U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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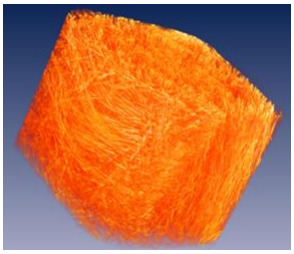
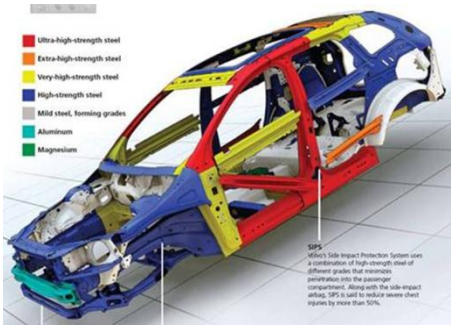
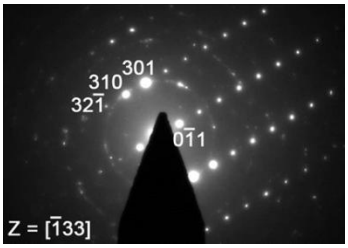




2011 PROJECT HIGHLIGHTS
LIGHTWEIGHTING MATERIALS
OAK RIDGE NATIONAL LABORATORY



2011 PROJECT HIGHLIGHTS
LIGHTWEIGHTING MATERIALS
OAK RIDGE NATIONAL LABORATORY

TABLE OF CONTENTS

Lower Cost Carbon Fiber

Advanced Oxidation of Precursors
Carbon Fiber Post Treatments to Facilitate Low-Cost High-Volume Composites
Carbon Fiber Research Pilot Line
Carbon Fiber Manufacturing Cost Modeling
Textile Based Precursors
Textile PAN-MA Precursors
Polyolefin Based Precursors

Projects Related to the Lightweighting Materials Carbon Fiber Program

Carbon Fiber Technology Facility
Carbon Fiber Test Standards
Commercialization of New Carbon Fiber Materials Based on Sustainable Resources

Polymer Composites

Predictive Modeling of Polymer Composites
Intermediate Strain Rate Crush of Crash Energy Management Structures
Muti-Materials Joining

Metals Multi-Material Enabling

Dynamic Characterization of Spot Welds in Advanced High Strength Steels
Friction Stir Spot Welding of Advanced High Strength Steels
Ultra-Sonic Solid-State Joining of Magnesium to Steel
On-Line Weld Non-Destructive Evaluation with Infrared Thermography
High-Strength, Lightweight Engines for Heavy-Duty Diesel Trucks
Advanced High Strength Steel Weld Fatigue Improvement
Infrared Treatment of Hybrid Steel-Aluminum Joints
Understanding Protective Film Formation by Magnesium Alloys

Metals Properties and Manufacturing

High Strain Rate Characterization of Magnesium Alloys
Fundamental Study of the Relationship of Austenite to Ferrite Transformations
Low Cost Magnesium Sheet Production Using Twin Roll Casting and Asymmetric Rolling

Metals Modeling and Computational Materials Science

Diffusion Database for Magnesium – ICME

Materials Crosscutting

Cost Modeling

2012 Project Highlights
Lower Cost Carbon Fiber and Composites Research and Development

Oak Ridge National Laboratory

Low Cost Carbon Fiber Production

Advanced Oxidation Technique

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

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Background

Oak Ridge National Laboratory (ORNL) is leading research and development efforts in lightweight materials for transportation, with a focus on lower cost carbon fiber which would be available at a target price of $5-7 per pound.

Significant automobile weight reduction and corresponding increases in fuel economy can be achieved by replacing dense materials (such as metals) with strong, lightweight composite materials. Carbon fiber reinforced composites are excellent candidates for this lightweight material. Carbon fibers, as the load-bearing components in these composites, offer significant weight saving potential because of their remarkably high strength, high stiffness, and low density. Carbon fiber strength is higher than that of steel at approximately the same stiffness with about a fifth of steel's density. It is estimated, that if carbon fiber composites were used in passenger automobiles that vehicle structure weights could be reduced by 50%.

While carbon fiber composites have proven themselves in high performance aircraft and other high performance applications, they are typically not used in passenger vehicles due to their high cost. Carbon fibers with the properties needed for automotive applications currently sell for $8 to $15 per pound. The most significant component of their cost is the cost of the carbon fiber itself and about half of that cost is the cost of converting the precursor (starting material) into finished carbon fiber. About half of the conversion cost is in the first step, oxidation.

The Technology

ORNL and ReMaxCo Technologies (RMX) are developing a plasma-based processing technique that rapidly and inexpensively oxidizes PAN precursor fibers. Conventional oxidation is a slow thermal process that typically consumes more than 80% of the processing time in a conventional carbon fiber (CF) conversion line. A rapid oxidation process could dramatically increase the conversion line throughput and appreciably lower the fiber cost. This technology will integrate with other advanced fiber conversion processes to produce low cost CF with properties suitable for use by the automotive industry. This technique has successfully oxidized both aerospace-grade and textile-grade PAN, and will be tested with other precursors as well. The approach currently being pursued is based on a new stabilization technique that utilizes advanced plasma-based thermochemical mechanisms to speed up the effective radial bulk diffusion of the physical and chemical changes required to prepare PAN for carbonization.

Efforts by the researchers in FY11 brought a dramatic development in this project. Stymied by issues that reduced the final mechanical properties of the carbonized fiber, the research team conducted feasibility tests of an alternative plasma-based method and configuration, the design of which was based on intuition and what had been learned to date of the stoichiometry of the process. The new technique was successful beyond expectations, and was scaled up for continuous processing. Over the course of the remainder of the fiscal year, the process was optimized to the point of oxidizing PAN precursor fiber in an average of 30 minutes while yielding carbon fiber with mechanical properties far exceeding the program requirements. A new patent disclosure was filed as

The Mulitple Tow Reactor.

Benefits

- Fully continuous process.
- Residence times less than half of conventional.
- Process could be incorporated into existing conversion lines.
- Does not require exotic source gases.
- Stabilizes all grades of PAN.
- Higher speed conversion of the precursor into carbon fiber yields cost savings.

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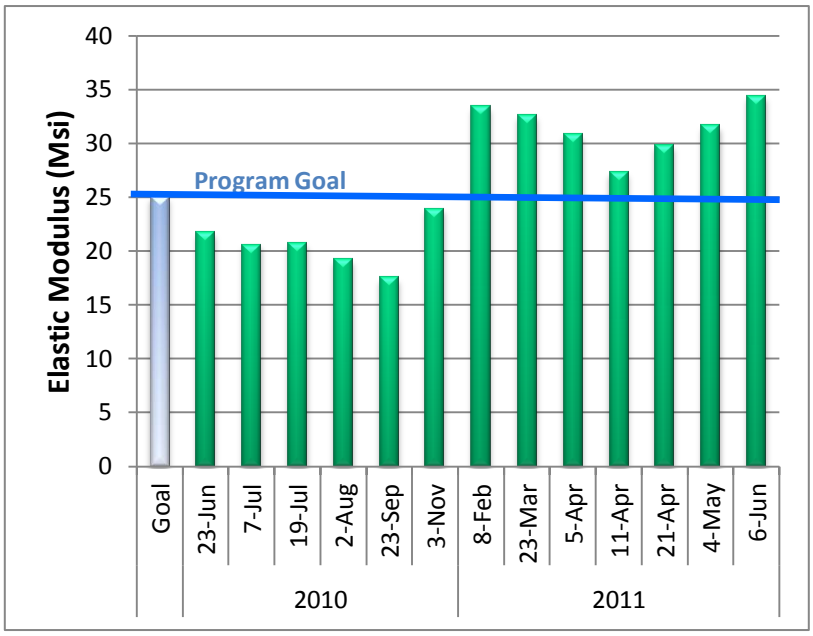
a result of this work. The figure below details the advancement of properties as a function of time for this project.



In addition to the core focus of advancing the oxidation process additional work took place this year in the application of the advanced oxidation technique to alternative precursors. The first alternative fiber used was textile grade precursors. These fibers are designed for use in textile applications such as clothing and carpet, and have not been considered applicable to structural applications. Nevertheless, another program at ORNL has produced textile grade PAN suitable for such applications, and this fiber has been processed with the advanced plasma-based oxidation technique practically reaching program mechanical requirements in as little as 45 minutes. Work with this fiber is ongoing.

The end of this fiscal year brings to a close the Phase I effort on the oxidation work. Phase II will commence in FY12 with the design and construction of a large scale oxidation reactor that will ultimately be installed at the ORNL Small Pilot Line for pilot-scale testing.

Technology Transfer

This project is just entering a scale-up phase of development, with the end goal of producing specifications for a demonstration-scale oxidation reactor to be utilized in ORNL's upcoming Carbon Fiber Technology Center (CFTC). At the conclusion of this project, the researchers will be positioned to procure, install, test, and operate a pilot scale plasma oxidation module in an advanced technology pilot line. The follow-on of this project will be the design and construction of the advanced technology pilot line that will then be installed in the CFTC. It will be used to validate system performance and scalability as well as to produce the required quantities of advanced technology carbon fibers to support LM program's advanced development activities.

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CARBON FIBER POST TREATMENTS TO FACILITATE LOW-COST HIGH-VOLUME COMPOSITES

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for transportation and particularly into the use of lower cost carbon fiber which would be available at a target price of $5-7 per pound.

The interface compatibility of carbon fibers when combined with lower cost resin is poor, resulting in poor property translation and **commercially unacceptable composites** (see Fig. 1). Typically with low cost resins, the carbon fiber/matrix interface bond strength is less than half what epoxy resin will yield. In addition, the current state of the art epoxy based sizing is not suitable for low cost composite processes and at all for high temperature (~300°C) thermoplastic composite manufacturing. For cost-critical applications such as transportation, windpower and other energy missions, high volume low cost carbon fibers will be combined with lower cost resins such as vinyl esters, polyesters, and thermoplastics instead of aerospace epoxy resin system. ORNL has developed scalable gas phase/atmospheric plasma surface treatment and sizing technologies under DoE's Vehicle Technology program with industrial partners.

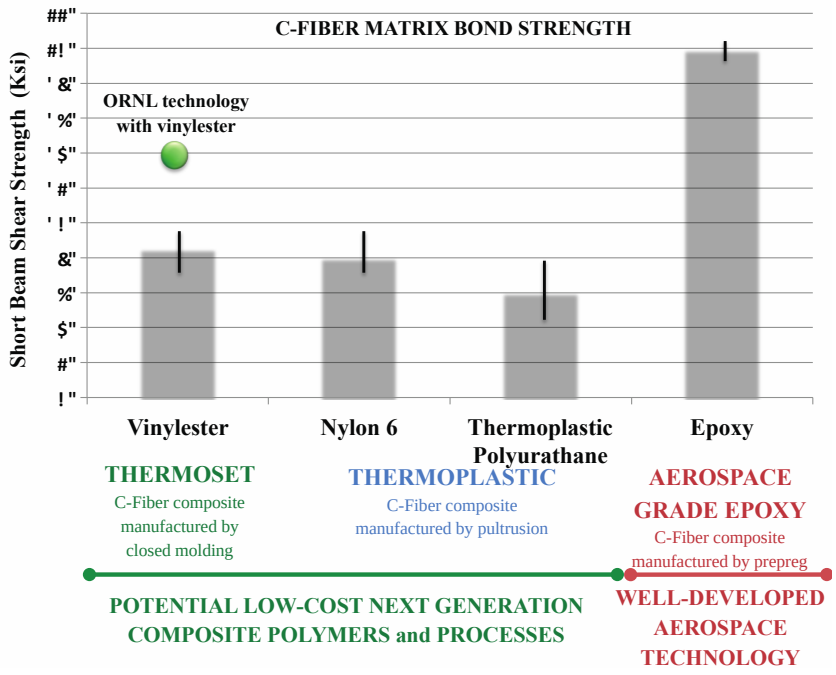
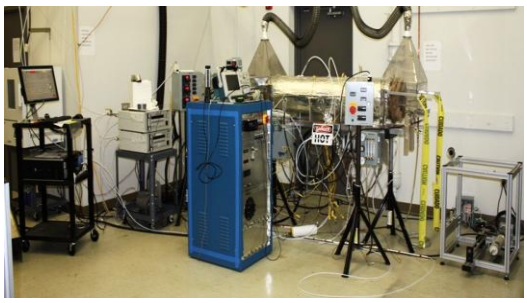


Figure 1. Comparison of the relative interface bond strength of carbon fibers with different resins. Industrial carbon fibers were used for all type resins and processes. ● : Vinyl ester composite made from carbon fibers using ORNL post-treatment technology.



ORNL-Lab-sclale experimental continuous thermochemical and atmospheric plasma based surface treatment applicators

Benefits

- **Developing of surface treatment and sizing addressing low cost carbon fiber will accelerate the utilization of low cost carbon fiber and composite process technology**
- **Develop specialty surface treatment and sizing recipes targeting resin systems for emerging energy industries where the low-cost carbon fiber can be utilized beneficially.**
- **Improved adhesion at the carbon/fiber interface will enable the fabrication of thinner parts with comparatively higher mechanical performance results in weight reduction and cost savings.**

The Technology

Novel gaseous surface treatment and sizing materials are being developed at ORNL to use in carbon fiber production addressing large volume low cost composites. The current surface treatment method is the processing of carbon fibers at a residence time of around 90 seconds. Up to 26% atomic oxygen content has been achieved at laboratory scale by continuous treatment with an ability to focus around the combination of desired functional groups. This is more than double of functionality on the surface that can be generated by industrial electrochemical surface treatment. We have developed low molecular weight polymer sizing at high viscosity that coupled with high quality of surface treatment in order to wet the high surface area (roughen carbon fiber surface). The developed sizing does not impede the penetration of vinyl ester resin and the tow bundle is soft and easily spread while protecting the carbon fiber and surface structure. Sizing is compatible in terms of solubility in and/or reactivity with the vinyl ester matrix resin. This allows the resin to penetrate the fiber bundle and interact with the fiber surface. The developed sizing also promotes the chemical bonding to matrix resin. Comparison of ORNL surface treatment with industrial practice and sizing results are shown in Fig 2.

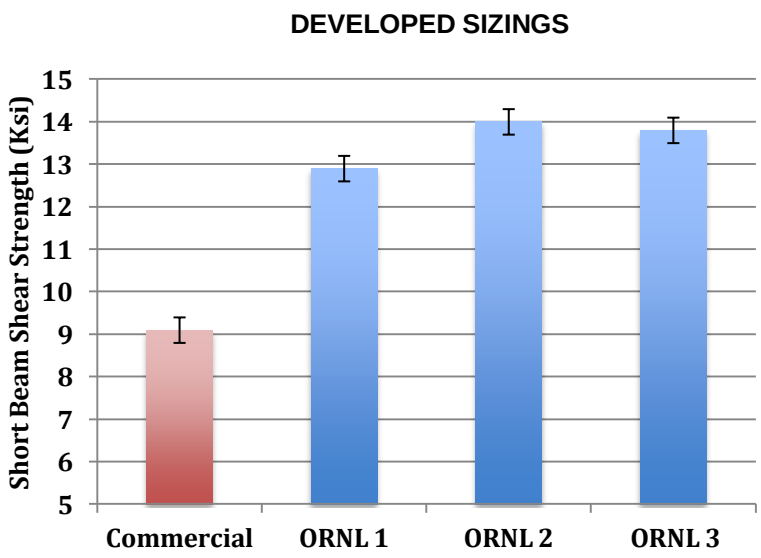


Figure 2. Short beam shear strength of vinyl ester composites are compared. Industrially surface treated fibers (commercial) versus ORNL developed sizing applied on carbon fibers.

Technology Transfer

ORNL and industrial partners are developing novel gas phase thermochemical and plasma based surface treatments, and sizing compatible with vinyl ester, polyesters and automotive thermoplastics. Development of specific surface treatment and sizing will be geared towards the utilization of next generation low cost-carbon fiber technology.

ORNL-Labscale continuous sizing line

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Carbon Fiber Research Pilot Line

Upgrades to Key Tool in the Research Suite

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for transportation and particularly into the use of lower cost carbon fiber which would be available at a target price of $5-7 per pound.

Significant automobile weight reduction and corresponding increases in fuel economy can be achieved by replacing dense materials (such as metals) with strong, lightweight composite materials. Carbon fiber reinforced composites are excellent candidates for this lightweight material. Carbon fibers, as the load-bearing components in these composites, offer significant weight saving potential because of their remarkably high strength, high stiffness, and low density. Carbon fiber strength is higher than that of steel at approximately the same stiffness and ~ 1/5 of steel's density. It is estimated, that if carbon fiber composites were used in passenger automobiles that vehicle structure weights could be reduced 50%.

