the specimen. These specifications were accomplished by a using a 400-gallon/minute (gpm) servo-valve and 50-gallon accumulators (see pictures 5 and 6). Another feature of the test machine is the use of low mass grips designed to reduce ringing in the system thereby minimizing inertial effects in the load signal. The grips were based on a Colorado School of Mines design and are shown in Figure 7.

Figure 5. High-rate (18-meter/second) coupon test machine.

Conclusions

TMAC provides a unique capability to measure the specific energy absorption on crush tubes and other specimen geometries as a function of (constant) impact velocity within a range from quasi-static to 8 meters/second. To complement this capability, another new machine was installed for conducting coupon-level tests up to 18 meters/second.

User interest in this equipment remains very high with follow-on projects and new projects being in the draft stage. TMAC was also instrumental in meeting project objectives for the A/SP. In all of these tests, high-speed video was recorded to document the failure mechanisms using a state-of-the-art, complementary metal-oxide semiconductor (CMOS) camera that was procured for the TMAC installation.

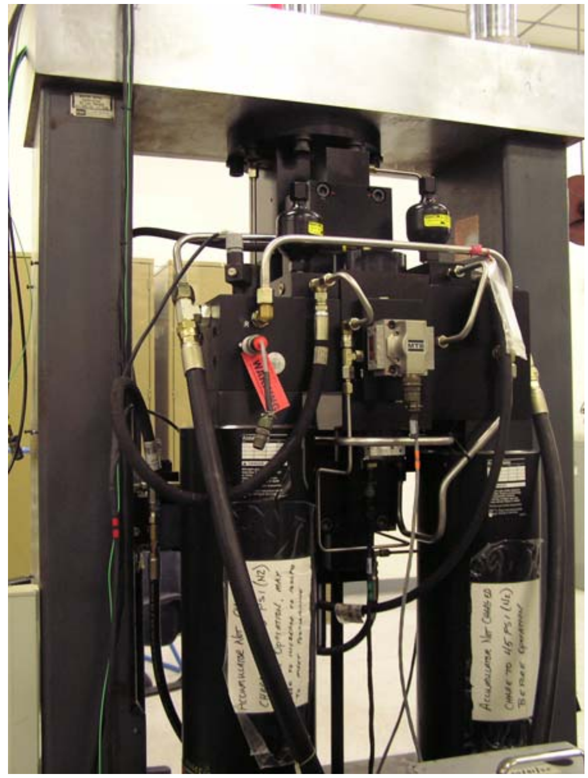

Figure 6. Accumulators and servo-valve for high-rate coupon-test machine.

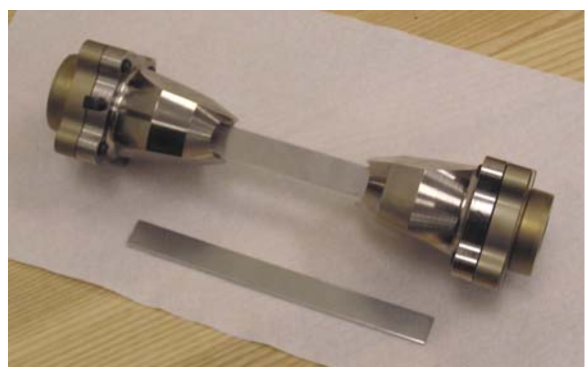

Figure 7. Low-mass grip used in high-rate coupon test machine.

Presentations/Publications/Patents

None.

C. High-Rate Damage and Fracture, Experimentation, Simulation and Visualization

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Objective

- Evaluate the strain rate failure of AZ31 magnesium (Mg) for a various stress states.
- Develop a damage model for stress-state dependence of dynamic damage evolution.
- Evaluate numerical procedures for the modeling of monotonic fracture of Mg.

Approach

- Characterize material behavior using Split Hopkinson Bar experiments in compression, tension and torsion.
- Characterize damage nucleation using molecular dynamics.
- Develop damage-evolution-based fracture.

Accomplishments

- Completed high strain-rate compression, metallurgical evaluation, and torsion testing of Mg AZ31.
- Initiated development of multiscale microstructure-property damage-based fracture simulation.
- Developed procedure for molecular-dynamics simulations of void nucleation at polycrystalline triple junctions.

Future Direction

- High strain-rate torsion and tension of AZ31.
- Implementation of microstructure-property damage-based fracture criteria in fracture-simulation code.
- Evaluate void nucleation, growth, and coalescence at the nano-size scale.

Introduction

This report summarizes the state of the experimental and numerical simulation study of fracture mechanisms in AZ31 Mg. This is a joint effort between ORNL and MSST. The aim is an enhanced, multiscale microstructure-property model that can be implemented into commercial codes and be used in high-fidelity crash simulations for the design and optimization of structural Mg components. The development effort will focus on the AZ31 Mg alloy, and a complementary experimental effort will provide experimental data for other Mg alloys that can be utilized for the development of microstructure-property model parameters.

One of the design aspects integral to the development of highly fuel-efficient vehicles is the reduction of overall vehicle weight. Mg has become a central focus in this effort due to its high strength-to-weight ratio, castability, machinability and damping. On a component basis, Mg can potentially result in 30 to 75% weight savings over conventional iron-, steel-, aluminum- and plastic- based designs (Osborne 2005).

Lightweight automotive designs must meet strength and stiffness performance requirements for normal monotonic and fatigue loading as well as provide acceptable response for abnormal loading conditions that lead to localized failure. Lightweight designs must be optimized with respect to weight and be robust with respect to damage, failure and energy absorption. Thus, the efficient use of Mg or any alloy requires the ability to accurately predict mechanical behavior under service loads as well as damage, failure and energy absorption under extreme loads.

The mechanical performance of structural components under service loads is well understood, as component design is based on well-established principles of linear-elastic solid mechanics. Under safety-critical, extreme-loading conditions such as crash, the mechanical behavior depends on a complex relationship between component geometry, loading, and material microstructure. In particular, component failure is controlled by microstructural (or smaller-scale) phenomena that vary according to deformation history, temperature, strain rate, and stress state.

The DOE and the United States Council for Automotive Research's (USCAR's) United States Automotive Materials Partnership (USAMP) funded the Structural Cast Magnesium Development (SCMD) project, a broad, multi-faceted effort to address concerns related to the use of structural Mg. One outcome of the SCMD project was the effort lead by Horstemeyer et al. (Horstemeyer, Oglesby et al. 2006) to develop a microstructure-property model that included microstructural details that act as the source of damage progression. Horstemeyer's work included detailed multiscale analysis and model development for several Mg alloys targeted for application in structural automotive components.

This current joint ORNL/MSST effort attempts to build on the experimental and computational work of Horstemeyer et al. (Horstemeyer, Oglesby et al. 2006), by extending the investigation of dynamic failure mechanisms and energy-absorption characteristics of Mg through experiment and simulation, as well as provide experimental data for additional Mg alloys. For this investigation, MSST will (1) experimentally evaluate the dynamic behavior of AZ31 Mg under high strain-rate, monotonic loading in compression, tension and torsion. The experiments will focus on the relationship between high strain-rate damage evolution and stress state, and will utilize Split Hopkinson Bar experiments in compression, tension and torsion. Test-sample evaluation includes interrupted tests as well as metallurgical evaluation.

In addition, MSST will initiate a comparative evaluation of existing numerical techniques for the simulation of component fracture in order to assess relative performance for the prediction of fracture evolution and energy release. Leveraging anticipated FY 2008 funding, ORNL will perform experimental evaluation of additional Mg alloys to provide data by which the damage model from Horstemeyer, Oglesby et al 2006 may be calibrated and assessed.

Experimental Evaluation

Commercial wrought Mg alloy AZ31, Table 1, has gained interest for application in lightweight structural automotive components. Significant attention has been directed toward the composition, processing, and mechanical properties of AZ31 (Styczynski, Hartig et al. 2004; Cao, Qian et al. 2006; Marya, Hector et al. 2006; Yi, Zaefferer et al. 2006; Li, Hsu et al. 2007). This study will be examined for failure processes under quasi-static and high strain-rate loading conditions in compression, tension and torsion.

Table 1. Typical composition (wt.%) of AZ31

Al	2.34 – 2.37
Zn	1.04 – 1.11
Mn	0.12 – 0.14
Si	0.06 – 0.11
Mg	Balance

High strain-rate testing has been initiated on a compressive Split Hopkinson Bar system (Lindholm and Yeakley 1968; Nemat-Nasser 2000). The specimens were disk shaped and were oriented perpendicular to the rolling direction. Specimen surfaces were ungrooved and were lubricated. Figure 1 shows the stress-strain response for strain rates ranging from 1000/s through 3000/s. The data reveal the effect of strain rate on yield stress and hardening properties.

Metallurgical evaluation is currently underway, and will consider changes in microstructural features, as well as failure mechanisms. High strain-rate tension and torsion will commence during the next fiscal year.

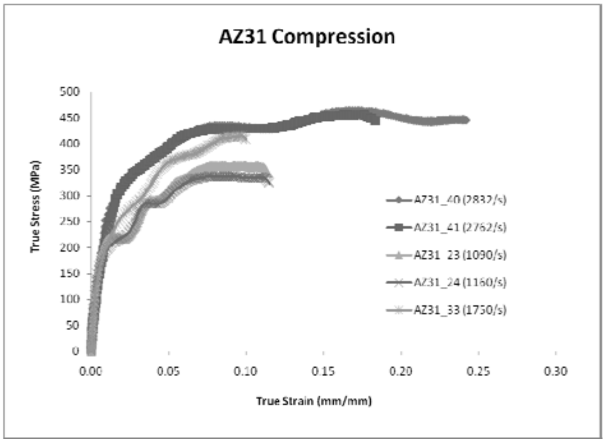

Figure 1. Stress-strain response of AZ31 for various strain rates.

Macroscale Fracture Modeling & Visualization

Ductile fracture initiates from a critical state of void nucleation growth and coalescence. Modeling of localization requires introduction of a length scale to make energy dissipation well defined. The approach taken here utilizes a finite-element framework (Rashid 1997; Rashid 1998) capable of incorporating material-specific, ductile fracture mechanisms into the failure model and that is independent of mesh topology.

Common methods for macroscale crack-growth simulations are reviewed in (Ingraffea 2004). The classical linear-elastic finite-element (Wawrzynek and Ingraffea 1987), enriched finite-element (Belytschko and Black 1999; Moës, Dolbow et al. 1999; Sukumar, Moës et al. 2000) and meshless (Belytschko, Lu et al. 1994; Fleming, Chu et al. 1997) approaches may allow arbitrary crack growth, but are generally limited to empirical representation of the fracture process. The cohesive-zone approaches can include the physically-based failure process models (Varias 1998; Siegmund and Brocks 1999; Pandolfi, Guduru et al. 2000; Zhai, Tomar et al. 2004) of the material-specific failure process, but limits crack growth to element interfaces.

In this work, we utilize the computational framework developed by (Rashid 1997; Rashid 1998). This approach takes the advantages of the approaches listed above: cracks can grow in any direction and physical fracture processes may be incorporated into the model. In this approach, a length scale is introduced in the form of a small "exclusion region" around the crack tip containing an assumed deformation field.
The application of the exclusion-region approach within the context of the finite-element method relies on arbitrary local mesh replacement (ALMR) method. The ALMR method uses two meshes to model a finite-element problem. The first mesh (patch mesh) is used to encompass the crack front and a small area surrounding the crack front. The second mesh is used to represent the entire problem (background mesh). The patch mesh supersedes the background mesh in the finite-element solver, Figure 2. A background element that is partially covered by the patch mesh can be treated utilizing the theory developed in (Rashid 1997; Rashid 1998; Rashid and Gullett 2000; Rashid and Gullett 2002) It should be noted that the exclusion region is a very small area at the center of the patch mesh and not the whole patch mesh.

Crack growth is the result of force balance and does not rely on a user- or discretization-imposed trajectory. This allows prediction of crack trajectory and linking growth to physically-based mechanisms associated with the fracture process in the near-tip region. Thus, the Finite-Element Fracture (FEFRAC) code is capable of predicting crack trajectory.

During the initial stages of this project, we have implemented a visualization technique within the Ensight visualization framework, and have begun development of a multiscale microstructure-property-based fracture criteria.

Nucleation Modeling & Visualization

Previous studies (Gall, Horstemeyer et al. 2000; Horstemeyer, Baskes et al. 2001b) have investigated the connection between the yield strength and the scale size. They observed similarities in deformation kinematics at various length scales despite significant variation of thermodynamic forces (stresses) at these length scales. Nanoscale simulations were shown to give results that agree with the phenomenological attributes of plasticity observed in macroscale experiments.

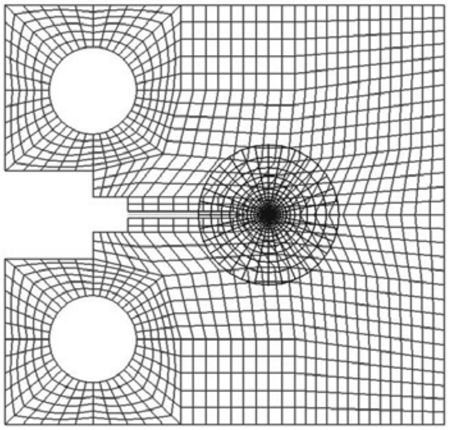

Figure 2. A compact-tension specimen simulated using exclusion-region theory combined with arbitrary local mesh replacement.

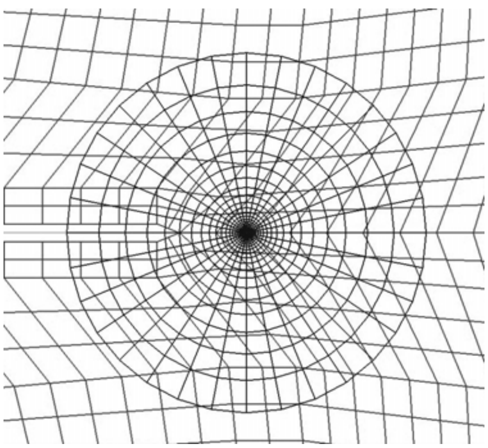

Figure 3. A zoomed-in view of the patch mesh centered at the crack tip.

As an extension of that work, this study utilizes molecular dynamics (MD) to analyze the relationship between dynamic void nucleation and size scale, and examines the applicability of the Horstemeyer-Gokhale continuum void-nucleation model (Horstemeyer and Gokhale 1999) at various nano-size scales.

The onset of damage occurs at the nanoscale by dislocations accumulation in the crystalline lattice. Nanovoids and cracks nucleate in very localized regions near inclusion particles, intermetallics, or at grain-boundary triple junctions. Recent studies (Potirniche, Horstemeyer et al. 2006a; Potirniche, Horstemeyer et al. 2006b) have shown that these voids and cracks grow and coalesce along the main shear bands which experienced intense plastic deformation. Most research efforts have concentrated on dislocation nucleation, e.g., Van Swygenhoven (Van Swygenhoven and Caro 1998; Van Swygenhoven, Spaczer et al. 1999; Van Swygenhoven, Caro et al. 2001), Schiotz (Schiotz, Di Tolla et al. 1998; Schiotz and Jacobsen 2003), Zhu (Zhu, Li et al. 2007), Bringa (Bringa, Caro et al. 2005), and Spearot (Spearot 2005; Spearot, Jacob et al. 2005). Recent efforts to examine high-rate void growth have thus far focused on single- and bi-crystalline systems (Chandler 2007; Chandler, Horstemeyer et al. Accepted; Chandler, Horstemeyer et al. Submitted) which evaluated void growth of nickel.