While carbon fiber composites have proven themselves in high performance aircraft and other high performance applications, they are typically not used in passenger vehicles due to their high cost. The most significant component of their cost is the cost of the carbon fiber itself and slightly more than half of that cost is the cost of the precursor (starting material) from which the fiber is made. Carbon fiber is made by a slow thermal pyrolysis of a relatively expensive precursor.

Carbon fibers with the properties needed for automotive applications currently sell for $8 to $15 per pound. About fifty percent of that cost is attributable to the cost of the precursor used to make the carbon fiber. ORNL is leading significant DOE-funded effort to develop and demonstrate alternative, significantly lower cost precursors and advanced energy efficient and cost-effective conversion technologies. Key tools in this research are a precursor evaluation system to evaluate bench scale precursor formulations and a fully integrated pilot line for demonstrating continuous conversion of these precursors in sufficient quantities to establish projected fiber properties. With this information, decisions can then be made on scaling materials and processes to pre-production manufacturing levels in the Carbon Fiber Technology Facility due to come online in 2013.

The Technology

In the carbon fiber conversion process, a precursor fiber is processed thermally at progressively higher temperatures and under stress to effect stabilization and oxidation necessary for higher temperature pyrolysis of the non-carbon elements remaining in the fiber. This carbonization is conducted in an inert atmosphere. The ovens and furnaces are quite large, usually occupying an area larger than that of a football field and consuming large amounts of energy. The residence time required for fiber in production is usually well over an hour, limiting the throughout from this large investment of energy and capital.

The precursor evaluation system transitions development from the individual process stages (e.g each of 4 stages of oxidation and 2 or more stages of carbonization) and working at the few grams and single or few filaments to single tow level to the multiple tow and fully integrated process development via our in-house conventional pilot line. ORNL's conventional pilot line enables the production of order 1-10 lb/day of 50k tow. Therefore, it is useful for making small quantities of fiber for tow and composite evaluations. It can also be used to

ORNL Small Pilot Line

ORNL Precursor Evaluation System

Benefits of Upgrades

- **Better understanding of material/processing conditions relationships**
- **Enhanced data accuracy and repeatability**
- **Enhanced capability to fine-tune process parameters to achieve targeted properties at lowest cost and minimum energy usage**
- **Capability to produce higher performing carbon fiber of interest in H2 pressure vessels, wind, and other applications**
- **Enhanced production volume capability for materials**

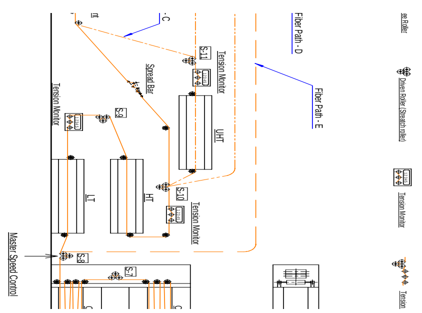
conventionally oxidize or carbonize tows that are partially converted by advanced processes. Minimum material requirements for evaluation on the pilot line are hundreds of feet of ≥ 3K tow, and startup time for the high temperature carbonization furnace is ≥ 10 hours. Providing a few pounds of samples for initial evaluation is a function of the pilot line as this is not very practical from the precursor evaluation system. Likewise, providing significantly larger quantities of materials from the pilot line is not practical. In almost all cases, full product development will require sample sizes only practical from the CFTF and end users will want pre-production scale demonstration at that level or above to justify commitment of the required resources.

Although the pilot line has itself proven to be a useful tool, it has limitations we are working to address including need for better control tension and stretching capabilities, more flexibility in operations, higher capacity, and enhanced process monitoring. These limitations are being addressed by addition of:

- Higher speed capability (from ~12 in/min to ~30 in/min)
- Increase in number of passes per oxidation oven
- Pre-stretching capability prior to oxidation
- Progressive stretching during oxidation
- Process bypass capability
- New Sizing unit
- Enhancement of controls and data acquisition systems

Technology Transfer

The precursor evaluation system and pilot line have already been utilized to successfully demonstrate textile PAN precursor properties and achieve polyolefin precursor milestones. Key property relationships are being established for a variety of materials; these capabilities have helped in other research to resolve issues with advanced oxidation property deficiencies. In combination, the precursor evaluation system, pilot line, and CFTF are a unique set of tools that position the Low Cost Carbon Fiber Program for establishing a pathway from bench scale research though low volume feasibility to semi-production-scale demonstration as the key steps towards commercialization to meet energy efficiency missions.



Schematic Outline of Upgraded Pilot Line

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Low Cost Carbon Fiber Production

Carbon Fiber Manufacturing Cost Modeling

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

The automotive industry has long been identified by carbon fiber manufacturers as a market with substantial growth potential. When manufactured with carbon fiber as opposed to traditional materials such as steel, automotive parts are able to achieve requisite levels of strength and stiffness with significantly less overall vehicle weight. These potential large reductions in vehicle weight, in turn, afford the opportunity for substantial improvements in fuel economy and greenhouse gas emissions.

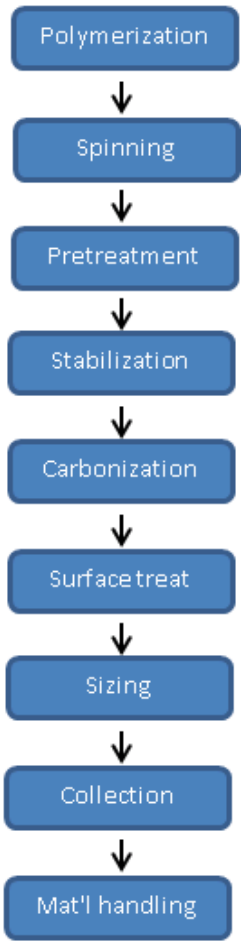
Despite their significant performance advantages, carbon fiber reinforced composites have enjoyed limited acceptance in the automotive industry due to high costs associated with both the manufacture of carbon fibers themselves as well as their composites. Traditional carbon fiber manufacturing uses polyacrylonitirile (PAN) as a precursor. This precursor requires a lengthy and energy intensive oxidative stabilization step so that the fibers can endure the high temperatures of the subsequent carbonization step without decomposing. At the conclusion of the carbonization step, approximately one half of the original PAN precursor mass has been lost as volatile effluent. This effluent contains toxic species requiring abatement before reintroduction into the environment. Following the carbonization step, carbon fibers undergo a surface treatment and sizing step which improves their ability to bond with composite matrix material. It is important that a carbon fiber manufacturing cost model be developed in order to evaluate the cost-effectiveness of alternative manufacturing pathways being considered by the industry today.

Approach

ORNL is investigating various alternative precursors and advanced manufacturing technologies with the potential to substantially reduce carbon fiber costs. Vehicle Technology Program goals include the development of industrial grade carbon fibers which are performance and cost competitive with traditional automotive materials. Specific targets are carbon fibers having strength of at least 250 Ksi, modulus of at least 25 Msi, and a selling price of $5-7 per pound.

Alternative precursors being examined include textile grade PAN, lignin, polyolefins, and PAN-lignin blends. Precursor costs represent approximately 50% of the total cost of conventionally manufactured carbon fibers due to the high cost of the main raw material (acrylonitirile), the low mass throughput of wet spinning, and the low mass conversion yield of precursor to carbon fiber. Alternative precursors have the potential to substantially reduce carbon fiber costs through lower raw material costs, higher mass throughput melt spinning as opposed to wet spinning, and higher mass conversion yields from precursor to carbon fiber.

Advanced processing technologies being investigated by ORNL include plasma oxidation, microwave assisted plasma carbonization, and advanced surface treatments and sizings. Plasma technologies have the potential to substantially reduce costs through lower energy requirements, smaller floor space requirements, and reduced processing times. For example, oxidation processing time has the potential to be reduced from 90-120 minutes for conventional processing to as little as 20 minutes for plasma oxidation.



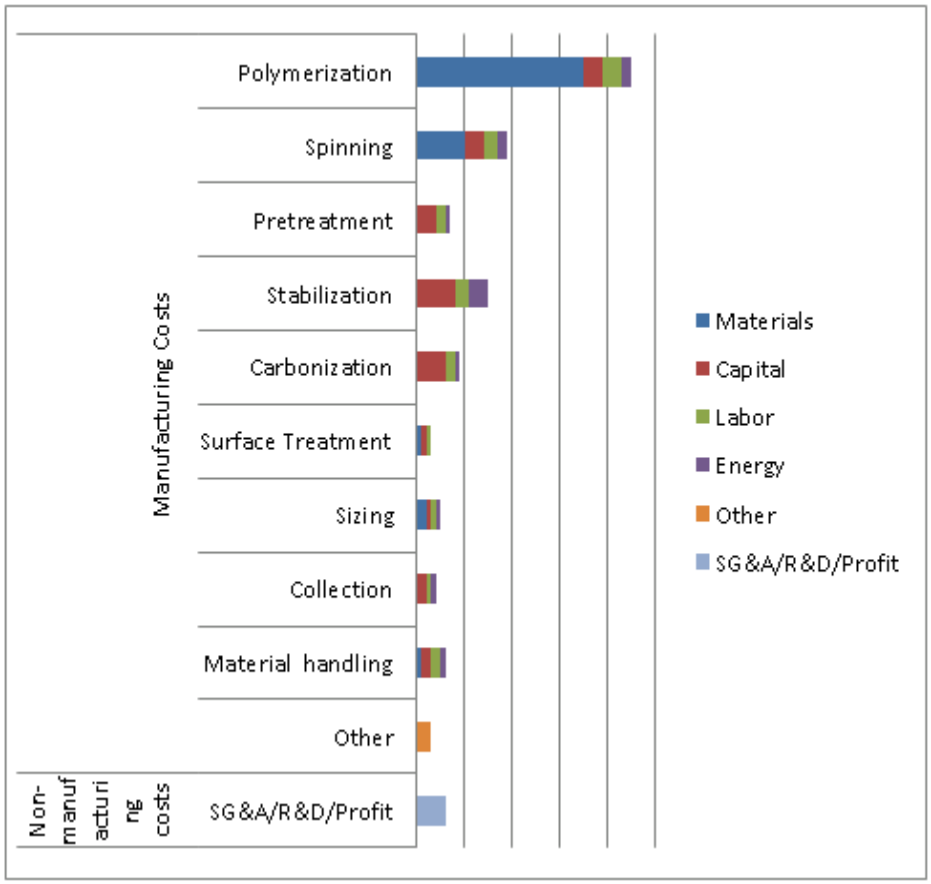
Benefits

- Highly customizable carbon fiber cost estimation using conventional or advanced precursors and processing technologies
- Road mapping and identification of alternative precursors and processing techniques with high potential for significant cost reduction
- Rapid carbon fiber cost estimation capability for new precursors and processing technologies using the model

Microwave assisted plasma carbonization may reduce costs through reduced energy requirements, faster processing times, and greatly diminished or eliminated abatement and surface treatment needs. Advanced surface treatments are also being examined, and have the potential to generate significant cost savings by increasing the bond strength at the carbon fiber-matrix interface in composites. Increased bonding strength, in turn, translates into a reduction in the mass of carbon fiber required to achieve a desired performance for carbon fiber reinforced composite strength.

A manufacturing cost modeling tool is being developed to accurately gauge the cost reduction potential and adoption risk of alternative precursors and advanced processing technologies. By disaggregating costs into major processing steps and cost categories, the cost modeling tool will allow the estimation of changes in cost due to changes in precursor types, processing technologies, and processing parameters. Monte Carlo simulation and sensitivity analysis will be used to assess the cost impact of uncertain and stochastic inputs such as commodity raw material prices.

Processing steps being examined are the precursor steps of polymerization and spinning, as well as the carbon fiber production steps of pretreatment, stabilization, carbonization, surface treatment, sizing, collection, and material handling. For each processing step, costs will be disaggregated into the major categories of materials, capital, labor, and energy. A modular design will facilitate the rapid incorporation of new precursors and processing technologies into the cost model environment.



Example bar chart of costs disaggregated by processing steps and cost components.

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Low Cost Carbon Fiber Production

Textile Based Precursors

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for transportation and particularly into the use of lower cost carbon fiber which would be available at a target price of $5-7 per pound.

Significant automobile weight reduction and corresponding increases in fuel economy can be achieved by replacing dense materials (such as metals) with strong, lightweight composite materials. Carbon fiber reinforced composites are excellent candidates for this lightweight material. Carbon fibers, as the load-bearing components in these composites, offer significant weight saving potential because of their remarkably high strength, high stiffness, and low density. Carbon fiber strength is higher than that of steel at approximately the same stiffness and ~ 1/5 of steel's density. It is estimated, that if carbon fiber composites were used in passenger automobiles that vehicle structure weights could be reduced 50% .

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Carbon fibers with the properties needed for automotive applications currently sell for $8 to $15 per pound. About fifty percent of that cost is attributable to the cost of the precursor used to make the carbon fiber. Recently, Hexcel and ORNL developed the baseline technology necessary to use textile based polyacrylonitrile (PAN) fiber as a very low cost precursor for making carbon fiber. The key to using textile PAN precursors is the application of a chemical pretreatment during manufacture of the precursor fiber. ORNL and FISIPE S.A. (Portugal) are working to complete development and commercialize this precursor to make it available to current and potential carbon fiber manufacturers.

The Technology

A collaborative international program by ORNL and FISIPE S.A. in Portugal is working to render textile-based polyacrylonitrile suitable for conversion into carbon fiber. Textile fiber sells for half the cost conventional carbon fiber precursors and would result in a savings of more than $2.00 per pound in the finished carbon fiber manufacturing costs.

Recently the two organizations have defined several textile formulations that yield suitable carbon fibers. They are modifying materials that can be oxidized near conventional oxidation temperature. In addition, they have developed a way to modify the chemistry of the starting materials by the addition of a small amount of

Textile Grade Polyacrylontrile Precursors

Benefits

- **Textile based PAN precursors cost less than half of the cost of traditional precursors**
- **Chemical pre-treatment is easily incorporated into existing textile mills**
- **Textile mill volumes can support the large increases in fiber quantity required for automotive applications**
- **Total saving in carbon fiber cost could exceed $2/lb**
- **Higher speed conversion of the precursor into carbon fiber yields additional cost savings**

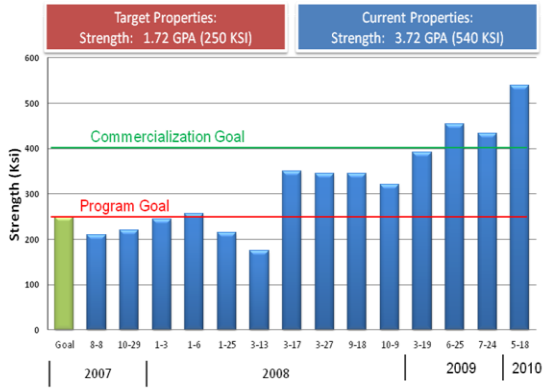
a third component to the polymer chemistry and have defined a chemical pretreatment protocol for further altering the fiber chemistry.

Different levels and conditions of the pretreatment were also evaluated. Key to incorporating these changes has been the ability to perform the chemical modification in current production facilities and at current production speeds and temperatures. Mechanical properties now well exceed the program requirement as shown in the figure below.

The oxidative stabilization of the modified textile precursors requires only ~70 minutes compared to a time of 80-120 minutes for conventional carbon fiber precursors. Oxidative stabilization is the low speed bottleneck in the carbon fiber conversion process. As a result modified textile precursors may be carbonized at much higher speeds and a significant production cost reduction achieved.

Technology Transfer

FISIPE is a commercial fiber production facility and intends to offer this new fiber as a lower cost precursor to current and future carbon fiber manufacturers. ORNL has other parallel efforts to develop new production technologies that will enable manufacturers to develop high volume, commercial carbon fiber plants that use textile based PAN precursors along with other advanced manufacturing methods.



Improvement in Fiber Strength During the Project

Improvement in Fiber Modulus During the Project

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Lower Cost Higher Performance Carbon Fiber

Textile PAN-MA Precursors

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

During the past several years, the Vehicle Technologies (VT) Program has been developing technologies for the production of lower cost carbon fiber for use in body and chassis applications in automobiles. Program goals target materials that have tensile strengths in excess of 250 Ksi and modulus of at least 25 Msi. Past work included the development of a vinyl acetate co-monomered, lower cost precursor and methods for manufacturing precursors into finished carbon fiber. A textile plant has been retrofitted to commercialize that fiber.