This work includes a systematic study of void nucleation, growth and coalescence at the nanoscale and microscale levels using modified embedded atom method (MEAM) (Potirniche, Horstemeyer et al. 2006b) based on MD principles. Previous studies (Baskes and Johnson 1994; Horstemeyer, Baskes et al. 2001a) have investigated the connection between the yield strength and the scale size and the kinematics of deformation that seems to be similar at various length scales, even though the thermodynamic forces (stresses) vary at these length scales. Nanoscale simulations were shown to give results that agree with the phenomenological attributes of plasticity observed in macroscale experiments (Horstemeyer 2001).

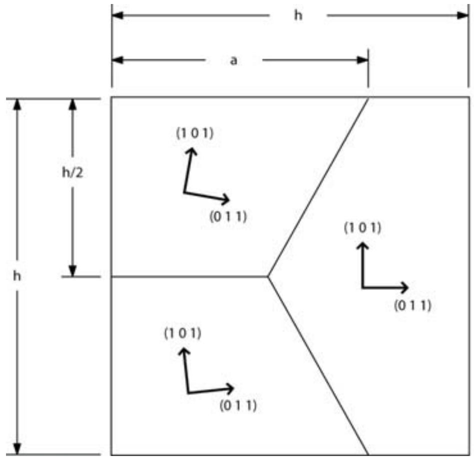

Figure 4. Geometry of polycrystalline specimens with a triple point. The direction vectors indicate the orientation of the crystalline (0 1 1) and (0 1 0) directions.

For this study, we consider computational specimens comprised of single-crystalline, bi-crystalline, and tri-crystalline atomic configurations. For tri-crystalline simulations, the specimen geometry show is shown in Figure 4, which represents lattice orientations with high-angle grain boundaries. Size effects on void growth will be evaluated using specimen sizes shown in Table 2. Atomic interactions will be modeled using the MEAM potential (Baskes 1992). We will consider both uniaxial and biaxial extension.

Table 2. Specimen considered for study of void nucleation at triple junctions.

	Number of Atoms		
Simulation	Ni	Al	Mg
Run1	3,544	3,532	2,096
Run2	14,420	14,408	8,252
Run3	57,608	57,596	33,388
Run4	230,424	230,412	133,056
Run5	921,636	921,628	531,882
Run6	3,686,576	3,686,472	2,128,105

Figure 5 shows the initial unstrained configuration with approximately 1 million nickel atoms. The grey scales represent local conformity to the face centered cubic (fcc) structure. Here atoms are grayscaled according to centrosymmetry (Kelchner, Plimpton et al. 1998) which measures local conformity to the fcc structure. Dark grey indicates fcc, while light grey indicates a distortion of the fcc structure.

Preliminary results of biaxial strain simulations are shown in Figure 6 which depicts void nucleation and growth localized at the triple junction, and along grain boundaries.

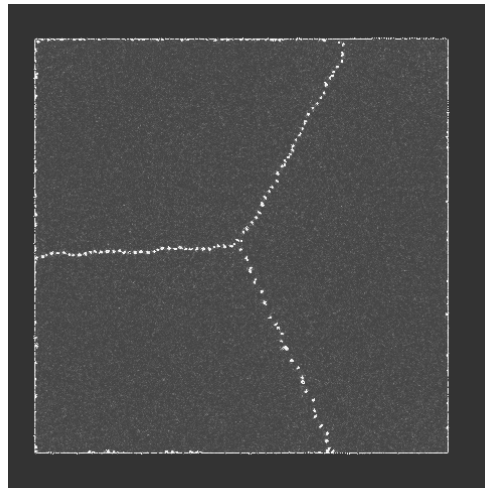

Figure 5. A triple junction with high-angle grain boundaries. Grayscales indicate local fcc structure. Dark grey indicates fcc, light grey indicates a distortion of the fcc structure.

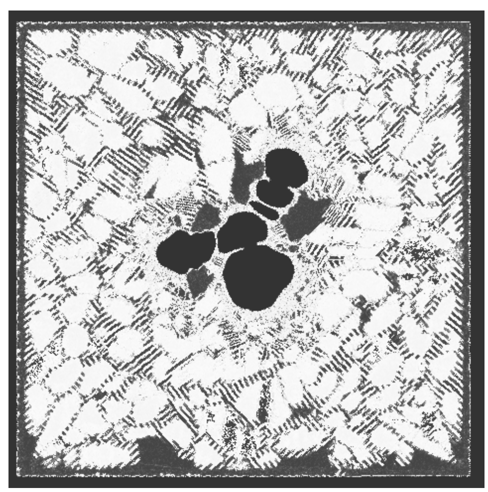

Figure 6. Void nucleation occurs at the triple junction and along grain boundaries when the system is subjected to biaxial loading.

In Figure 7, void volume fraction is plotted against nominal applied strain for five simulation size scales. The plot reveals that size scale has little effect on void growth rates for systems subjected to uniaxial extension loads.

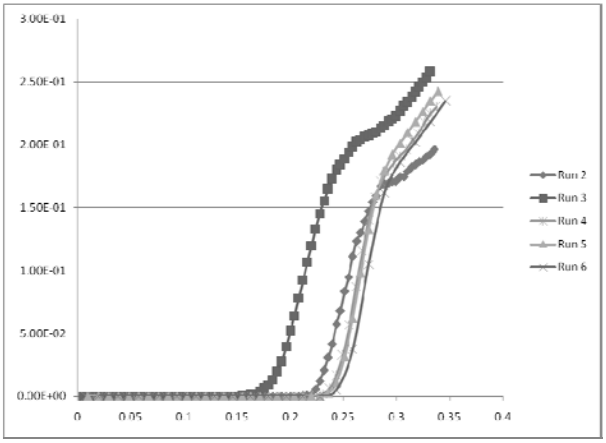

Figure 7. Void growth-rates systems subjected to uniaxial tensile loads reveal relatively minor size scale effects for initial stages of void nucleation and growth.

Conclusions

This is a new program started in the spring of 2007. We have completed compression testing of AZ31 Mg and have begun development of simulation capabilities at the macroscale and the nanoscale in support of development of multiscale modeling techniques for efficient design of lightweight automotive applications. The program is on time and on budget.

Presentations/Publications/Patents

None in FY 2007.

References

1. Baskes, M. I. (1992). "Modified Embedded-Atom Potentials for Cubic Materials and Impurities." Physical Review B-Condensed Matter **46**(5): 2727-2742.
2. Baskes, M. I. and R. A. Johnson (1994). "Modified Embedded-Atom Potentials for Hcp Metals." Modelling and Simulation in Materials Science and Engineering **2**(1): 147-163.
3. Belytschko, T. and T. Black (1999). "Elastic crack growth in finite elements with minimal remeshing." International Journal for Numerical Methods in Engineering **45**(5): 601-620.
4. Belytschko, T., Y. Y. Lu, et al. (1994). "Element-Free Galerkin Methods." International Journal For Numerical Methods in Engineering **37**(2): 229-256.
5. Bringa, E. M., A. Caro, et al. (2005). "Ultrahigh Strength in Nanocrystalline Materials Under Shock Loading." Science **309**(5742): 1838-1841.
6. Cao, P., M. Qian, et al. (2006). "Effect of manganese on grain refinement of Mg-Al based alloys." Scripta Materialia **54**(11): 1853-1858.
7. Chandler, M. Q. (2007). Multiscale Modeling of Hydrogen Enhanced Void Nucleation. Mechanical Engineering. Mississippi State, Mississippi State**:** 157.
8. Chandler, M. Q., M. F. Horstemeyer, et al. (Accepted). "Hydrogen Effects on Nanovoid Nucleation in FCC Single Crystals." Acta Materialia.
9. Chandler, M. Q., M. F. Horstemeyer, et al. (Submitted). "Hydrogen Effects on Nanovoid Nucleation at Nickel Grain Boundaries." Acta Materialia.
10. Fleming, M., Y. A. Chu, et al. (1997). "Enriched element-free GALERKIN METHODS FOR CRACK TIP FIELDS." International Journal for Numerical Methods in Engineering **40**(8): 1483-1504.
11. Gall, K., M. F. Horstemeyer, et al. (2000). "Atomistic simulations on the tensile debonding of an aluminum-silicon interface." Journal of the Mechanics and Physics of Solids **48**(10): 2183-2212.
12. Horstemeyer, M. F. (2001). From atoms to autos: a new design paradigm using microstructure-property modeling. Part 1: Monotonic Loading, Sandia National Labs**:** 260.
13. Horstemeyer, M. F., M. I. Baskes, et al. (2001a). "Computational nanoscale plasticity simulations using embedded atom potentials." Theoretical and Applied Fracture Mechanics **37**(1-3): 49-98.
14. Horstemeyer, M. F., M. I. Baskes, et al. (2001b). "Length scale and time scale effects on the plastic flow of fcc metals." Acta Materialia **49**(20): 4363-4374.
15. Horstemeyer, M. F. and A. M. Gokhale (1999). "A void-crack nucleation model for ductile metals." International Journal of Solids and Structures **36**(33): 5029-5055.
16. Horstemeyer, M. F., D. Oglesby, et al. (2006). From Atoms to Autos: Designing a Mg Alloy Corvette Cradle by Employing Hierarchical