The previously developed fiber has strengths below 500 KSI, which is suitable for automotive structural applications but insufficient for many higher applications with higher performance requirements. In order to preserve the cost advantages of using a high volume polyacrylonitrile (PAN) fiber, and simultaneously meet the needs of higher performance applications, this project is developing the capability to use methyl-acrylate based, textile grade, PAN as a carbon fiber precursor. Previous work by Hexcel, Inc. has demonstrated the feasibility of being able to use this material.

The most significant obstacle to the incorporation of carbon fiber as a lightweighting structural material in wind energy, gaseous fuel storage, oil and gas, energy storage, energy transmission, infrastructure and many other industries is the high cost of the carbon fiber. Carbon fiber price varies significantly based upon the performance requirements required from the fiber with the higher performance fibers being significantly more expensive. Carbon fibers with the properties needed for hydrogen storage currently sell for $15 to $30 per pound. About fifty percent of that cost is attributable to the cost of the precursor used to make the carbon fiber

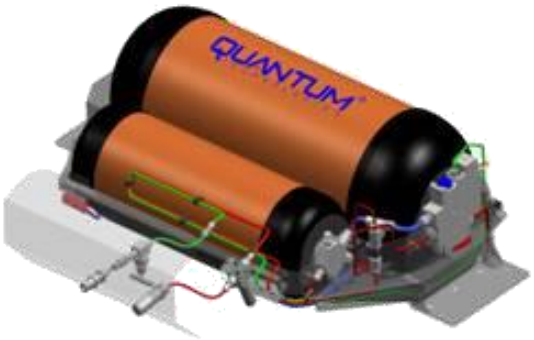
The Technology

A collaborative international program by ORNL and FISIPE S.A. in Lisbon, Portugal is working to render methyl-acrylate co-monomered, textile-based polyacrylonitrile suitable for conversion into carbon fiber.

Recently the two organizations have defined several textile formulations that yield suitable carbon fibers. They are modifying materials that can be oxidized near conventional oxidation temperature. In addition, they have developed a way to modify the chemistry of the starting materials by the addition of a small amount of a third component to the polymer chemistry and have defined a chemical pretreatment protocol for further altering the fiber chemistry.

The down-selection of chemical compositions and formulation started in April of 2011. The main issue related to achieving the proper formulation was the generation of the PAN-polymer with a higher AN content. FISIPE generated 11 candidate compositions. Three compositions were down-selected and sent to ORNL for molecular evaluations.

DSC curves from those three compositions were generated. In addition



Benefits

- **Textile based PAN precursors cost less than half of the cost of traditional precursors**
- **Chemical pre-treatment is easily incorporated into existing textile mills**
- **Textile mill volumes can support the large increases in fiber quantity required for hydrogen storage applications**
- **Total saving in carbon fiber cost could exceed $4/lb**
- **Higher speed conversion of the precursor into carbon fiber yields additional cost savings**

nuclear magnetic resonance spectroscopy was conducted on all three compositions and the conventional samples that these were compared against. All samples had a lower than desired AN content which may be increased in future iterations of the candidate precursors. Based on the results of both tests two formulations were selected for the first precursor samples.

Technology Transfer

FISIPE is a commercial fiber production facility and intends to offer this new fiber as a lower cost precursor to current and future carbon fiber manufacturers. ORNL has other parallel efforts to develop new production technologies that will enable manufacturers to develop high volume, commercial carbon fiber plants that use textile based PAN precursors along with other advanced manufacturing methods.

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Low Cost Carbon Fiber Production

Polyolefin-Based Precursors

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

With the assistance and direction of the U.S. Department of Energy, Office of FreedomCAR and Vehicle Technologies, the Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for transportation. Carbon fibers offer significant weight saving potential because of their remarkable high strength, high modulus, and low density. The large volume use of carbon fibers is currently restricted because of their high cost which is $8 to $15 per pound. Forty to fifty percent of that cost is attributable to the cost of the precursor. Currently, common commodity grade carbon fibers are produced from polyacrylonitrile (PAN) based precursors. PAN-based textile precursor is a potential candidate for low-cost carbon fibers with the projected costs savings being around $2.00 per pound of finished carbon fiber. Polyolefin-based fibers (polyethylenes and polypropylene) are industrially produced in USA and are low-cost commodity plastic fibers ($0.50 - 1.00/lb). The cost of these precursor fibers is less than half of that of the PAN-based precursor fibers.

However, since polyolefin fibers are melt-spun, a stabilization route needs to be developed prior to carbonization of the precursor fiber without melting. In the past, conversion of polyolefin precursors was attempted by a few research groups via sulfonation of the precursor fibers. Although the reported practical carbon yield was very high (~78%) for the polyolefin fibers, in comparison to that of the PAN based fibers (~50%), unfortunately the residence time requirement in stabilization step was very high. ORNL researchers have developed a conversion technology for polyolefin precursors that requires non-conventional stabilization and direct carbonization without any further oxidation step.

The Technology

Polyolefin fibers were melt-spun in collaboration with an industrial melt-spinning equipment manufacturer in the USA. Mechanical properties of the filaments can be tailored depending on the degree of filament draw down ratio.

A systematic investigation optimized the stabilization conditions for 100 to 1500 filament tow of 10 to 20 μm diameter fibers. A semi-continuous operation was established for those tows using a simple reactor as shown in the following figure. Optimization of conversion parameter is underway with an overarching goal to produce polyolefin precursor-based lower-cost carbon fiber. To date, carbonized fibers with 200 ksi strength and modulus of 21 Msi have been produced.

Almost 60-70% carbon yield was observed from the said precursor materials.

Spools of as-spun PE fibers

Set up for semi-continuous functionalization of filaments

Benefits

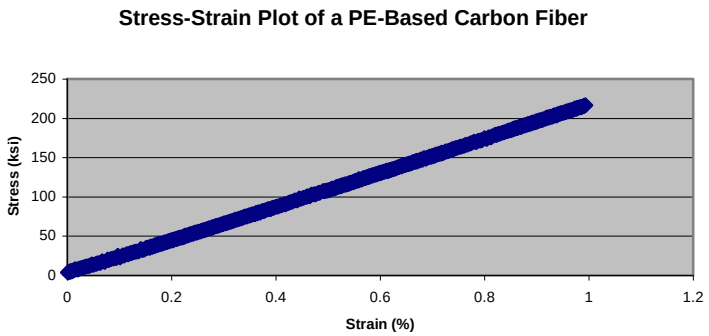
- **Polyolefin based precursors are significantly lower in cost compared to the PAN based precursors.**
- **Melt spinning is less expensive than solution spinning**
- **Fibers can be spun at high speed.**
- **Total saving in carbon fiber cost could exceed $2/lb**
- **Reduced unit investment cost**
- **Melt-spun polyolefin fiber is available in the market.**
- **Polyolefins offer significantly high carbon yield (60-75%).**

The issues of incomplete functionalization of the fiber core and inter-filament bonding during thermal treatment have been successfully resolved.

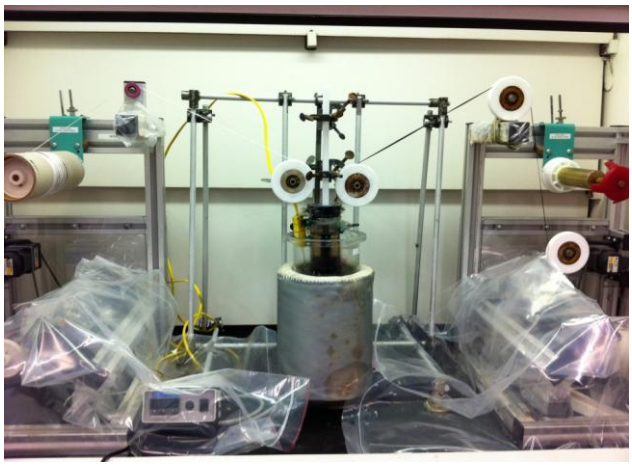
Probability of inter-filament bonding for ~ 10 μm diameter filaments has been completely eliminated.

Technology Transfer

Polyolefin-based precursor development is being conducted at ORNL in collaboration with a multinational polyolefin manufacturer.



Recently processed carbon fibers from polyolefin shows 200 Ksi strength and 21 Msi modulus.



Modified Set up for continuous stabilization of filaments

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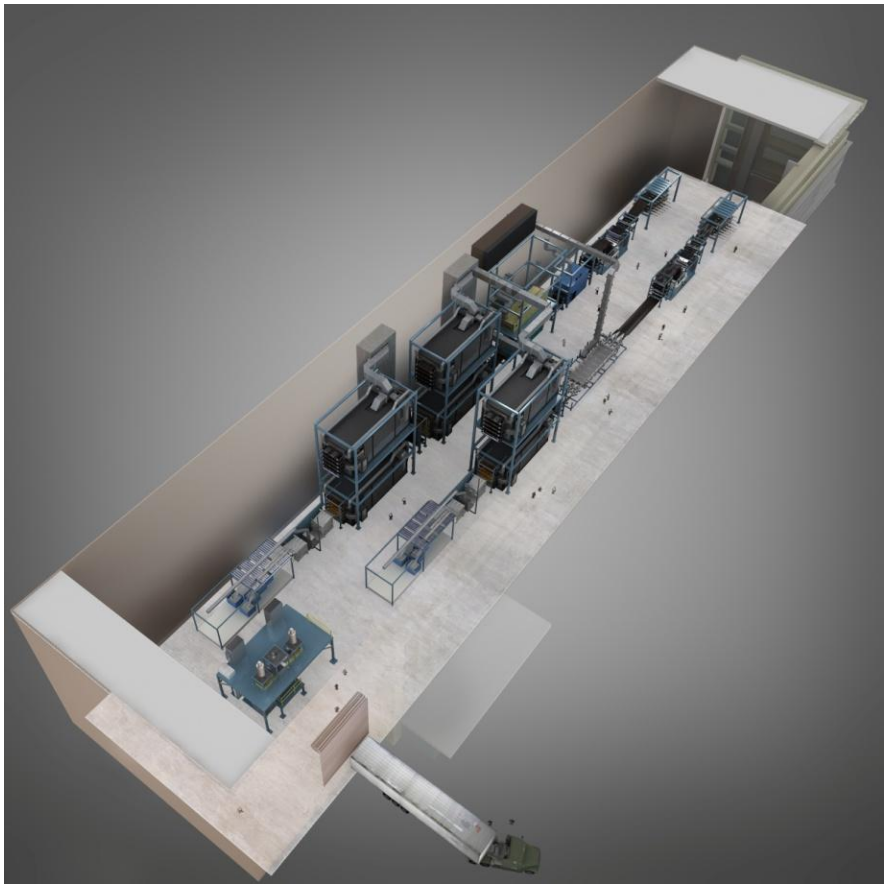
2011 PROJECT HIGHLIGHTS PROJECTS RELATED TO THE LIGHTWEIGHTING MATERIALS CARBON FIBER PROGRAM



OAK RIDGE NATIONAL LABORATORY

Carbon Fiber Technology Facility

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

With the assistance and direction of the U.S. Department of Energy, Vehicle Technologies Program, the Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for transportation. Carbon fiber reinforced composites are excellent candidates for this lightweight material. Carbon fibers offer significant weight saving potential because of their remarkable high strength, high modulus, and low density. The use of carbon fibers is currently restricted by their high cost which is $8 to $15 per pound. ORNL is developing new precursors and conversion processes for manufacturing low-cost carbon fibers (LCCF).

The Technology

There is an anticipated future need for the capability to demonstrate scalability of low-cost carbon fiber (LCCF) technology, and to produce tons of LCCF for evaluation by composites manufacturers and OEM's. The Carbon Fiber Technology Facility (CFTF) will be a highly flexible, highly instrumented LCCF technology facility for demonstrating and evaluating new low-cost precursors and manufacturing processes at semi-production scale. The CFTF will promote successful LCCF commercialization. It will have the capabilities to:

- Demonstrate the scalability of the science and technology for lowering the cost of carbon fiber by approximately 50%
- Produce and make available up to 25 tons/year of conventionally converted fibers (made from low-cost precursors) to potential end users and upper-tier suppliers in multiple industries
- Accommodate advanced conversion technologies
- Produce precursor fibers made from a variety of precursor materials, e.g., lignin and polyolefin, on a melt-spinning line in sufficient quantity to feed the conversion lines
- Enable industrial and university collaborations to effectively leverage expertise of Laboratory personnel in developing low-cost manufacturing techniques for carbon fiber components
- Educate and train a highly skilled future workforce for LCCF implementation

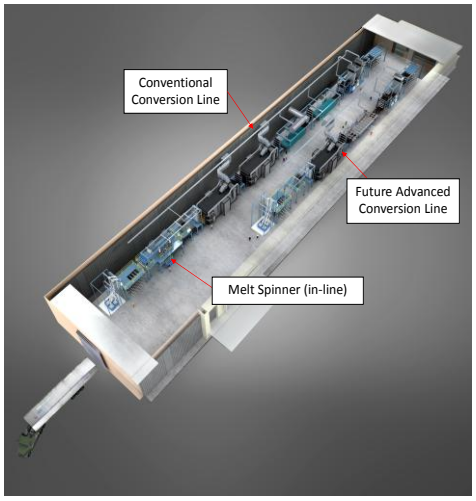
Technology Transfer

The CFTF is intended to promote commercialization of all LCCF technologies. Prospective commercialization partners should contact C. David Warren.

CFTF Status

CFTF is scheduled to startup in February 2013. The building is ready to receive equipment for installation, while trim and finish work continues in some of the office and support areas.

The carbon fiber line and melt spinning line design are both nearing completion and equipment is currently in fabrication. Equipment delivery for installation is scheduled to begin in March 2012.



CFTF Rendering

Benefits

- **Demonstrate LCCF scalability**
- **Produce several tons of LCCF for evaluation by composites manufacturers in multiple industries**
- **Promote industrial and university collaborations**
- **Educate and train a highly skilled future workforce**

Assembled oven center section

High temp furnace in fabrication

Oven end seal

Building photos

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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Carbon Fiber Test Standards

Collaboration as part of the International Energy Agency

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

Carbon fiber is categorized in many ways according to tow size, precursor, and end use application. The amount and speed of growth of the carbon fiber industry in the future will be determined by the requirements of various industries that may employ this material.

There continues to be a strong demand for higher strength fibers (>750 KSI: 5.2GPa) in the aerospace industry. Intermediate structural fibers (> 550 KSI: 3.8GPa strength) could be employed in wind energy, oil & gas, electrical energy storage, electrical energy transmission, pressure vessels and non-traditional energy and industrial applications. Lower strength fibers (< 550 KSI: 3.2GPa) are prime candidates for applications in automotive, wind energy, oil and gas, infrastructure, non-aerospace defense, electronics and aerospace secondary structures. Based on some market analysis done at ORNL, these markets have potential volume requirements of 1.4 – 52 billion kilograms per year of carbon fiber.

Key to any material becoming widely used in commodity volumes is the existence of standard methods for determining the properties of the material from different suppliers and under different conditions. Recognizing that there are gaps in the standard procedures for determining carbon fiber properties, the International Energy Agency is proposing to facilitate development of those standards. For example, Table 1 lists relevant carbon fiber properties within the broad categories of: Mechanical Properties, Physical Properties, Chemical Properties, Thermal Properties and Electrical Properties.

Standards Development Plan

The approach adopted to develop carbon fiber test standards has four key elements intended to both prioritize research and development and foster the adaptation of those methods by various international standards organizations and industrial uses. The four basic elements are:

Steering Committee: A steering committee comprised of representatives from government, aircraft manufacturers, automotive manufacturers, carbon fiber manufacturers, research laboratories, and universities was established. The steering committee provides technical direction to the development teams and determines the priorities for the development of standards.

Standards Development Projects: The standards indicated will be proposed developed, written and proposed for adoption by individual teams.

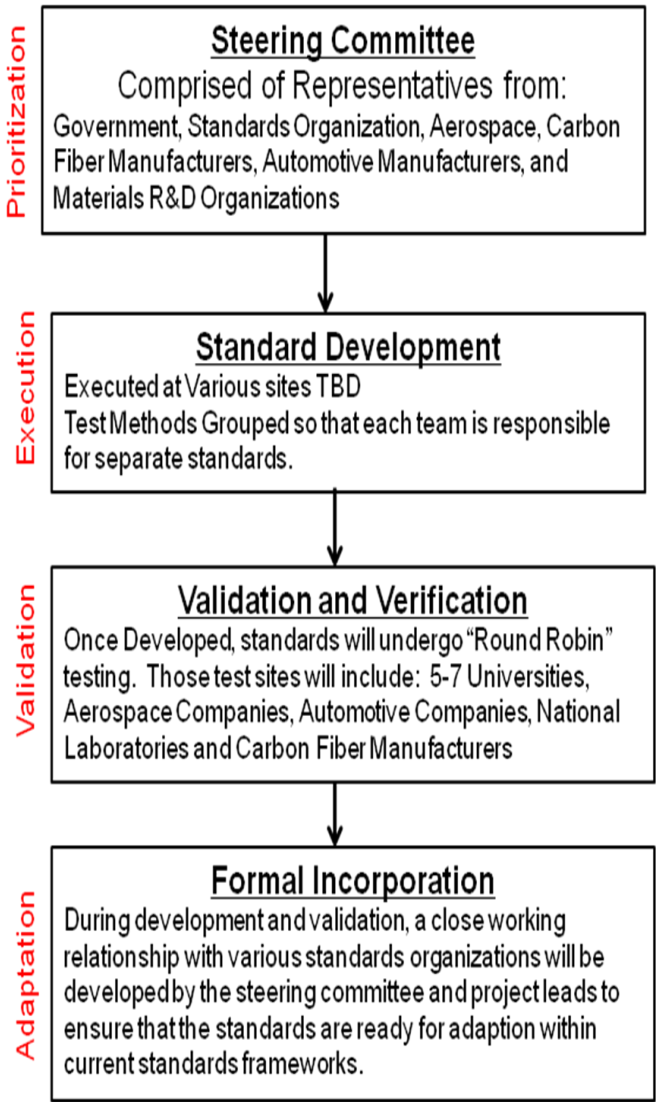
Validation and Verification: After development of each standard, a round robin testing program will be conducted to validate the precision and sufficiency of each standard. The testing will involve an iterative feedback loop between validators and developers.

Mechanical Properties
Modulus
Strength
Strain to Failure
Shear Modulus
Shear Strength
Compressive Strength
Compressive Modulus
Poisson's Ratio
Physical Properties
Dimensions (Diameter)
Density
Shape
Cross-Sectional Area
Porosity
Anisotropy
Crystallinity (graphitic structure)
Linear Density
Surface roughness
Filament Count
Chemical Properties
Carbon Content %
Elemental Composition
hydrophilic/hydrophobic characteristics
Fiber-Resin Adhesive Strength
Limiting Oxygen Index
Surface functionalization
Thermal Properties
Coefficient of Thermal Expansion
Thermal Conductivity
Anisotropy
Flame Retardancy (ox-PAN) LOI
Oxidation Rate/Onset (Usage limit)
Electrical Properties
Resistivity - multiple directions
Internal Conductivity - Multiple directions

Formal Incorporation: Adoption of the standards will occur within the framework of various international standards organizations during the development and validation of the proposed standards. Both the steering committee and the protocol developers will be highly active in this final but critical stage.

Standards are being developed for large tow, small tow and single filament testing.

The Figure below indicates the proposed process.



The current steering committee meetings are held via teleconference and include participants the United States, United Kingdom, Germany, Australia, Japan, Canada and France.

Benefits

- **Standard methods for determining properties.**
- **Acceptable test methods to assure reliable fiber to fiber comparisons/**
- **Increase in the utility of reported data.**
- **Standard property determination methods aid designers and modelers and foster an environment for greater acceptance of carbon fiber composites.**

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Commercialization of New Carbon Fiber Materials Based on Sustainable Resources for Energy Applications

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Advanced Manufacturing Office

Oak Ridge National Laboratory
UT-BATTELLE

Background

Under the sponsorship of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, the Oak Ridge National Laboratory (ORNL) is conducting research and development into lightweight materials for energy applications. Carbon fibers offer compelling functional and/or structural benefits for many energy applications. Carbon fiber properties can frequently be tailored to deliver one of high strength, high stiffness, high or low thermal conductivity, high surface area, etc. Example energy applications include: (i) lighter weight structures for transportation and wind energy, (ii) thermal insulation for high temperature processes, (iii) high efficiency filtration, and (iv) electrical energy storage. The use of carbon fibers is typically restricted by their high cost. ORNL is developing new precursors and conversion processes for manufacturing low-cost carbon fibers (LCCF).

The Technology

Isotropic carbon fibers can be made from lignin, the "glue" holds trees (and other cellulosic plants) together. Lignin is an inexpensive, abundant, renewable resource that is a by-product of pulp mills and biorefineries. Lignin is not currently used as a precursor for the commercial production of carbon fibers.

Pitch-based, isotropic carbon fibers are currently used in thermal insulation for very high temperature processes. These pitch-based fibers are typically foreign sourced, costing more than $10/lb, with unstable pricing and availability. The deployment of domestic lignin carbon fiber technology will reduce cost, improve stability of price and supply, and recapture lost US jobs.

Lignin-based carbon fibers can be produced at an estimated "mill cost" of $4 - $6/lb and thus offer a compelling cost advantage over current technologies. Lignin-based carbon fibers made in ORNL's laboratories have been shown to satisfy the technical requirements for high-temperature thermal insulation. The technology is now being scaled to demonstrate that it can meet the technical and business requirements at pilot scale. ORNL has recently compounded and pelletized more than one ton of lignin, and has produced 1,200 lb of lignin fibers in three batches of 400 lb each. **This is the first reported production of lignin fibers in a batch size exceeding 10 lb.**

Technology Transfer

The project is being conducted in partnership with a major US industrial partner that will license the technology and insert it into an existing thermal management product line with carbon fiber demand exceeding 500 tons/year. This partner is a participant in the project and evaluating the resulting products. The project is being conducted in accordance with the partner's stage-gated product development and launch process.

Pilot production of lignin fibers

Benefits

- **Low cost**
- **Stable pricing**
- **Stable raw material supply**
- **US jobs**
- **New value stream for pulp mills and biorefineries**

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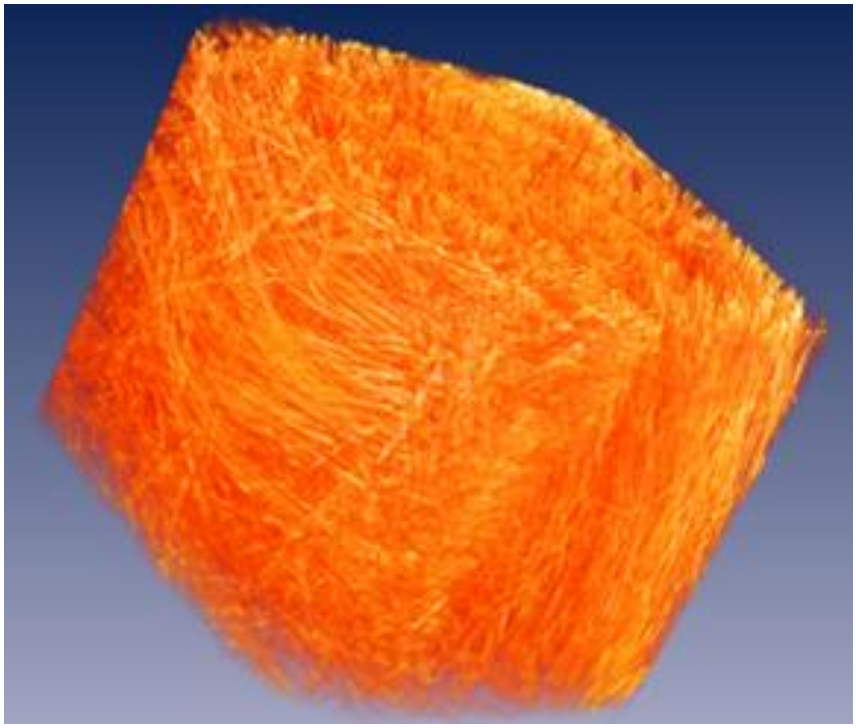
2011 PROJECT HIGHLIGHTS
POLYMER COMPOSITES
RESEARCH AND DEVELOPMENT



OAK RIDGE NATIONAL LABORATORY

Predictive Modeling of Polymer Composites
Injection Molded Long Fiber Thermoplastics

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

A collaborative program between Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) has been conducting research that has resulted in improved predictability of lightweight materials for transportation.

Long-fiber reinforced thermoplastics generated interest within the automotive industry due to their low cost, rapid production and good mechanical properties. These materials have already been used for semi-structural application and applications in primary structures are being explored. Long fiber thermoplastics produced by injection-molding present the advantage of low cost part production since conventional injection-molding equipment can be modified to produce long fiber thermoplastic parts.

The application of reinforced plastics and polymer composites in automotive structures has been limited by the inability to accurately predict the stiffness, strength, long-term durability, and service life of these materials based on their constitutive properties and processing parameters.

Approach

This project has addressed the limited predictability by developing, implementing and validating models for the process of injection molding. Models for property prediction have also been developed, implemented, validated and linked to the property prediction models, allowing complete prediction from process to property in as-formed component.

Characterization methods have been developed to measure actual microstructure and properties of long fiber reinforced thermoplastics to generate a database of measured experimental data. This data was then used to develop models reflecting observed material characteristics and behavior.

Platforms prevalent in the automotive industry were selected to commercialize tools developed in this project. Flow models are implemented by Autodesk Inc. into commercial code Moldflow. Licensing by PNNL for property prediction tool developed under Abaqus software environment of Dassault Systemes is in progress. Both flow and property prediction tools are being tested by industry professionals at this time.

Status

Validation of predictive tools was completed for two dimensional plaque geometries in fiscal year 2011. A match between prediction and experimental measurements was achieved within 8%, which exceeded project target of 15% for a go - no go decision for this project.

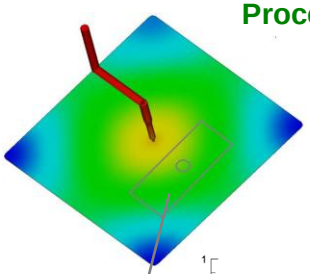
To complete development of predictive tools for long fiber reinforced thermoplastics, realistic automotive part was selected in collaboration with industry experts. This part contains complex three-dimensional features, which were not considered in previous development. Test articles will be molded with materials identical to those used for validation on plaque geometry under similar processing conditions

Recent Progress

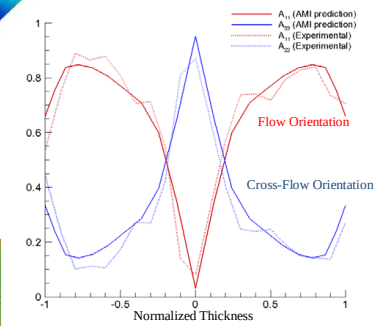
Two molding trials were performed for large plaques. Materials representative for the automotive industry were selected – polypropylene/40% and PA6,6/40% glass. Radial and linear flow was achieved by center gating and edge gating of samples. To change the microstructure of the resulting material and exercise the predictive models, fill speed and back pressure were varied during the molding.

First molding trial resulted in incomplete set of samples due to equipment problems. Additionally, initial X-ray experiments have shown leaks through the center gate

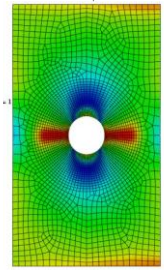
Process to Property Prediction



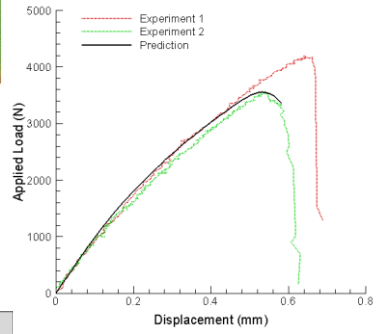
Global Flow Prediction



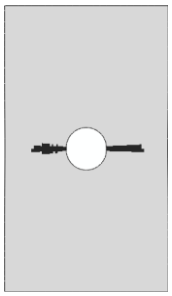
Fiber Orientation: Prediction-Experiment Comparison



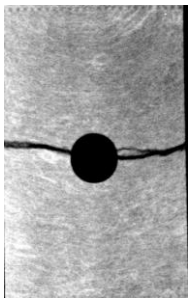
Global Stress Prediction



Stress-Strain Response: Prediction-Experiment Comparison



Progressive Failure Prediction

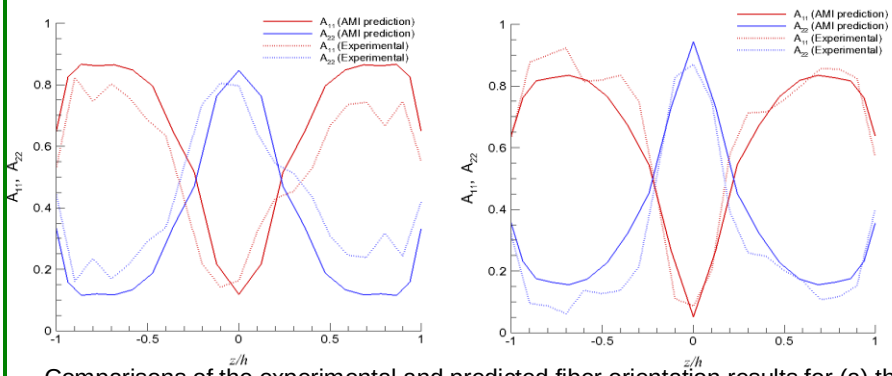


X-Ray of Failed Sample

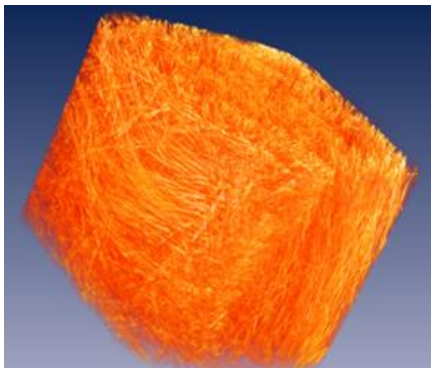
during molding of edge-gated plaques and significant weld lines in portion of the plaques.

Experimental data measured for second molding trial with ACC plaques point to consistent material properties, which include appropriate dispersion, lack of weld lines in sample regions and an entangled fiber network with a relatively wide core. Therefore, test data obtained from these plaques are well suited for validation of ARD-RSC flow model and EMTA-NLA property prediction software.

The ability to accurately predict fiber orientation is crucial for subsequent prediction of material properties. Three locations in each plaque type molded were evaluated experimentally and compared to predictions. Predictions were performed with a single set of parameters for a given material. Prediction and experimental results for 24 cases evaluated matched within 8% on average. The best and worst predictions are shown below. The nature of flow, including the variation in core and shell thickness was captured for all cases. Subsequent predictions of mechanical properties based on these orientation results further confirmed high fidelity of predictive models developed in this project.



Comparisons of the experimental and predicted fiber orientation results for (a) the 40% slow-fill glass/PP center-gated plaque, worst case (b) the 40% fast-fill glass/PA6,6 center-gated plaque, best case, A11- flow direction orientation, A22- cross-flow direction orientation.



X-ray computed tomography reconstruction of entangled fiber network within long fiber injection molded thermoplastics.

Benefits

- **Prediction of fiber location, orientation and concentration**
- **Prediction of failure location(s)**
- **Prediction of material properties in localized regions of parts**
- **Mold design tool to reduce processing costs**

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Collaborators and Contributors:

University of Illinois
Virginia Polytechnic Institute
DuPont, Dow, Styron, RTP, SABIC

Intermediate Strain Rate Crush of Crash Energy Management Structures

TMAC

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

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.

The Technology

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, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (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 to the sophisticated simulation and control software that permits velocity uniformity to within 10%.

The TMAC is used by a number of different partners for a variety of tests. Below is a listing of a few of those:

- Tested prototype sandwich panel specimens to support a future user program with the University of Utah.
- Conducted preliminary magnesium tube tests in support of future user programs with the University of Swinburne.
- Quantified specific energy absorption in composite bonded structures, high strength alloy steels, and stainless steel honeycomb.
- USCAR/ACC in conjunction with Multimatic Engineering Services Group ran preliminary high rate tensile tests at two different rates (1

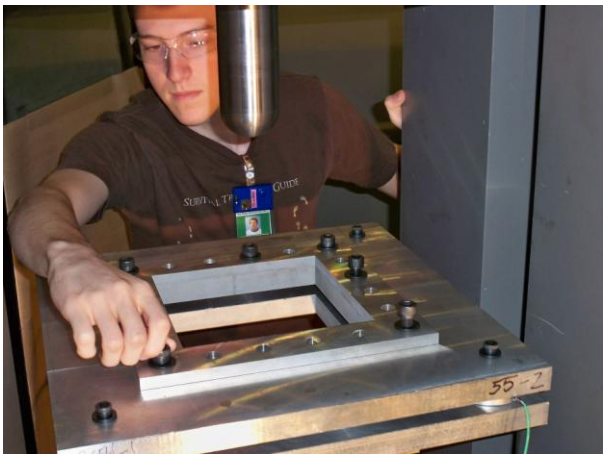
Testing Machine for Automotive Crashworthiness (TMAC)

Benefits

- **Test capabilities allow for constant strain rates and not simply constant loads.**
- **User program allows for access by a wide number of industrial partners.**
- **Testing is done at intermediate strain rates (0-8 m/s)**
- **Test data critical for the development of predictive crash models.**
- **Customized data acquisition.**
- **Can be operated in tension or in compression.**
- **Maximum stroke 25 cm.**

mm/s Quasi-Static and 4 m/s) on the TMAC. The information from these tests namely load-displacement trace and the high speed video was used to evaluate a hybrid joint being considered for the composite automotive underbody project.