Multiscale Microstructure-Property Models for Monotonic and Cyclic Loads. Mississippi State, Mississippi State University**:** 296.

17. Ingraffea, A. R. (2004). Computational Fracture Mechanics. Encyclopedia of computational mechanics. E. Stein, R. d. Borst and T. J. R. Hughes. Chichester, West Sussex, John Wiley. **2**.
18. Kelchner, C. L., S. J. Plimpton, et al. (1998). "Dislocation nucleation and defect structure during surface indentation." Physical Review B **58**(17): 11085.
19. Li, H., E. Hsu, et al. (2007). "Determination of Active Slip/Twinning Modes in AZ31 Mg Alloy Near Room Temperature." Journal of Materials Engineering and Performance **16**(3): 321-326.
20. Lindholm, U. and L. Yeakley (1968). "High strain-rate testing: Tension and compression." Experimental Mechanics **8**(1): 1-9.
21. Marya, M., L. G. Hector, et al. (2006). "Microstructural effects of AZ31 magnesium alloy on its tensile deformation and failure behaviors." Materials Science and Engineering: A **418**(1-2): 341-356.
22. Moës, N., J. Dolbow, et al. (1999). "A finite element method for crack growth without remeshing." International Journal for Numerical Methods in Engineering **46**(1): 131-150.
23. Nemat-Nasser, S. (2000). Introduction to High Strain Rate Testing. Mechanical Testing and Evaluation Handbook, ASM. **8:** 427-428.
24. Osborne, R. J. (2005). A joint USCAR-USAMP material project with DaimlerChrysler, Ford, General Motors and Industry. Southfield, Detroit.
25. Pandolfi, A., P. R. Guduru, et al. (2000). "Three dimensional cohesive-element analysis and experiments of dynamic fracture in C300 steel." International Journal of Solids and Structures **37**(27): 3733-3760.
26. Potirniche, G. P., M. F. Horstemeyer, et al. (2006a). "Atomistic modelling of fatigue crack growth and dislocation structuring in FCC crystals." Proceedings of the Royal Society, A **462**: 3707-3731.
27. Potirniche, G. P., M. F. Horstemeyer, et al. (2006b). "A molecular dynamics study of void growth and coalescence in single crystal nickel." International Journal of Plasticity **22**: 257-278.
28. Rashid, M. M. (1997). "A new theory for free-surface formation in solid continua." International Journal of Solids and Structures **34**(18): 2303-2320.
29. Rashid, M. M. (1998). "The arbitrary local mesh replacement method: An alternative to remeshing for crack propagation analysis." Computer Methods in Applied Mechanics and Engineering **154**(1): 133-150.
30. Rashid, M. M. and P. M. Gullett (2000). "On a finite element method with variable element topology." Computer Methods in Applied Mechanics and Engineering **190**(11-12): 1509-1527.
31. Rashid, M. M. and P. M. Gullett (2002). Formulation of a Finite Element Method with Arbitrary Element Geometry. Modeling and Simulation-Based Life Cycle Engineering. K. P. Chong and J. E. Harding. London, Spon Press.
32. Schiotz, J., F. D. Di Tolla, et al. (1998). "Softening of nanocrystalline metals at very small grain sizes." Nature **391**(6667): 561-563.
33. Schiotz, J. and K. W. Jacobsen (2003). "A Maximum in the Strength of Nanocrystalline Copper." Science **301**(5638): 1357-1359.
34. Siegmund, T. and W. Brocks (1999). "Prediction of the Work of Separation and Implications to Modeling." International Journal of Fracture **99**(1): 97-116.
35. Spearot, D. (2005). Atomistic Calculations of Nanoscale Interface Behavior in FCC Metals. Mechanical Engineering. Atlanta, Georgia Institute of Technology**:** 276.
36. Spearot, D. E., K. I. Jacob, et al. (2005). "Nucleation of dislocations from [0 0 1] bicrystal interfaces in aluminum." Acta Materialia **53**(13): 3579-3589.
37. Styczynski, A., C. Hartig, et al. (2004). "Cold rolling textures in AZ31 wrought magnesium alloy." Scripta Materialia **50**(7): 943-947.
38. Sukumar, N., N. Moës, et al. (2000). "Extended finite element method for three-dimensional crack modelling." International Journal for Numerical Methods in Engineering **48**(11): 1549-1570.
39. Van Swygenhoven, H. and A. Caro (1998). "Plastic behavior of nanophase metals studied

by molecular dynamics." Physical Review B **58**(17): 11246.
40. Van Swygenhoven, H., A. Caro, et al. (2001). "A molecular dynamics study of polycrystalline fcc metals at the nanoscale: grain boundary structure and its influence on plastic deformation." Materials Science and Engineering A **309-310**: 440-444.
41. Van Swygenhoven, H., M. Spaczer, et al. (1999). "Competing plastic deformation mechanisms in nanophase metals." Physical Review B **60**(1): 22.
42. Varias, A. G. (1998). "Constraint effects during stable transient crack growth." Computational Mechanics **21**(4): 316-329.
43. Wawrzynek, P. A. and A. R. Ingraffea (1987). "Interactive finite element analysis of fracture processes: An integrated approach." Theoretical and Applied Fracture Mechanics **8**(2): 137-150.
44. Yi, S. B., S. Zaefferer, et al. (2006). "Mechanical behaviour and microstructural evolution of magnesium alloy AZ31 in tension at different temperatures." Materials Science and Engineering: A **424**(1-2): 275-281.
45. Zhai, J., V. Tomar, et al. (2004). "Micromechanical simulation of dynamic fracture using the cohesive finite element method." Journal of Engineering Materials and Technology-Transactions of the Asme **126**(2): 179-191.
46. Zhu, T., J. Li, et al. (2007). "From the Cover: Interfacial plasticity governs strain rate sensitivity and ductility in nanostructured metals." PNAS **104**(9): 3031-3036.

D. Multi-Material Vehicle (MMV) Research and Development (R&D) Initiative (MMV 701[i])

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Contractor: U.S. Automotive Materials Partnership (USAMP)[i]
Contract No.: DE-FC05-02OR22910 through the DOE National Energy Technology Laboratory

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Objective

The MMV R&D Initiative is a new umbrella focal project established in fiscal year (FY) 2007 to connect and relate the USAMP's Auto/Steel Partnership (A/SP), Automotive Composites Consortium (ACC), Automotive Metals Division (AMD) and Non-Destructive Evaluation (NDE) projects together so that they address vehicle issues in addition to materials issues. The project's main near-term objective is to define new opportunities across the various single-area-focused projects that bridge lightweight materials R&D to applications on a donor vehicle and potential future production implementation, addressing integration, joining and assembly, testing and validation, and advanced vehicle design/architectures.