- Ran round robin high rate tensile and crush tests for the Federal Aviation Administration composite materials program.
- Did rapid crush testing of steel honeycomb blocks for Benecor Corporation to enable decisions to be made on a reactor restart.
- Crush testing for North Carolina State on metallic foam blocks. Approximately 50 specimens were tested successfully.
- High-rate three point bend testing was conducted with Plasan using the TMAC to measure the impact test data at a constant velocity in a three point bend configuration.
- Tests were run to characterize and understand the high strain rate tensile properties of Innegra S yarns compared to competitive reinforcing yarns and to characterize and understand the high speed impact performance of composite panels containing Innegra S along with other reinforcements.
- Tube tests were completed on TMAC in support of the Auto/Steel Partnership (A/S-P) Strain Rate Characterization Project.
- Tests were performed for L&L Products who manufactures reinforced composite/steel box beam structural components that are integrated into key locations in vehicles to improve vehicle crashworthiness.
- A General Motors/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.



Technology Transfer

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 a high-rate tension machine can be used for conducting coupon-level tests up to 18 meters/second. Large scale specimens and structural components can also be tested in tension on the TMAC by adding a slack adapter and appropriate grips. Fixtures also exist for flat panel and beam type specimen geometries. User interest in this equipment remains very high with follow on projects and new projects being in the draft stage. Use of the machine is available for industry.

Partners:

Automotive Composites Consortium
General Motors
Plasan
University of Utah
University of Swinburne
Federal Aviation Administration
Innegra
Auto.Steel Partnership
L&L Products

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Multi-Materials Joining

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

Oak Ridge National Laboratory (ORNL) is developing testing and modeling methodologies to predict the effects of mechanical loadings and environmental exposures on the durability of an automotive composite-to-metal (multi-material) joint. The focus application is the joining of a polymer matrix composite (PMC) underbody to the rest of the vehicle structure.

Significant automobile weight reduction and corresponding increases in fuel economy can be achieved by replacing dense materials (such as metals) with strong, lightweight composite materials. Technologies for attaching/joining PMC parts with other metallic components enable the wide-spread integration of composites into a predominantly steel vehicle's design and manufacture. This design strategy requires reliable technologies for joining components made of dissimilar materials.

Issues associated with multi-material joint design include long-term reliability (durability) and manufacture. Generic tools for predicting the performance of any composite joint design do not exist and so validated modeling tools must be created to allow original equipment manufacturers (OEMS) to predict the durability of composite structures with the same level of confidence as metal assemblies. Consequently, the joint and materials to be used in the PMC underbody must be studied for this particular application.

One of the principals of automotive structural joint design is that the limiting factor be the strength of the materials comprising the vehicle structure - not the joint strength. Identifying and understanding the location of failure and failure mechanisms is therefore as important as the failure strength and durability. Once understood, it can be determined where in the vehicle the joint will be most effective based on the different types of loads the structure will experience at that location. Combined with modeling and analysis, the appropriate factors for designing the joints (materials, material properties, geometry, etc) can be established.

The Composite Underbody Attachment project addresses several critical technology barriers identified by the Automotive Composites Consortium (ACC) Underbody Design and Joining teams to reliably manufacturing a vehicle with a PMC underbody.

Technology

ORNL, Multimatic, Inc and the ACC are collaborating to develop testing and modeling methodologies to predict the effects of mechanical loadings and environmental exposures on the durability of an automotive composite-to-metal (multi-material) joint. This research directly supports the Composite Underbody project (Focal Project 4).

Research focus is the evaluation and comparison of PMC-to-steel joint specimens prepared with weld bonded and adhesive bonded joint configurations. The specimens are manufactured using the same fabric sheet molding compound (SMC) material that has been selected for the ACC composite underbody.

Weld bonded multi-material joint (PMC-to-steel)

Benefits

- **Weight savings in automotive structures translates into energy savings**
- **Technologies for attaching/joining PMC parts with other metallic structures enables integration of composites into a steel vehicle's design and manufacture**
- **The understanding of joint strength, durability and failure mechanisms across a range of loading scenarios is crucial to effective joint design in a vehicle**
- **These testing and modeling methodologies can be made applicable to other types of multi-material joints, including other material**

Quasi-static and cyclic fatigue testing are being conducted for the load cases of tension, torsion, and bend. Environmental stressors include ambient, 80°C and -40°C temperature conditions. These load cases have been identified by the automotive industry as significant to the performance and durability of a composite underbody joint. The development of a dynamic (high strain rate) tensile test has been initiated using the Test Machine for Automotive Crashworthiness (TMAC) to simulate joint loading during crash. Nondestructive evaluations (NDE) using infrared (IR) thermography aid in the identification of initial failure locations and mechanisms.

Computer-aided engineering (CAE) modeling of the underbody joint using existing tools is being conducted by Multimatic Engineering Services Group to determine the applicability of these models to this material system and geometry. The validity of these models will be established by comparing the predicted results to the test data generated using the multi-material joint specimen and testing methodology.

Technology Transfer

This project will generate coupon-level durability data needed for this project's model development and validation efforts. In addition, the data will also provide important joint durability information on design hardware to the automotive community. By directly supporting these ACC team goals, this project facilitates the demonstration and deployment of the composite underbody, and demonstrates the viability of this and other PMC components that are designed to carry crash loads in vehicle structures. Increased deployment of PMC composites decreases vehicle weight and thus supports a key Vehicle Technologies objective.

Tension-tension fatigue testing
MTS test machine/oven chamber
(elevated temps, LN2 cooling)

Cyclic torsion fatigue test
MTS axial-torsional test machine

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2011 Project Highlights
Metals Multi-Material Enabling Research and Development

Dynamic Characterization of Spot Welds

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

A primary driver for increased use of advanced high-strength steels (AHSS) and other high-strength lightweight materials such as Al alloys and Mg alloys in auto-body structures is the improvement in crash performance while reducing the weight. Resistance spot welding (RSW) is by far the most common joining process used in automotive manufacturing. Typically, there are several thousands of spot welds in a vehicle. Because the separation of spot welds can affect the crash response of welded components, the dynamic behavior of spot welds is a critical factor in vehicle design and manufacturing.

Computer-aided engineering (CAE) simulation has become an indispensable tool that enables rapid and cost-effective design and engineering of crash resistance auto body structures. Currently, CAE crash prediction of spot weld behavior in AHSS and other lightweight materials is generally unsatisfactory, which impedes effective use of these materials in auto-body structures to achieve the balance of fuel efficiency, safety, performance, and cost target metrics.

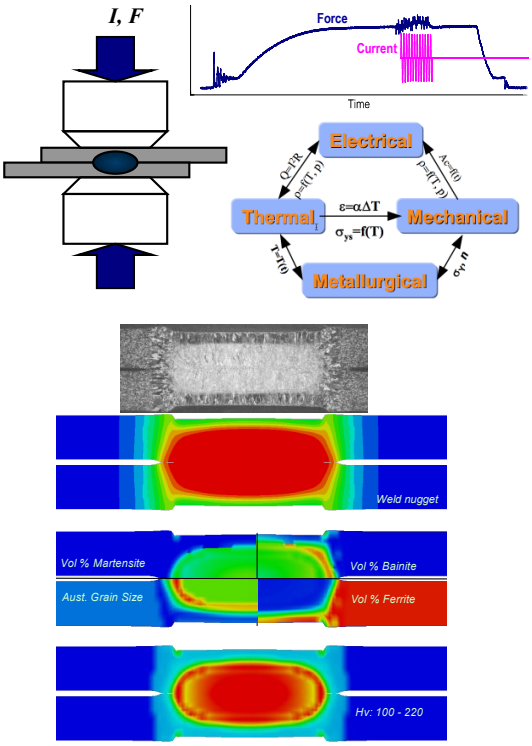
Approach

Under the sponsorship of the U.S. Department of Energy Office of FreedomCAR and Auto/Steel Partnership, Oak Ridge National Laboratory is developing a robust spot weld modeling approach, supported by experimental data that can be implemented in crash simulation FEA codes used by the automotive crash modelers. The development employed a three-pronged approach: (i) a spot weld element (SWE) formulation and associated constitutive models for its robustness in CAE simulation, and with the complexity to incorporate weld geometry and microstructure effects, (ii) a physics based integrated electrical-thermal-mechanical-metallurgical spot weld process model to generate the weld geometry, microstructure and residual stress results needed by SWE, and (iii) companion weld characterization and impact test database for development and validation of the new spot weld modeling approach.

Progress

We have successfully completed the development of the spot wel modeling framework that links the integrated spot weld process and performance model to the rubust spot weld element model for spot weld crash simulation. The effectiveness of the spot weld modeling framework has been demonstrated for two steel grades. The initial version of simulation software has been licensed for industry applications. The modeling framework is being extended to cover the range of materials, weld configurations, welding conditions, and loading modes required for industry CAE implementation.

In addition, a comprehensive spot weld experimental testing data base has been developed that covers a wide range of steel grades (including joining of different steel grades), 2T and 3T spot weld configrations, different loading modes. A web-based user friendly interface is available to retrieve the testing

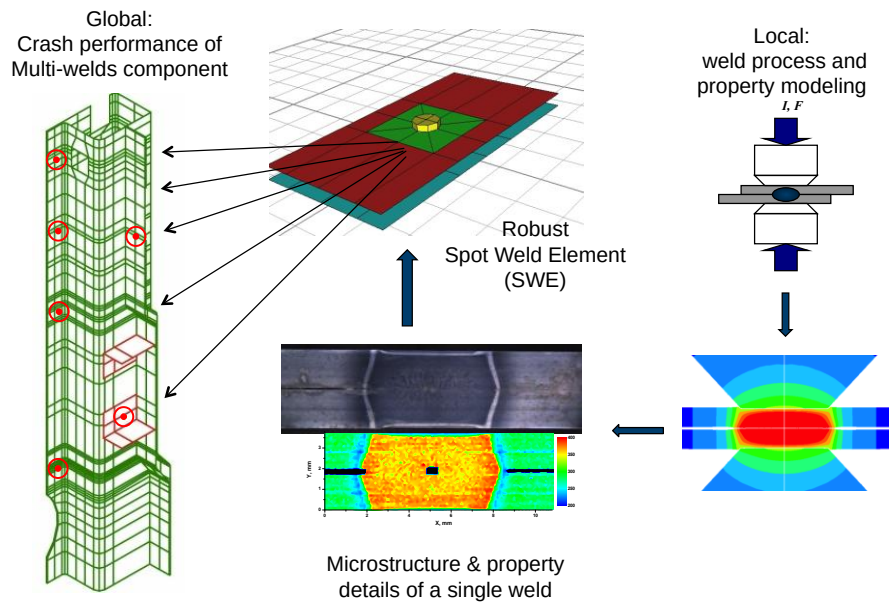


The integrated RSW process model predicts the weld microstructure and property gradients in a steel weld

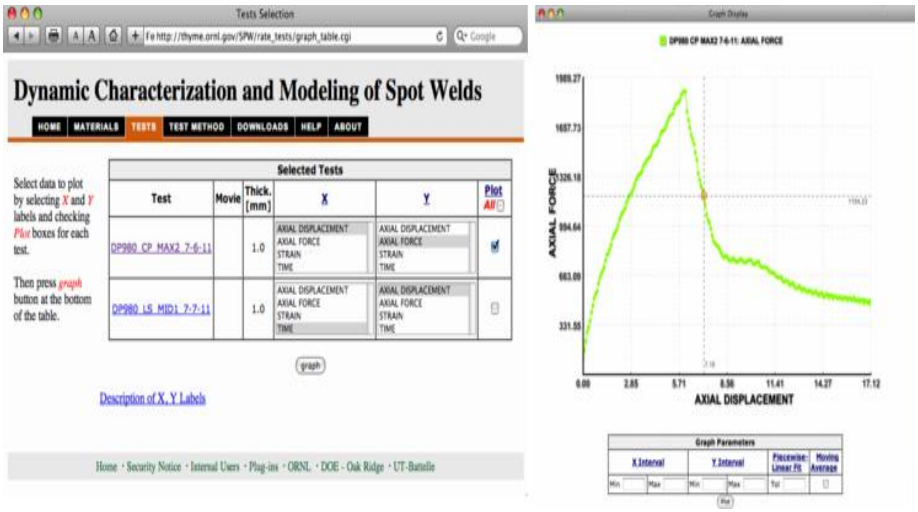
Benefits

- Support rapid and optimum insertion of AHSS and other lightweight materials in auto-body structures through advanced crashworthiness CAE
- Enable widespread use of high-strength lightweighting materials in auto-body structure to achieve the 20% vehicle weight-reduction target for petroleum displacement

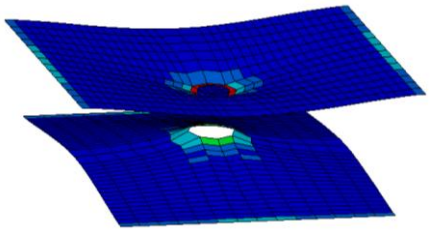
results from the comprehensive database.



The local-global approach used in development of the rubust spot weld crash simulation framwork.



Online spot weld testing data retrieval and analysis



Similulation of cross-tension testing. predicted failure mode: button pull-out.

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Friction Stir Spot Welding of Advanced High Strength Steels II

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

An initial project on friction stir spot welding (FSSW) of advanced high-strength steels (AHSS) confirmed that FSSW of AHSS could be accomplished with currently available tool materials, and that the process could make spot welds with high tensile lap-shear strengths.

Two important conclusions of the initial project related to process cycle time and tooling costs. For FSSW to be accepted as a viable alternative to resistance spot welding (RSW) in automobile manufacturing it must not require too large of a penalty in weld cycle time. Resistance spot welds on steels like DP780 can be made in a fraction of a second. This is because RSW relies on melting to create bonds. In contrast, FSSW relies on the combined effects of time, temperature, pressure, deformation, and recrystallization to create a metallurgical bond. It is unlikely that this process will ever have spot welding times competitive with those of resistance spot welding. However, because it avoids melting FSSW has the potential to overcome important technical challenges related to using RSW on AHSS. This is the fundamental reason for continuing the study of FSSW of AHSS.

The second important conclusion was that reducing the cost of tooling or significantly increasing durability are critical hurdles for FSSW to compete directly with RSW of AHSS. Alternatively, there must be other compelling technical reasons, e.g., better control of microstructures and properties, to use FSSW on AHSS rather than RSW.

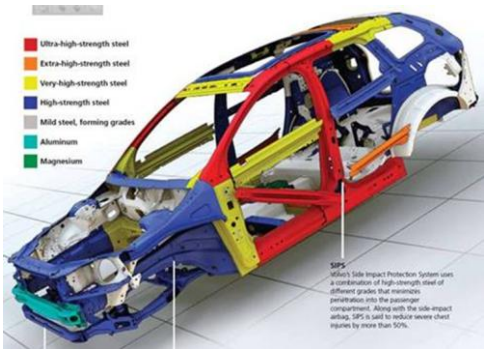
Approach

This follow-on project is designed to demonstrate that friction stir spot welding (FSSW) is an acceptable, cost effective alternative for AHSS that are difficult to resistance spot weld (RSW), and that FSSW will support lightweighting objectives through down-gaging of sheet thicknesses by enabling dissimilar steel bonding. Compared to previous work, the overall approach will involve:

- More comprehensive characterization of mechanical behavior including fatigue strength, T-peel strength, cross-tension strength, possibly impact behavior, and metallurgical examinations
- Identification and characterization of liquid metal embrittlement phenomena
- Concentrated evaluation of candidate materials for friction stir tools
- Interaction with equipment suppliers to so that their constraints help guide decisions about welding parameters and tooling.

Progress

Numerous spot welds were made on the combinations of steel shown in Table 1 using Si_3N_4 stir tools. Processing parameters included tool rotation speeds of either 800 rpm or 1600 rpm, plunging of 1, 2, or 3 time segments, and total welding times of either 4 s or 8 s. For each combination it was possible to make spot welds where lap-shear strengths exceeded the minimum AWS values for resistance spot welds of the weaker of the two steels. For two of the combinations, HSBS-TRIP780 and DP780GA-HSBS,



Lightweight auto body-in-white structure highlighting components that either are now or will be made from advanced high-strength steels.

Benefits

- **Future vehicle structures will be hybrids of many materials. Some like Advanced High Strength Steels are challenging to weld.**
- **FSSW can enable implementation of additional alloy combinations and stack-ups that provide additional weight and cost savings.**

Stir tool made from Si_3N_4

a total of 50 additional welded coupons was made each and supplied to the University of Michigan for fatigue testing and analysis under a subcontract.

Table 1: Initial results for FSSW of uncoated TRIP steel

AHSS Alloys	RPM	Plunge Steps	Avg. LSS, kN	AWS Min, kN
TRIP590 to DP780	800	2	11.0	7.98
DP780 to TRIP590	800	2	10.9	7.98
DP980 to TRIP780	800	1	12.6	10.32
HSBS to TRIP780	800	1	11.4	10.32
DP780GA to HSBS	800	1	12.2	10.32
DP780GA to HSBS	800	2	11.2	10.32

A concerted effort was also undertaken with Ceradyne to examine issues related to durability of Si_3N_4 tooling and to reduce its cost. Figure 1 show the estimated conditions under which FSSW tooling would reach cost parity with that used for RSW. For instance, FSSW tools costing around $10 each would need to last at least for 5000 spot welds to approach the same cost as RSW tooling. According to Ceradyne, FSSW tooling costs will be sensitive to volume, and amenable to scalable economics. Approaching conditions of cost neutrality with RSW appears possible.

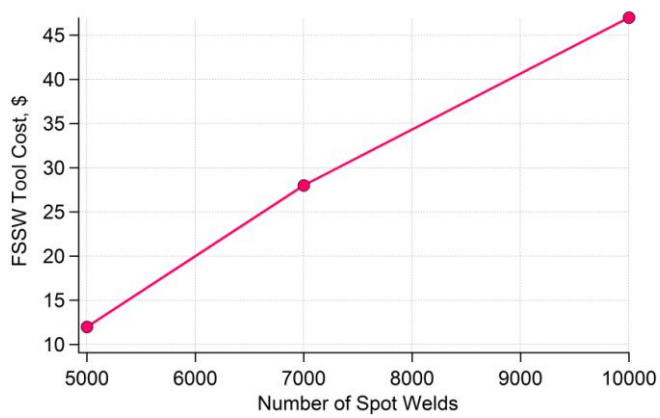


Figure 1: Estimate of the conditions of FSSW tool cost and life that will produce approximate cost neutrality with RSW

Technology Transfer

The project includes a committee of consultants from Chrysler, Ford, GM, Kawasaki (robot manufacturer), MegaStir (producer of PCBN friction stir tooling) and Ceradyne (producer of Si3N4 tooling) and General Motors. The technology is not restricted by intellectual property rights.

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Ultrasonic Solid-State Joining Magnesium to Steel

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

A significant increase in the amount of magnesium in automobiles can reduce fuel consumption by reducing overall vehicle weight. Achieving that goal will require cost-effective solutions to some of the technical challenges related to the disparities in physical and mechanical properties between steels and Mg alloys. One specific area of concern for broader use of Mg is development of reliable joining methods. For instance, the ability to reliably make durable, high-strength joints will become increasingly important as Mg alloys are considered for various structural subframes that require attachment to steel passenger-compartment structures.

A natural candidate for making high-strength Mg-alloy-steel joints is welding, but the use conventional welding processes suffers from various complicating factors. For instance, the boiling point of Mg is about 400°C lower than the melting temperatures of typical automotive sheet steels. Consequently, melting Mg alloys and steel together as might be done in resistance spot welding would vaporize Mg creating unacceptable levels of porosity in the completed welds.

Ultrasonic welding (USW) has some potential to avoid issues related to conventional welding processes, but its use in automotive assembly is virtually nonexistent. Desirable characteristics of USW include the ability to make spot welds in a few seconds or less with equipment that is compact and energy efficient. More importantly for Mg-alloy-steel spot welding, USW is considered a solid-state bonding process that does not depend on or require melting for strong bond formation. These and other important technological characteristics motivated this study of using USW for spot welding AZ31 to mild steel.

Approach

The goal of the project is to emphasize understanding of:

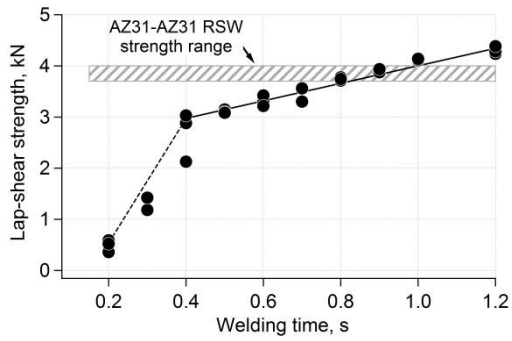
- Metallurgical bonding during USW
- The influence of process parameters on joint strength and performance
- The properties of joints including lap-shear strength, fatigue properties, corrosion issues, and microstructural characteristics

Barriers to the use of ultrasonic welding for Mg-steel joints include:

- Lack of understanding of the basic materials and processing issues required to achieve robust joints
- Lack of data on joint performance
- Lack of fundamental understanding of the response of materials and joint geometries to process characteristics (high-frequency insonation, for instance)
- Lack of understanding of the corrosion protection and mitigation strategies

Progress

Testing showed that spot welds with lap-shear strengths up to 4.2 kN can be made between sheets of AZ31 and hot-dip-galvanized mild steel. These



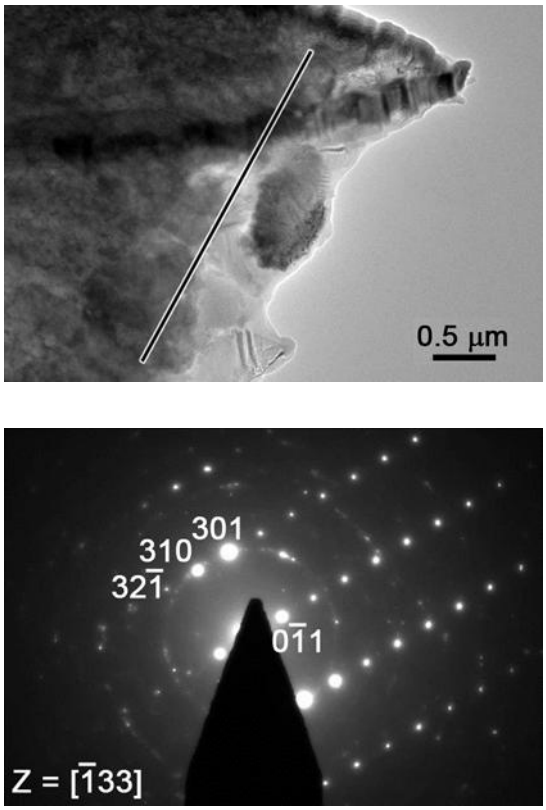
Variation of lap-shear strength (maximum failure load) with welding time for USW spot welds between andAZ31 and galvanized mild steel. Strengths comparable to AZ31-AZ31 resistance spot welds are possible.

Benefits

- **USW is an effective technology for Mg-steel bonding that can support strategies for vehicle weight reduction.**
- **USW can enable better integration of Mg and steel components providing opportunities for cost and performance improvements.**
- **USW has potential for Mg-steel welding while avoiding problematic metallurgical issues.**

lap-shear strengths are comparable to those of AZ31-AZ31 joints made by both resistance spot welding and friction stir spot welding. Failures in the AZ31-steel joints propagated through the AZ31 indicating that the strength of the AZ31-steel interfaces was greater than the strength of the AZ31 near the welded interfaces. This remarkable result led to examining the AZ31-steel interfaces in greater detail to better understand the bonding mechanism(s).

For welding times above about 0.3 s, the AZ31 reacted with the zinc coating of the galvanized steel producing liquid phases that were eventually completely squeezed from the spot weld regions. An intermediate layer remained at the AZ31-steel interface and it was identified as Al_5Fe_2 by electron diffraction and microchemical analysis. Strong bonding between the AZ31 and the mild steel was attributed to the presence of the Al_5Fe_2 intermediate layer.



Microstructure of Al_5Fe_2 at AZ31-steel USW spot weld interface (top); and, diffraction pattern used for identification (bottom)

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On-Line Weld NDE with IR Thermography

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

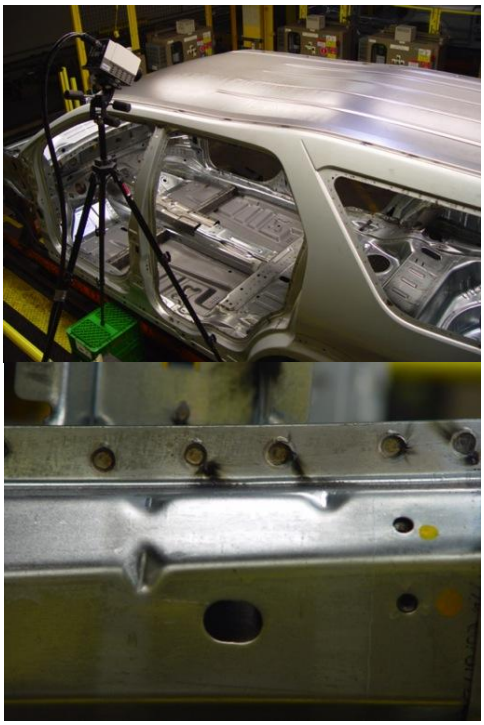
The development of resistance spot welding (RSW) for advanced high strength steels (AHSSs) is critical for enabling the broader implementation of AHSSs in vehicle structures for light-weighting and crashworthiness. It is estimated that a 16% weight reduction for body-in-white (BIW) is achievable by utilizing AHSS intensive automotive body structure. Variations in welding conditions, part fit-up, and other production conditions inevitably occur in the complex, high-volume BIW assembling process. These variations can result in out-of-tolerance joints that impair the quality and performance of the vehicles. The increasing usage of AHSSs and other lightweight metals is expected to pose even more stringent requirements on the joint quality. Reliable quality inspection techniques are crucial for achieving and ensuring high-quality joints on the assembly line. For it to be successfully adopted by the automotive industry, any new quality inspection technology needs to be low cost, fast, and highly accurate.

Traditional destructive inspection methods for RSW quality are labor-intensive and time-consuming. To over those shortcomings, a new RSW quality inspection technology based on Infrared (IR) thermography is being developed at Oak Ridge National Laboratory (ORNL). The technology development focuses on two key aspects: (1) developing a fully-automated, efficient and robust system based on low-cost IR camera to determining weld quality for both real-time (online) and postmortem (offline) applications, and (2) acquiring weld quality database to cover a wide range of steels, thickness gauges etc. Both are essential steps towards technology commercialization.

Approach

For the IR based inspection technique to be accepted in the intended automotive body structure manufacturing environment, it needs to cover a variety of AHSSs with different grades, thickness gauges, coatings, and stack-up configurations in the current and future generations of lightweight vehicle structures. We have conducted extensive welding experiment and data collection for both the real-time and post-weld approaches. In the experiment, the welding parameters were carefully controlled to produce welds with varying attributes (the nugget size and the existence of surface cracking, etc.). Several replicates for each condition were produced to understand the statistical variation in weld quality. Real-time IR images during welding were acquired during the experiment. The resulting welds were further analyzed using the postmortem inspection procedure. Approximately over 500 welds were made and thermal images were acquired.

The fully-automated image analysis algorithms function by reading and/or collecting the IR image data for online or offline inspection. The algorithms then identify and select the area of interests, and effectively analyze the data to obtain characteristic signature of the thermal images in correlation to the weld defect and quality. The efficiency of the algorithm meets the online/offline inspection time requirements (data collection for online 1-2 sec; data collection for offline <4 sec; data analysis and decision making <1 sec).

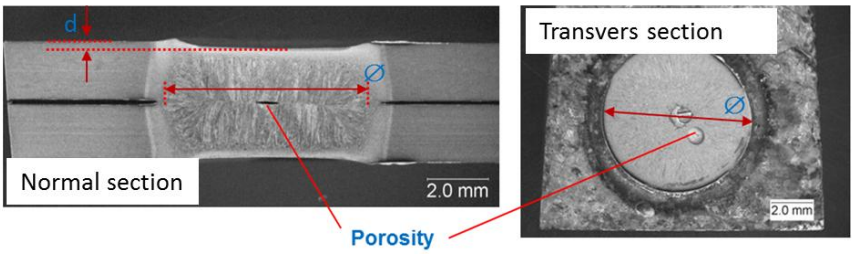


Benefits

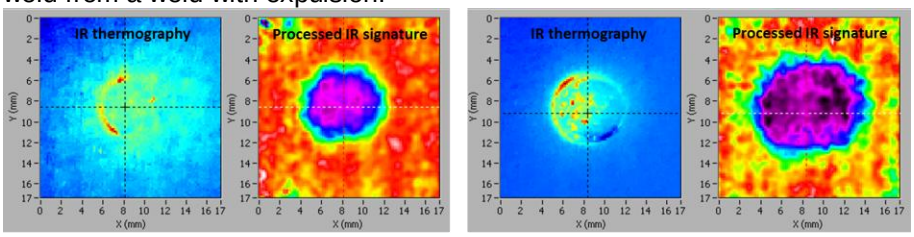
- Low-cost and fully-automated weld quality inspection
- Non-contact inspection method and fast inspection time
- Improvement of weld quality control with reduction of the cost

Progress

Destructive measurement of weld nugget attributes: The nugget size (Φ), indentation depth (d) and porosity can be readily determined from the weld normal and transverse sections.



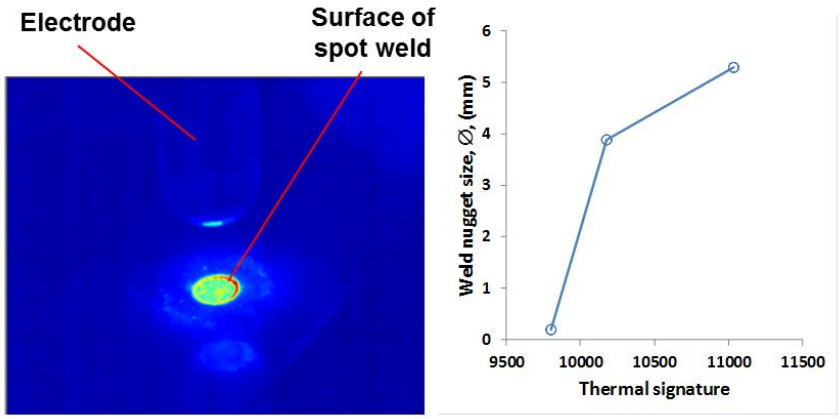
***IR post-mortem weld quality inspection*:** Preliminary results demonstrate the ability of automated data analysis algorithms to distinguish an acceptable weld from a weld with expulsion.



acceptable weld

weld with expulsion

***IR on-line weld quality inspection*:** Preliminary results illustrate the quantitative correlation of an IR thermal signature to weld nugget size in the real-time inspection



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Chrysler
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High-Strength, Lightweight Engines for Heavy-Duty Diesel Trucks

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory

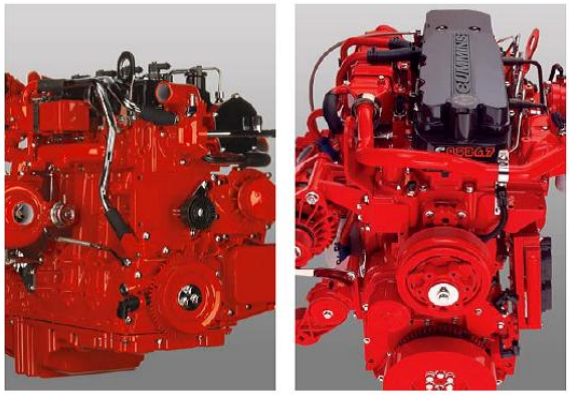
UT-BATTELLE

Background

The increasing use of High-Efficiency Clean Combustion (HECC) technologies is pushing the performance requirements of various materials used in heavy duty diesel engine blocks, cylinder heads, and other major components including reciprocating components. Stronger materials are needed for engine blocks and cylinder heads to withstand the higher projected operating pressures. In addition, high temperature spikes in cylinder heads are a concern. At the same time, lighter-weight materials are needed for heavy-duty engines to lighten the truck cab in order to meet the Department of Energy (DOE) "SuperTruck" goal of 50% improvement in freight efficiency (ton-miles/gallon). The purpose of this Cooperative Research and Development Agreement (CRADA) between ORNL and Cummins Inc. is to identify the weight savings opportunities afforded by materials replacements in engine components, and to develop and qualify materials required to achieve weight savings in these components. The activities in this project will mitigate the risks and accelerate the use of advanced materials in the SuperTruck program and subsequent high-efficiency diesel engines by developing cost-effective materials and processing techniques relevant to commercial heavy duty diesel engines.