The MMV R&D Initiative deliverables will include:

- Gap/Needs analysis to identify inhibitors to production and manufacturing.
- Attribute performance, mass-reduction and cost implications for multi-material vehicle components, sub-assemblies and systems.
- Vehicle Technical Specifications for donor vehicle for aligning other USAMP projects (crash performance, dynamic stiffness, durability, etc.).
- Computer-aided design (CAD) and computer-aided engineering (CAE) models for the baseline donor vehicle for alignment of other USAMP projects.
- Baseline cost estimates for steel donor vehicle for alignment of other USAMP projects.

Approach

The MMV R&D Initiative will define new opportunities across USAMP that bridge lightweighting materials R&D to applications on a donor vehicle, addressing integration, joining and assembly, testing and validation, and advanced vehicle design/architectures to accommodate alternative energy powertrains. It is anticipated that the MMV will help motivate USAMP's partner organizations (suppliers, academia, and national laboratories) to accelerate research in areas of importance.

- An MMV R&D Steering Committee, consisting of two representatives per original equipment manufacturer (OEM), will be formed to assess the current USAMP project portfolio, identify technology gaps, and to advocate, "bubble-up" and transition new projects in joining, integration and assembly technologies to individual consortia or project teams across USAMP.
- A donor-vehicle platform will form the baseline for affecting the light weighting technology improvements, and will be the focus for the three initial technology "seed" projects addressing major light weighting initiatives: A/SP's Future Generation Passenger Compartment (FGPC; see 5.I), AMD's Magnesium Front End (MFE; see 6.B and 6.C) and the ACC's composite underbody (see 8.A).

Results from demonstration of the three initial seed projects on a large, rear-wheel drive (RWD) passenger vehicle platform will be extrapolated to address light weighting strategies for other vehicle architectures.

Accomplishments

During FY 2007, the MMV project began operations. This year, the accomplishments primarily surround initiating efforts and aligning the three USAMP body subassembly projects.

- Selected a consensus donor-vehicle platform to serve as a benchmark to quantify and compare technology improvements. The selected vehicle is a General Motors (GM) large RWD passenger vehicle.
- A corresponding MMV Technical Specification was collaboratively defined by the MMV team and selected CAE vendor, consisting of required load cases, prioritizations for meeting compliance, and generally tracking the design maturity of MMV modules.
- Initiated a baseline MMV donor-vehicle systems-level manufacturing and assembly cost-modeling project.
- Advocated the technical and business case for new multi-material joining R&D projects by engaging with experts in joining technologies. One new joining R&D concept-feasibility project was selected for sponsorship.

Future Direction

- The MMV R&D initiative will be closely linked in to the emerging needs of the three USAMP MMV "seed" projects, and remain opportunistic in attracting new project ideas from USAMP in multi-material joining technologies.
- A newly-started project to develop a full-vehicle cost model of the MMV baseline-vehicle manufacturing will be tracked closely for comparing with cost performance of lightweight-vehicle body systems resulting from the three MMV "seed" projects.
- Another new project investigating forming metallurgical bonds between steel and cast aluminum as well as between steel and cast magnesium will be initiated.

Introduction

The MMV R&D Initiative is a USAMP umbrella focal project, supporting FreedomCAR goals and timeline, with the primary objective of investigating vehicle weight-reduction opportunities and issues associated with incorporating multiple materials in multiple locations.

The MMV R&D portfolio emphasizes design, joining, corrosion, energy management, manufacturing processes, and other technologies that facilitate mixed-material systems that can support delivery of FreedomCAR goals by 2015.

In its first year since charter in FY 2006, the MMV team was directed by the USAMP to focus on standardization of analytical, design, cost-modeling and benchmarking studies supporting the three 'seed' technology projects. Longer-term focus of MMV R&D will be on integration and joining/assembly technologies as well as new vehicle architectures utilizing lightweight materials and associated processes developed for manufacturing discrete parts and sub-assemblies in high-volume.

Significant accomplishments in program standardization are reported below under each sub-task heading.

Baseline MMV Vehicle

The MMV team identified a common baseline vehicle, the GM unibody (body-frame-integral) RWD vehicle. This provided a single-focus vehicle for each of the following three initial 'seed' projects:

(a) AMD 603 and AMD 604 Magnesium Front End projects.

(b) ACC Composite Underbody.

(c) A/SP Advanced High Strength Steel Future Generation Passenger Compartment.

Figures 1 – 3 illustrate baseline modules being researched within USAMP and being held to engineering-performance targets set by MMV.

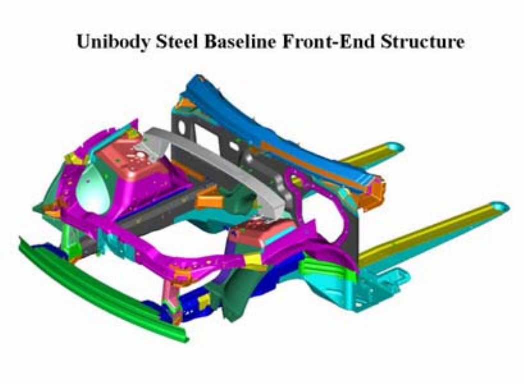

Figure 1. AMD Magnesium Front End project. Steel baseline is shown as the design basis.

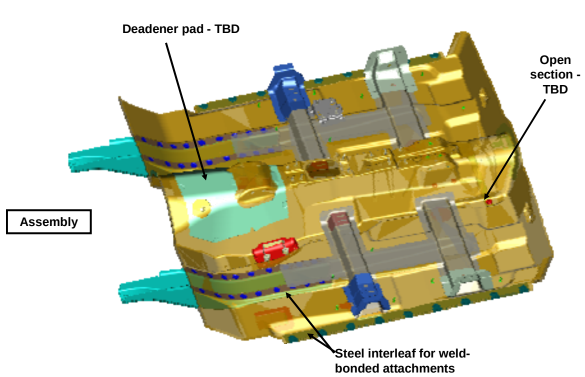

Figure 2. ACC Composite Underbody.

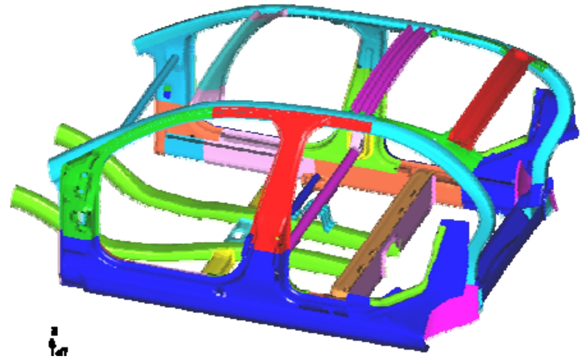

Figure 3. A/SP Advanced High Strength Steel Future Generation Passenger Compartment.

Common MMV Technical Specification

The MMV began FY 2007 by developing a consensus technical specification for comparisons and validation of vehicle performance modeling with respect to the large RWD passenger donor vehicle contributed by GM. The MMV specification was updated by team members to incorporate new Federal Motor Vehicle Safety Standard (FMVSS) requirements, and was then disseminated to all the USAMP consortia overseeing the three core MMV "seed" projects. The MMV specification is being used to drive design and lightweight materials and manufacturing technology developments across the initial three 'seed' projects that would be compliant to the specification.

Engineering Performance Targets

MMV established the engineering targets and manufacturing goals for each of the three "seed" projects to meet anticipated 2015 functional requirements or match the baseline production-vehicle performance. A tracking mechanism for assessing progress in design maturity towards meeting these targets was also established – a detailed spreadsheet is being maintained by Multimatic (lead design vendor for the ACC underbody project) under contract to the MMV, and involves the regular participation and input of the other two 'seed' project leaders and their respective lead design vendors.

The specific MMV engineering targets relate to:

- Structural Performance (stiffness, dynamic frequencies, mode shapes)
- Manufacturability (cycle time, paint issues, repair procedures in-plant and in-service)
- Safety (front, side, rear, roof, restraints, cargo-retention, bumper requirements)
- Durability and Target Life
- Ride and Handling
- Towing and Trailer

In addition, the three "seed" projects, in proposing new module designs incorporating lightweight materials, must also identify how they could be integrated into a full vehicle-manufacturing scenario capable of producing 100,000 units per year at an affordable cost.

MMV Baseline Cost-Model Development

The MMV Baseline Cost Model development is being led by Camanoe Associates with close oversight and input from the MMV team. Camanoe will estimate the piece costs and assembly costs for the donor vehicle and for each of the subassemblies for the three "seed" projects, the A/SP FGPC, the ACC Composite Underbody and the AMD Magnesium Front End. Having the cost model and estimate as a single project through MMV minimizes the work and costs to each of the three "seed" projects. Also, this effort will provide many inputs for the cost models for each of the three "seed" projects.

The expected results will include cost estimates for the stamped-steel baseline donor-vehicle. Specifically, the cost of each individual part will be estimated based on the material and manufacturing technique, i.e., typical stamping operations. Additionally, the cost of assembly for the full vehicle structure will be estimated based on the donor-vehicle assembly process. Finally, the assembly cost of the three subassemblies matching the three "seed" projects, passenger compartment, underbody and front end, will be estimated.

These estimated costs will be the basis for comparisons with the lightweight investigations in each of the three "seed" projects. By having a consistent baseline estimate, cost opportunities and risks can be identified with respect to the high-volume implementation of the lightweight concepts.

Identification of Critical R&D Gaps

In parallel, the MMV team also began identifying new strategies for promoting mass savings across the USAMP project portfolio which included coordination with the USAMP Materials Technology Team. The MMV team also began resolving design/analytical information discrepancies, as well as assessing critical technology gaps and R&D needs across these three "seed" projects.

The highest priority technology development identified was in multi-material joining technology relevant to the assembly needs of the 'seed' projects. A Joining Technology focus meeting was held with subject matter experts from Edison Welding Institute, Pacific Northwest National Laboratory and the University of Michigan to assess the state-of-the-art and define joining requirements. A future project will address metallurgical joining of cast aluminum to steel and of cast magnesium to steel to address one of the vehicle-integration issues associated with lightweight material introductions.

Conclusion

The USAMP Multi-Materials Vehicle Research and Development Initiative (MMV 701) has been successfully started, with a baseline vehicle identified, engineering and manufacturing performance targets established, and a consistent source for baseline design, models and engineering performance analysis established.

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[i] Denotes project 701 of the Multi-Material Vehicle (MMV) Working Group of the United States Automotive Materials Partnership (USAMP), one of the formal consortia of the United States Council for Automotive Research (USCAR, www.uscar.org) set up by Chrysler, Ford and General Motors to conduct joint, pre-competitive research and development.

E. Mission Eggcellence – K-12 Outreach Program

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Contract No.: 4000054701

Objective

- The Mission Eggcellence Project is designed to develop a commitment from CAVS to the children of the State of Mississippi through curriculum instruction and competitions dealing with the design of a vehicle bumper and/or seatbelt for passenger safety. This instruction and student competitions will create an awareness of the importance of design in safety implications, and of the real-world applications of mathematics, science, and problem-solving skills. Mission Eggcellence will create awareness among the Mississippi school-age population of future job opportunities in the State of Mississippi as well as college majors associated with these jobs.

Approach

- Create a grade-appropriate curriculum with experiments associated with the physics of car crashes for grades K-3 (Objective 1).
- Create a grade-appropriate curriculum with experiments associated with the physics of car crashes for grades 4-6 (Objective 2).
- Develop a Teacher Workshop for grades K-3 teachers for training in use of the grade-appropriate curriculum in the regular classroom. Equipment necessary to conduct the experiments and compete in the competitions is given to each teacher participant (Objective 3).

- Develop a Teacher Workshop for grades 4-6 teachers for training in use of the grade-appropriate curriculum in the regular classroom. Equipment necessary to conduct the experiments and compete in the competitions is given to each teacher participant (Objective 4).
- Design a competition for grades K-3 incorporating bumper design for passenger safety (Objective 5).
- Design a competition for grades K-3 incorporating car design for passenger safety (Objective 6).
- Design a competition for grades 4-6 incorporating bumper design for passenger safety (Objective 7).
- Design a competition for grades 4-6 incorporating car design for passenger safety (Objective 8).
- Create a grade-appropriate curriculum with experiments associated with the physics of car crashes for grades 7-9 (Objective 9).
- Create a grade-appropriate curriculum with experiments associated with the physics of car crashes for grades 10-12 (Objective 10).
- Develop a Teacher Workshop for grades 7-9 teachers for training in use of the grade-appropriate curriculum in the regular classroom. Equipment necessary to conduct the experiments and compete in the competitions is given to each teacher participant (Objective 11).
- Develop a Teacher Workshop for grades 10-12 teachers for training in use of the grade-appropriate curriculum in the regular classroom. Equipment necessary to conduct the experiments and compete in the competitions is given to each teacher participant (Objective 12).
- Design a competition for grades 7-9 incorporating bumper design for passenger safety (Objective 13).
- Design a competition for grades 7-9 incorporating car design for passenger safety (Objective 14).
- Design a competition for grades 10-12 incorporating bumper design for passenger safety (Objective 15).
- Design a competition for grades 10-12 incorporating car design for passenger safety (Objective 16).

Accomplishments

- Completed curriculum for grades K-3 (Objective 1).
- Completed curriculum for grades 4-6 (Objective 2).
- Completed Teacher Workshop for teachers of grades K-3 (Objective 3).
- Completed Teacher Workshop for teachers of grades 4-6 (Objective 4).
- Completed Bumper Design Competition for grades K-3 (Objective 5).
- Completed Car Design Competition for grades K-3 (Objective 6).
- Completed Bumper Design Competition for grades 4-6 (Objective 7).
- Completed Car Design Competition for grades 4-6 (Objective 8).

Work Plan for 2007-08

- Develop curriculum for grades 7-9 (Objective 9).
- Develop curriculum for grades 10-12 (Objective 10).
- Develop Teacher Workshop for teachers of grades 7-9 (Objective 11).
- Develop Teacher Workshop for teachers of grades 10-12 (Objective 12).
- Develop Bumper Design Competition for grades 7-9 (Objective 13).
- Develop Car Design Competition for grades 7-9 (Objective 14).
- Develop Bumper Design Competition for grades 10-12 (Objective 15).
- Develop Car Design Competition for grades 10-12 (Objective 16).

Introduction

The CAVS at MSST is teaming with the local school districts and the Mississippi Children's Museum to develop a sophisticated Science & Technology area in the form of workshops in the museum with teachers to inspire young minds to explore the worlds of math, science, and engineering. We will create powerful, interactive-learning/teaching kits for K-12 students with a program based upon materials design, which will be supported by ASM International (ASM). We already have an ASM-supported program in development entitled ***Mission Eggcellence***. It is worth explaining the Mission Eggcellence notion further as illustrative of our other ideas.

Mission Eggcellence provides students with a hands-on introduction into vehicular crashworthiness through applying basic concepts of physics (students are provided with simple definitions from physics such as mass, velocity, momentum and energy and how they are used during crash), explanations of what actually happens during a crash (using the physics terms and defining what is necessary to enable passengers to survive a crash), and examples of safety devices (explanations and examples of some devices such as bumpers, seatbelts, airbags and safety cages, used in cars and trucks, with simulations to demonstrate how they work). Other explanations provided will include manufacturer goals (creating a vehicle that is lightweight for the lowest price possible, creating a vehicle that demonstrates good fuel efficiency, creating a vehicle that is aesthetically pleasing in appearance) versus consumer goals (a vehicle that is strong enough to protect passengers from impact, a vehicle that is light enough to provide economical fuel consumption, a vehicle that has a pleasing appearance, a vehicle that has a memory of its shape and can be repaired faster, less expensively and easier) and the difficulties involved in balancing these requirements.