Approach

We plan to identify and/or develop key materials, and evaluate their critical properties to enable the design and development of a lightweight, high power density engine, with enhanced temperature capability in the cylinder head and reduced heat-loss to the atmosphere, and improved efficiency. In particular, the project will immediately assist the SuperTruck program in qualification of materials for engine heads, blocks, and other critical or high risk engine components as identified by the program as critical to meeting the targeted goals for fuel efficiency, cost, and power density. This project will identify the materials needs, identify/develop alternate materials and/or processing techniques for lightweighting components to be used in the next generation of heavy duty diesel engines thus enhancing the efficiency of these engines beyond that achievable within the SuperTruck program.



Heavy duty engines such as the ones manufactured by Cummins Inc. have significant potential for lightweighting

Benefits

- **Identify weight saving opportunities in heavy duty engine components**
- **Evaluate and qualify materials for a "materials replacement" strategy**
- **Mitigate the risks and accelerate the use of advanced materials in next generation heavy duty engines**
- **Develop cost-effective materials and processing paradigms for light-weighting of heavy duty diesel engine and improving efficiency**

Progress

The CRADA agreement between the parties was executed in the fourth quarter of FY11. Cummins and ORNL have been involved in several face-to-face discussions to identify critical components and materials that will have maximum impact on lightweighting and improving the efficiency of heavy duty diesel engines.

As part of the initial component evaluation study, candidate components, materials, designs, and manufacturing processes were assessed and an initial evaluation of the critical improvements needed to meet the engine efficiency goals of the DOE's SuperTruck Teams was completed. Particular emphasis was placed on components that contribute significantly to the weight of the engine such as the head, block, and reciprocating components. As shown in Table 1, this assessment shows that the cast iron block and head offer the greatest potential for lightweighting a heavy duty diesel engine.

Component	Current weight (lbs)	Savings potential (10%) (lbs.)
Block	670	67
Head	400	40
Exhaust Manifold	45	4.5

Finite element modeling (FEA) and/or Computational Fluid Dynamics (CFD) analysis of components will be conducted to compute the anticipated critical stresses and temperatures. These results will be used to identify materials properties required to sustain the calculated stresses and temperatures. Based upon the results of this evaluation, an initial set of materials, materials microstructure, materials property requirements, and a materials characterization matrix will be proposed. Key component manufacturing routes and the potential implications on materials microstructure and properties will be evaluated. Based upon the potential to meet performance targets, program requirements, commercial issues such as cost, manufacturability, and availability of advanced materials, viable component design options will be selected for component fabrication. Performance of the components fabricated using the new design and improved materials will be compared with requirements.

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IR Treatment of Hybrid Steel-Al Joints

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

Cosma manufactures a structural bi-metallic engine cradle, which has four bi-metallic (aluminum-steel) joints that are heat treated. The joints are formed during casting, wherein the end portion of a "capped" steel tube is enveloped by molten aluminum to form a joint (see Figure 1). Heat treating of aluminum increases the strength and hardness of the metal and ultimately reduces the amount/weight of aluminum needed. The resulting weight savings has a corresponding energy savings in terms of fuel efficiency. Since conventional convection heat treating is slow and applied to the entire part, this project will investigate and develop Infra-Red (IR) heat treatment processes of the aluminum with minimal heat exposure to the steel. IR heat treatment has been demonstrated to reduce processing time and energy requirements while providing the improved material properties in aluminum relative to convection thermal heat treatment methods.

Fabrication and thermal processing of a bi-metallic structure comprised of two dissimilar materials presents processing challenges to mitigate/reduce many materials issues such as residual stresses, interfacial reactions, changed properties, etc. It is believed that a novel IR heat treatment approach may be able to reduce processing time, achieve the desired mechanical properties and tailor the temperature profile post casting to better manage the residual stresses and achieve a superior joint. The purpose of this project is to investigate IR heat treatment processing to increase yield strength and elongation of the cast aluminum plates and aluminum–steel bi-metallic joints, avoiding fatigue-related failure and promoting mass optimization.

Figure 1 an aluminum-steel joint consisting of an A356 casting (top) around a steel tube (bottom, diam. =57 mm) with an end cap (end cap buried in the aluminum casting).

Approach

As-cast, flat, aluminum plates and as-cast aluminum-steel joint samples will be supplied by Cosma. ORNL and Cosma will develop the IR heat treatment, design and assemble a prototype IR lamp for curved joint samples. Additionally, thermal and mechanical property measurements will be conducted and a residual stress determination done. Finally, a finite element analysis model for the heat treatments and subsequent residual stresses will be developed. The goal of the proposed research is to develop and model a heat treatment process based on IR heating of cast aluminum and a bi-metallic joint to produce a T5 temper in a shorter period of time than is currently practiced and, separately, a modified T6 temper for improved mechanical properties of the aluminum casting. In the case of a bi-metallic joint, heat treat without loss of joint integrity.

Status

There are five main tasks: Thermal profile determinations, residual stress analysis, IR process development, mechanical testing and model development. As part of IR process development, the emissivity of the as-received sample surfaces was measured. Emissivity, ε, is the ability of a surface of a particular material to emit energy by radiation relative to the energy radiated by a black body at the same temperature (Wikipedia, 2011). This ratio is dimensionless and for a real object $\varepsilon < 1$ ($\varepsilon = 1$ for a true black body). In production, a colloidal graphite mold release agent is used. The surfaces of the as-cast, flat, aluminum plates have residual mold release on them. This residual coating would be present in production and impacts the emissivity of the sample surface. For these samples, one surface was darker (more

Benefits

- Reduced cost
- Increased vehicle fuel efficiency
- Reduced emissions
- Support DOE's overall goal by enabling America to use less petroleum.

residual graphite coating) than the other. Spectroscopic reflectivity measurements were made using a Perkin-Elmer Lambda 900 spectrophotometer with an integrating sphere attachment, which can be used measure diffuse reflectance samples. The emissivity of a typical flat casting sample was estimated as 1-ρ, where ρ is the reflectivity (Pitts and Sissom, 1977). In Figure 2, the gray hemispherical emissivity was estimated to be 0.88 and 0.84 for the darker and lighter surfaces, respectively.

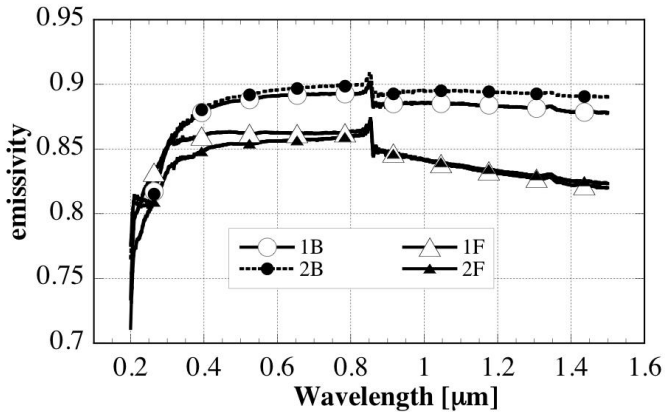

Figure 2 Emissivity of carbon coated flat casting samples obtained from spectroscopic reflectivity measurements. (note: 1B refers to sample #1, back surface which is the darker surface).

Figure 3 shows the microstructure of the as-received as cast samples. A356 is a hypoeutectic aluminum-silicon alloy (ASM Handbook, 2004) with alloying contents less than the amount of Si (92.2 Al/7.1 Si/ 0.4 Mg/0.3 other). A network of gray silicon particles surround the dendritic Al-Si eutectic phase (Metals Handbook, 1972). The dendritic structures appear to be about the same size in Figures 3A and B, but are significantly larger in Figure 3C. This difference is likely due the differences in grain nucleation and growth driven by the fast and slower cooling of the outside surface relative to inner/middle regions of the casting.

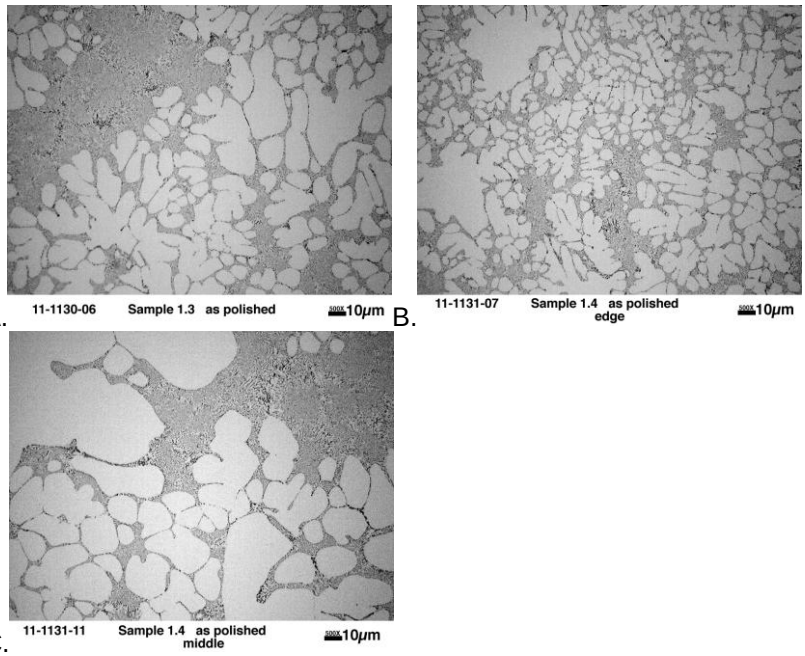

Figure 3 - Optical micrographs of an as-received as-cast sample: A. in-plane, B. cross-section near the top surface, C. cross-section near the middle.

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Understanding Protective Film Formation by Magnesium Alloys

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

Magnesium alloys are of great interest to automotive manufacturers due to their attractive combination of low density, good strength, amenability to casting, ease of recycling, etc. A major obstacle to the widespread adoption of magnesium alloys is susceptibility to corrosion. Magnesium is considered the most reactive structural material and is susceptible to multiple forms of corrosion; including dissolution, galvanic coupling, localized corrosion, and stress corrosion cracking. Surface treatments/coatings are needed for many applications, which result in increased cost and can be a source of component durability issues.

The corrosion of magnesium alloys has been the subject of intense research activity, with significant gains in mechanistic understanding in recent years for both “pure” magnesium and magnesium alloys. These studies have identified the inability of magnesium alloys to establish a continuous and fully protective surface film under many exposure conditions as a key factor underlying their susceptibility to corrosive attack. Alloying has been shown to modify surface film performance; however, a detailed understanding of how and why is currently lacking. Such understanding is needed to develop improved alloys and surface treatments/coatings to permit more widespread adoption of magnesium alloys. The goal of the proposed effort is to develop an improved understanding of how alloy composition, microstructure, and exposure conditions effect the establishment, continuity, nature, and growth of protective films on magnesium alloys.

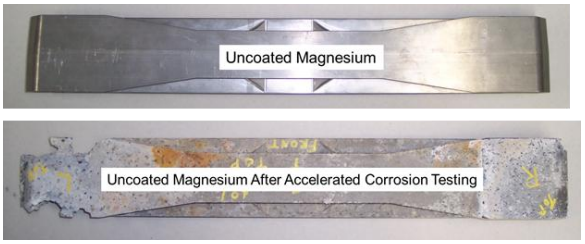
Approach

The ambient corrosion of magnesium differs from many corrosion-resistant structural alloy classes in that the protective surface films can become quite thick, on the order of tens to hundreds of nanometers, rather than the few nanometers typically encountered in stainless steels, for example. As such, corrosion resistance is influenced not only by classical thin film electrochemical passivity considerations, but also thermodynamic and kinetic considerations typically encountered in thick-film, high-temperature alloy oxidation phenomena.

The proposed experimental approach will seek to merge ambient and high-temperature corrosion study approaches, leveraging extensive and unique expertise in these areas at General Motors Global R&D (GM), Magnesium Elektron North America (MENA), and Oak Ridge National Laboratory (ORNL). It will also take advantage of the world-class characterization capabilities available at ORNL to more fully probe and understand the chemical, morphological, and structural features of the surface films formed on magnesium alloys as a function of alloy composition, microstructure, and exposure condition.

Planned First Year Efforts

This is a new project for FY 12. A major goal for the first year will be to



Corrosion susceptibility of uncoated magnesium under simulated aggressive automotive exposure conditions

Benefits

- ***Gain improved understanding of protective film formation by magnesium alloys as a function of alloy chemistry and impurities, microstructure, and exposure conditions***
- ***Gain improved understanding of protective film formation during conversion coating processing of magnesium alloys***
- ***Provide fundamental basis to design and optimize new magnesium alloys and/or conversion coating processing to improve corrosion resistance under automotive relevant conditions***
- ***Ultimate goal is to permit more widespread use of magnesium alloys in automotive applications to fully realize energy savings potential of reduced component weight***

complete assessment of which advanced characterization techniques are most amenable to providing new insights into film formation on magnesium alloys. This is a key activity as magnesium alloys are notoriously difficult to work with, sample procedure techniques will need to be developed, and not all proposed characterization approaches will prove effective. Advanced characterization approaches to be investigated include:

1) D_2O and/or O^{18} tracer studies to gain insight into the ionic growth aspects of the surface films. The approach will initially be assessed using model films formed on high-purity magnesium and commercial alloys pre-formed by elevated temperature exposure in dry or humid air (<150°C) followed by exposure to the tracer. These sequentially exposed samples will then be characterized by secondary ion mass spectrometry (SIMS). The distribution of the tracer in the film will provide a basis to understand competing aspects of inward vs. outward ionic growth, which can play a major role in determining the stress state and relative compactness and protectiveness of the surface film. Including alloy chemistry as a variable will then potentially permit correlation of specific alloy additions and impurities with growth mechanism changes.

2) In-situ x-ray diffraction (XRD) will be used to track formation of surface oxides, hydrides, and alloy precipitates as a function of time, temperature and atmosphere.

3) Ex-situ focused ion beam (FiB) sample preparation and analytical electron microscopy (AEM). The relatively thick surface films formed on magnesium alloys should prove amenable to FiB/AEM cross-section techniques to obtain chemical and structural assessment of the surface film, the underlying alloy, and the interface between them.

4) Neutron studies. With the spallation neutron source (SNS) and the high flux isotope reactor (HFIR), ORNL possesses world-leading capability for material analysis by neutrons. Exploration of ex-situ neutron scattering techniques (small angle and inelastic) will be pursued in an attempt to characterize magnesium alloy surface film nano-porosity and hydrogen species incorporation as a function of alloy composition and exposure condition (corrosion and conversion coating processing).

5) Atom probe tomography (APT) techniques. ORNL has world-class capability for APT and an attempt will be made to employ newly developed laser-assisted APT to provide 3D quantification of chemistry at the atomic scale in the bulk magnesium alloy and the alloy in the vicinity of the alloy-surface layer interface to characterize corrosion-driven alloy clustering or precipitation phenomena. Attempts will also be made to obtain atomic scale data within the oxide/hydroxide surface layer regions.

The down selected advanced characterization techniques from year 1 will then be systematically applied to surface film formation as a function of exposure conditions for both commercial and single/multi-phase model alloys and conversion surfaces in years 2 and 3 of this effort.

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2011 Project Highlights
Metals Properties and Manufacturing Research and Development

High Strain-Rate Characterization of Mg Alloys

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

Low density and excellent machinability of Mg alloys make them excellent candidates for light-weight constructions of components in automotive industry. However, they also exhibit much more complex mechanical behavior than more common automotive materials. The mechanical response of Mg alloys involves anisotropy, non-isotropic hardening, yield asymmetry, lower ductility, and significant degradation of effective properties due to the formation and growth of micro-defects under in-service loading. Under crash conditions, Mg alloys exhibit a strong tendency for fracturing in contrast to the large plastic deformation of conventional materials. The plastic deformations are exploited for crash energy dissipation in current designs. Accordingly, the material characterization procedures and constitutive models should be much more complex than the commonly used uniaxial tests and isotropic plasticity material models for steel. Another issue of concern for automotive designers is the strain rate sensitivity of Mg alloys. However, the lack of strain rate sensitivity information, experimental methods, and understanding of loading-induced property degradation add to the uncertainty, overdesign, and reservations about wider use of Mg alloys. We are developing methods that enable characterization of the material internal state and its evolution under impact. The new information and models that result from this research will reduce uncertainties in component design thereby reducing the overdesign and vehicle weight.