Vehicles, materials, eggs, workbooks/worksheets, and instruction will be provided to the students, with which they must design a safety barrier for each team's vehicle that will prevent the egg from breaking upon impact during an impact competition. The vehicles are released upon a ramp, which is elevated to a higher degree of angle, from 15 degrees to 70 degrees, at each step of the impact competition, and the vehicle(s) in which the eggs do not break can win. The winners are determined by the lightweight designs. Competitions are expected to be state-wide. Undergraduates and graduate students will play a large role in communicating the principles and overseeing the activities. They will also be used to help monitor the tournaments and mentor some of the K-12 students.

Each curriculum consists of eight grade-appropriate experiments for the physics concepts of velocity, acceleration, Newton's Third Law, momentum, impulse, elastic and inelastic collisions. These experiments include a bumper design and car design. In the bumper-design competitions for grades K-3 and 4-6, the bumper is tested by rolling a wooden car, with the bumper attached, down a ramp using a raw egg as the passenger. Winner is steepest incline with the egg intact. The tie breaker is lightest mass. In the K-3 and 4-6 car design competitions, a car is designed using Knex pieces from a kit. Winner is steepest incline with egg intact. The tie breaker is lightest mass.

Academic/Research Excellence Basis

An overarching theme of multidisciplinary design integration motivates our research as well as our multilevel educational activities in K-PhD and continuing education. Our educational approach is structured to overcome the knowledge compartmentalization and overspecialization of traditional technical education that stand as barriers to the implementation and dissemination of science-based engineering. Core university collaboration seeks to empower a broad range of students, through a fusion of exciting new science-based tools with design habits of mind, team creativity and effective multidisciplinary communication. Our *Mission Eggcellence* design project work will be enhanced by the emerging technology of a distributed web-based collaborative environment. We have a clear education accountability structure administered by the CAVS Chair Professor, Mark Horstemeyer. In addition, CAVS has a strong extension/ outreach center in which quick implementation of research is plausible.

Project Objectives and Expected Outcomes/Impacts

In alignment with the objectives and expected outcomes of this task (which are to empower and inspire all our state's children, regardless of their social, educational or economic background, and to discover their potential through tapping their curiosity and creativity, through hands-on and engaging exhibits and programs), we will create a dynamic and competitive program that will:

- Provide children the opportunity to perform hands-on experiments, to learn the value of mathematics, physics and engineering and how their uses in the experiments correlate with "real world" engineering problems, and to create for themselves the experience of mastering tasks they would normally perceive to be difficult. This will increase their self-esteem, which will be demonstrated by increased performance levels in school.
- Address the needs of Mississippi children, especially in the areas of math, science and engineering.
- Reach children in schools and communities throughout the state through our Outreach Program.
- Complement the mathematics, physics and science programs being taught in school.
- Promote a desire to learn more about the world in which the children live and how it works.

We really need a creative K-PhD program that anticipates the current and future high-tech jobs revolving around the automotive industry in our state. Children need to be excited by math, science, and engineering, and the Mississippi Children's Museum can enkindle that passion. If we can help them develop a passion for learning, they are going to want to understand how things work and how to make things work better. For Mississippi to advance in the science and technology fields, children must become excited about learning, and this is the fundamental mission of a children's museum.

Mission Eggcellence, among other materials-design projects, can provide a science/engineering experience that will inspire children to want to return time and time again; each time that they return, they will learn things about their world that inspires them to want to return and learn more. The imaginative and experimental Mission Eggcellence is relevant to the students' class-work and can be correlated with "real world" safety, reliability, and crashworthiness issues that are faced today within the automotive industries.

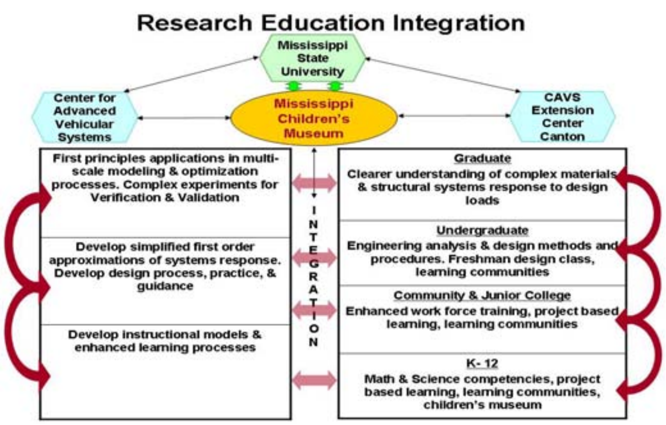
Contributions to the Long-Term and Sustainable Engagement of the Team/Unit

MSST is developing an "Automotive Experience" strategic program that includes K-12, undergraduate work, and graduate-level work. A new course and certificate are being developed in real time for this endeavor. For MSST to have an excellent PhD pool, we need to have students aligned in the K-12 pipeline. We are viewing these grant funds as start-up funds only, but the program will continue long into the future.

From the Department of Energy (DOE) - Southern Regional Center for Lightweight Innovative Design (SRCLID) Statement of Program Objectives (SOPO), the transfer of knowledge obtained from leading-edge research to K-12 educational programs is a core requirement. CAVS is required to develop an educational program to integrate lightweighting-design concepts with crashworthiness into student curricula. A K-PhD program will be developed that communicates the important issues of crashworthiness and safety. Crash kits will be developed for appropriate educational levels, and state and regional tournaments will be fostered to further interest in the technology and resultant designs.

Specific subtasks include:

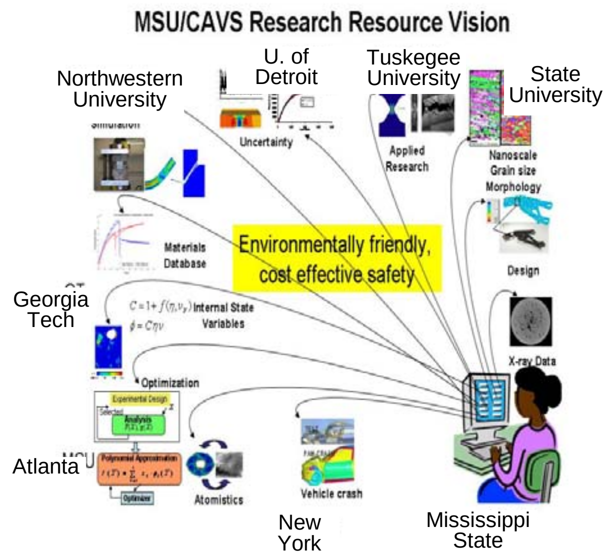
Task 1. Develop crash kits for K-2, 3-6, 7-9, and 10-12.
Task 2. Develop tournaments with crash kits for Mississippi-wide contests.
Task 3. Assist in the development of modules for Mississippi Children's Museum.
Task 4. Assist Choctaw School for Native Americans and the Houston High School Solar Car team in their solar car designs.



The graphic above represents the integration of education, industry and outreach as they will be applied in technology transfer to the children via the Mississippi Children's Museum.

CAVS will design materials kits and crash kits with their associated documentation (student and instructor) and provide engineering specialists as keynote speakers, trainers, and lecturers. Rosemary Cuicchi (Starkville Jr. High physics instructor and teacher of academically-gifted classes at Armstrong Middle School in Starkville) is involved in developing the program. ASM will also be involved in helping develop the program. Nissan North America (Canton, MS) and Vista Engineering Inc. have both donated in-kind contributions to the SRCLID program with specific interest in the educational development aspects of the program.

The Mississippi Children's Museum administrators and staff will be involved in designing and setting up the exhibits within the museum, as well as establishing agendas for exhibit changes. Dr. Mark Horstemeyer is helping design the regions within the Children's Museum to help explain the math, science, and engineering aspects.



The graphic above represents the CAVS research resource vision through which data, research materials, materials-design methodologies, and basic science aspects will be made available to students through this task, sponsored by DOE and the Mississippi Children's Museum.

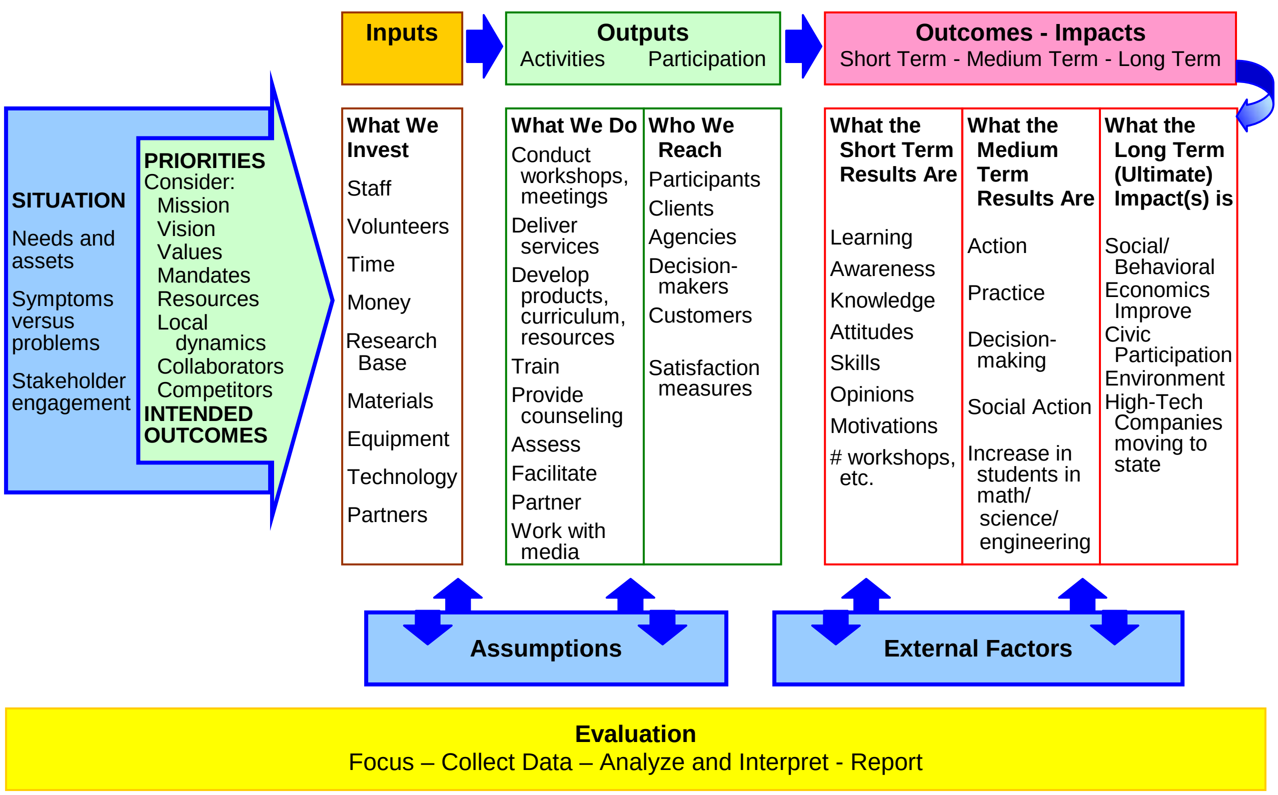
Evaluation

The program will be evaluated both internally by MSST staff and externally by partnering organizations, committee members, and visitor surveys. Internal evaluation will take place at monthly meetings where staff members take the opportunity to debrief with the entire group, provide feedback and troubleshoot issues. External evaluations will be completed through a Mississippi Children's Museum Partner Survey. When evaluating the program, staff will review the types of programs/activities offered to ensure that they accurately represent the culture, as well as whether an organization's participation in the program helped to provide access to the Mississippi Children's Museum for members of the community. In addition, staff will track the number of:

- Individuals who participated in the special events, workshops and programming.
- Communities served (Examples are Latino, Native American, African-American, Asian and Caucasian).

- Community-based organizations with which we partner.
- Opportunities created for cross-cultural programming.
- Artists and performers who benefit through participation.
- Number of events we will offer at the museum during the year's Passport programs.
- Number of events/community festivals we will participate in during the next year.

Materials Design Logic Model



Making a Difference within the Community and the University

University metrics will demonstrate the effectiveness of the program by showing increases in students coming to MSST and other colleges and universities in the fields of math, science and engineering. Within the community, we expect to see a higher rate of students becoming involved in math, science and engineering and, in the long run, expect to see more high-tech companies moving into the state as a result of this program. If we increase the rates of students in math, science and engineering, indicating a more highly educated future work force, the number of incoming high-tech companies will increase.

Interpreting the Accompanying Materials Design Logic Model (see above)

Situation: The situation, as it applies to this project, is that children in Mississippi do not have access to innovative, open-ended, educational hands-on programs in which they can be exposed to viable applications of math, science and engineering. Because the Mississippi public educational system is not considered to be strongly effective in graduating students who are strong in math, science and engineering, few high-tech companies consider Mississippi to be an economically-viable target for relocation or expansion of businesses.

Priorities and Intended Outcomes

The priorities of this project are thoroughly integrated within the mission and vision of CAVS, especially as defined by the DOE-SRCLID Statement of Program Objectives (SOPO). Specifically, the transfer of knowledge obtained from leading-edge research to K-12 educational programs via developing an educational program to integrate lightweighting design concepts with crashworthiness into student curricula will be accomplished by developing crash kits for appropriate educational levels, and by fostering state and regional tournaments to further interest in the technology and resultant designs. The intended outcome will be increased numbers of students at all educational levels who will have a deeper understanding of math, science and engineering and an appreciation of these fields of study in real-world applications.

Inputs: CAVS, MSST, the CAVS Extension (Canton) and the community will integrate into a synergistic teaming effort to provide staff, volunteers, time, money, basic research, materials, equipment, technology and partners to ensure the success of this program.

Outputs **–** What Will We Do? Personnel from the core facilities mentioned above will conduct workshops and meetings, will deliver services, will develop products, curriculum and provide resources, will provide training, will provide counseling, will assess the program and its effectiveness, will work with the partnering organizations, and will work with media to ensure proper dissemination of information to the public.

Who Will We Reach? We will reach participants (children, parents and teachers), clients, agencies, decision-makers and customers, all of whom should, over time, provide satisfaction feedback.

Outcomes – Impacts – Short Term: We anticipate an increased interest by students in math, science and engineering as demonstrated by improved learning, awareness, knowledge, attitudes, skills, opinions and motivations, as a result of student participation in the workshops, *et cetera*.

Outcomes – Impacts – Medium Term: We anticipate seeing an increase in museum student participation (Actions), an increase in classroom participation (Practice), an increase in understanding and application of lessons-learned by students in their respective schools (decision-making), an increase in awareness of potential impacts upon society of vehicle lightweighting and crashworthiness (social action), and an increase in students interested in math, science and engineering.

Outcomes – Impacts – Long Term: We anticipate students graduating from their respective schools and entering colleges and universities to pursue degrees in math, science and engineering, who will have a stronger working knowledge and understanding of math, science and engineering as they relate to societal/behavioral, economic, civic and environmental impacts, as well as seeing an increase in the number of high-tech companies moving to Mississippi, as a result of having a more-informed and more-highly-educated student labor base from which future employees can be selected.

Evaluation: The effectiveness of this program will be determined by follow-up investigations, over time, to collect data, analyze and interpret the data, and report on the increase in students who enroll in institutions of higher learning in the fields of math, science and engineering.

Conclusions

The Mission Eggcellence Program has been developed for the grades K-3 and 4-6. The Teacher Workshop for these grades was very successful. Eighty percent of the teachers who attended the workshop had students compete in both the bumper-design and car-design competitions. Feedback was excellent. Curriculum and competitions for grades 7-9 and 10-12 are in the developmental process.

Acknowledgement

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