Approach

- Develop and evaluate multiple sensors for accurate force and displacement measurements for tests conducted under various strain rates ranging from quasi-static up to 1,000/s. Develop test methods and procedures that can be standardized for widespread use.
- Establish testing methods for high strain rate tensile and shear mechanical property characterizations of Mg alloys with our new characterization method.
- Control the imparted strain at high strain rates using novel specimen designs and full field deformation mapping technique.
- Develop test methods and procedures for microstructure internal damage evolution analysis.
- Develop material models and properties for automotive design using Finite Element Method.

Progress

High strain rate tensile tests: We have developed new techniques to generate reliable tensile stress-strain data within the intermediate strain rate regime for the sheet form of Mg alloys and used them in tests on Mg alloys AZ31 and AM60B. The tests are conducted on a custom-designed high-speed servo-hydraulic machine combined

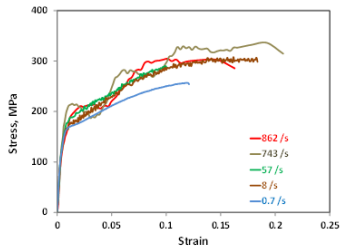
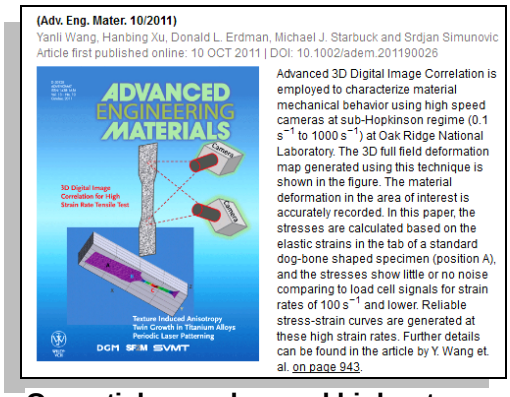


Figure 1. Strain rate effect on AM60B



Our article on advanced high rate characterization of Mg alloys is selected as Journal cover

World Wide Web interface is established and used for technology transfer

Benefits

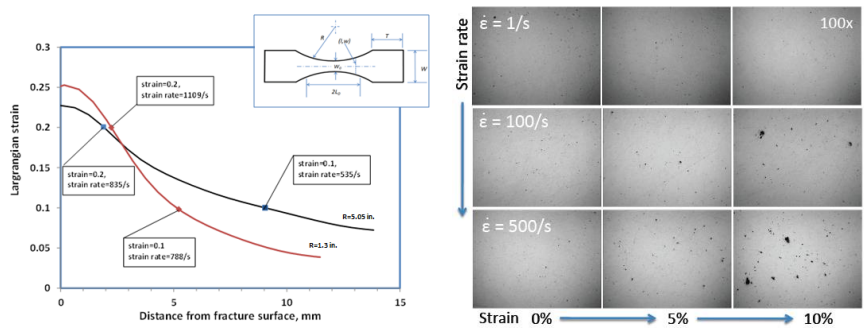
- **Provides information about Mg alloys of interest for automotive applications**
- **Development of new tests for characterization of materials in automotive impact regime**
- **Reduces uncertainties associated with using new material with complex behavior**
- **Improves reliability of the automotive components**
- **Develops material models for computational modeling and design of vehicle components**

with three-dimensional (3D) digital image correlation method (DICM). Using this technique, the stresses measured at strain rates of 100 s^{-1} and lower show little or no noise compared to load cell signals. When the strain rates are higher than 250 s^{-1}, the noise and oscillations in the stress measurements are significantly decreased (from ~250 MPa to ~50 MPa), The test results for AM60B is shown in Figure 1.

High Speed Shear property characterization for Mg alloys: A new specimen design is developed to confine the shear deformation within the shear ligament. The shear strain in the specimen was measured using 3D DICM. The shear strength for AZ31 is in the range of ~183 MPa to 200 MPa for the tested strain rates of 1/s to 167.5/s. AM60B shows lower shear strength than AZ31 with values of ~160 MPa to 180 MPa for the tested strain rates.

Strain Limiting Achievement and Microstructure Damage Analysis for AM60B: We have developed a new method for strain limiting tests that combines specially shaped specimens (shown in Fig.2a) and 3D DICM. Figure 2a shows the application of this technique to Mg alloy AM60B top hats with radii of 5.05 in. and 1.3 in. that were tested at 500 in/s. Different levels of strain were achieved across the specimen length within one specimen. The location-specific strain rates were also achieved by changes in the specimen curvature. This new specimen design and testing procedure can produce continuously varying levels of plastic strain achieved at various locations in the specimen and at different strain rates. This specimen design also reduces the size of conventional test matrices and overall testing time and permits more focus on test analysis and modeling. The method is currently under U.S. patent application.

Further, we have developed procedures for quantification of evolving stages of damage based on image processing and our newly developed method for controlled strain application. Figure 2b shows and example of the effect of strain rate on void growth for AM60B. It shows not only that the void growth is dependent on the applied strain but also that it is dependent on the strain rate.



(a) ***(b)***

Figure 2. a) Strain distributions in AM60B specimens with two different radii. Tests were conducted at nominal speed of 500 in/s. **b)** Material porosity as a function of strain and strain rate for AM60B alloy.

Technology Transfer

This project is the first systematic investigation of Mg automotive alloys as a function of loading speed, extent of deformation, and loading type. The data is used by OEM, material suppliers and consortia such as Magnesium Front End Research and Development project. The research results are disseminated through the project's web site.

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Fundamental Study of Austenite-Ferrite Transformation in AHSS

U.S. Department of Energy

Energy Efficiency and Renewable Energy Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

Metals comprise about 80% of all the materials used for passenger and other light vehicle construction, and, by a wide margin, the largest fractions of the metals are steels [Source: 2007 Great Designs in Steel presentations of R. A. Schultz and J. Schnatterly. Steels represent about 62% of average vehicle weight. Of the various steel mill products used for auto construction about 70% of the total, or 839 kg of 1,970 kg average light vehicle weight, is supplied as flat-rolled carbon steel for chassis parts and body panels.

The traditional sheet steels used for chassis and body constructions are the so-called “mild” steels. The combined interests of improving crash worthiness and reducing vehicle weights were at least partially responsible for the development of the first generation of advanced high strength steels (AHSS). What is now desired is a third generation of AHSS that borrows from previous alloy development efforts to achieve intermediate strengths and ductilities, but at costs that would make acceptance for automotive construction feasible. Controlling cost will likely require that Gen III AHSS be no more than modestly alloyed compared to Gen I AHSS, and capable of being produced within existing steel mill infrastructures.

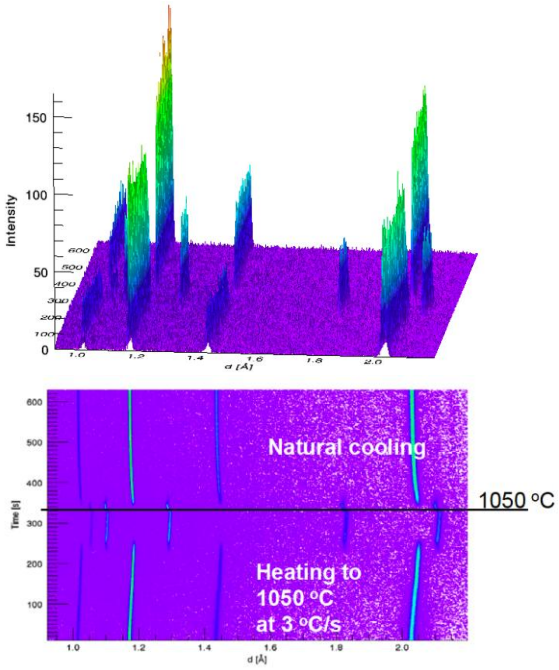
It is well known that retaining austenite in automotive sheet steels can markedly improve ductility at high strength through transformation-induced plasticity, i.e., the TRIP effect. Better fundamental understanding of austenite-ferrite transformations will enable a more scientific approach to improving properties through novel processing that can be achieved with existing infrastructure.

The Technology

Most of the experiments are being conducted with the uncoated dual-phased steels, DP780 and DP980 (ArcelorMittal). *In-situ* diffraction experiment techniques are developed and applied to understand the non-equilibrium austenite-ferrite phase transformation kinetics under various thermal heat treatment conditions, with the technology being further developed to mimic various thermal-mechanical processing conditions in steel making.

Initial experiment was performed on the UNICAT X-33 bending magnet beamline at the Advanced Photon Source (Argonne National Laboratory, Argonne, Illinois). X-ray data are captured by a charge-coupled device (CCD) on which the diffracted beams were integrated over a 1 s exposure. Diffraction patterns are acquired at a maximum rate of about 1/s. Data analysis begins by converting the 2D images recorded by the CCD detector into 1D plots of diffracted intensity versus d spacing. The 1D plots were then analyzed for texture effects, and ferrite and austenite phase volume fractions using published methods.

Neutron diffraction measurement was conducted at the Vulcan beam line at the Spallation Neutron Source, Oak Ridge National Laboratory. The deep penetration of neutrons avoids the potential surface issues in the



Neutron Diffraction Patterns of steel phase transfomration at 3°C/s heating rate

Benefits

- Detailed description of ferrite-austenite transformations during rapid heating/cooling conditions that characterize commercial steel production
- Continuous monitoring of austenite retention during cooling
- Possible method for developing processing routes to maximize austenite within existing steel plant infrastructures
- Transformation behavior and lattice parameter results will support development of new steel alloys with improved strength-ductility relationships

synchrotron experiments. Utilizing a special sample environment and a novel pulsed neutron data collection and analysis procedure, sub-second resolution of the neutron diffraction pattern was achieved. Since the sample can be heated to an extreme temperature (e.g., 1100°C) within minutes, and data can be collected fast enough before it settles into equilibrium, the investigation of the material behavior is in real time. As shown in the figure on the right, at a heating rate of 3°C/s, the DP980 steel passed through a phase transformation as its lattice planes expanded with the steady rising temperature.

Technical issues being addressed include:

- Making direct, in-situ observations of the time dependence of austenite-ferrite transformation behavior at elevated temperatures, during rapid heating/cooling, and during low temperature treatments designed to maximize retained austenite
- Measuring partitioning of carbon between austenite and ferrite during processing
- Understanding effects of critical alloying elements such as carbon, manganese, and silicon on transformation behavior and retention of austenite.

The figure below shows the overall response of DP780 to being heated to 970°C and held for 2 minutes followed by holding at 800°C for 2 minutes, holding for 460°C for 2 minutes and then cooling to room temperature. This is time-temperature heat treatment basically simulates what could be used to produce a dual-phased steel. The transformations between the ferrite (bcc crystal structure) and austenite (fcc crystal structure) phases are clearly evident and austenite is retained in the final microstructure. Recent improvements to experimental techniques significantly improved the consistency of the diffraction results with corroborating data from independently conducted experiments and thermodynamic calculations of equilibrium. Additional experiments and analyses are continuing to refine the diffraction results and to extract additional information from the experimental diffraction data that would establish this approach as a unique capability in the development of Generation III AHSS.

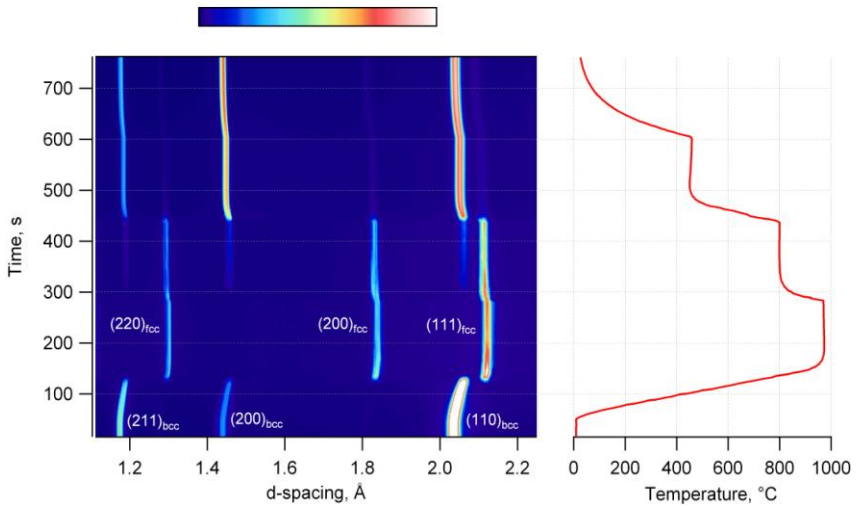


Image representation of diffracted intensity shows the transformation behavior of a carbon steel during austenitizing and cooling to room temperature.

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Low Cost Magnesium Sheet Production Using the Twin Roll Casting Process and Asymmetric Rolling

Background

Higher cost of sheet production, and the lower formability relative to steel and aluminum due to strong basal texture of magnesium sheet are the two major factors inhibiting the widespread use of magnesium in automotive applications. The conventional method for magnesium sheet production, the process of direct chill casting of slab followed by sequential rolling, is time, energy, and labor-intensive resulting in high initial sheet cost. A modern sheet production technology, called twin-roll casting which involves the solidification of a liquid metal stream between a gap formed between two cooled rolls, has been successfully applied to magnesium on a laboratory scale to produce sheets 3-8 mm thick. These sheets can be finish rolled using 2-3 passes to achieve a final gage material of 1.5-2mm that is required for automotive applications. The new process eliminates losses from scalping, and minimizes resource consumption associated with breakdown rolling and a number of warm rolling passes, thus reducing sheet cost.

Although twin roll casting has the potential to produce lower cost materials with a finer grain structure, and with a finer and more uniform distribution of inclusion resulting in greater ductility, the predominant basal texture still restricts its formability. The purpose of this project is to examine the feasibility of modifying the basal texture of twin roll cast sheet magnesium alloys using asymmetric rolling and evaluate the formability characteristics of the asymmetrically rolled sheet. This project will be carried out as part of the Memorandum of Understanding (MOU) between Oak Ridge National Laboratory and CANMET-MTL and will be supporting the Clean Energy Dialogue between the United States and Canada

Approach

A synergistic approach that combines experimental work with computational modeling will be pursued in this project. Twin roll cast magnesium alloy sheets (AZ31B) will be obtained from CANMET and will be characterized for the grain size, and grain orientations. Grain size, and grain orientations will be provided as input for computational modeling. Computational modeling using a crystal plasticity based deformation model combined with a Monte Carlo based annealing model will be used to predict the texture evolution during shear rolling. The deformation path experienced by a volume element at different depths in the sheet during shear rolling will be first modeled using the continuum finite element code ABAQUS. The deformation history at different depths is then used as input to the micromechanical deformation and annealing models. The deformation model incorporates the appropriate slip and twin systems that are involved in a HCP unit cell of the Mg alloy. The critical resolved shear stress and strain for slip and twin respectively are obtained form the available literature for AZ31. A key feature of the annealing model is a sub-model for the recovery of the deformation substructure. The model based on the assumption that the fraction of the geometrically necessary dislocations (GNDs) generated with a volume element is proportional to the misorientation of the element with respect to its neighbors resulting from the deformation process. The recovery of the stored energy within the volume element is the sum of two processes: self recovery due to

Asymmetric Rolling Mill Equipped with Independently Driven Heated Rolls Designed and Fabricated for Production of Magnesium Alloy Sheets

Benefits

- **Evaluate the microstructure and mechanical properties of twin roll cast sheet and compare with sheet manufactured from DC cast slab**
- **Evaluate the formability of twin roll cast sheet**
- **Demonstrate the benefits of twin roll casting and asymmetric rolling**
- **Reduce the cost of magnesium sheet for the automotive market**

the formation of subgrain boundaries from the GNDs and the recovery due to the sweeping of the element by a recrystallization front. The deformation and annealing models are coupled by breaking down the annealing into a number of sub-steps consisting of a deformation step and an annealing step. Effect of temperature and different deformation history on texture modification will be computationally evaluated.

Using the newly installed asymmetric rolling mill, asymmetric rolling of twin roll cast AZ31B will be performed at different temperatures in the range of 135°C to 300°C, different velocity ratios (thus shear), and roll speeds. Texture evolution due to asymmetric rolling will be characterized using x-ray texture measurements and the effect of asymmetric rolling parameters on texture evolution will be evaluated. Feedback from this data will be provided for improvement of the computational models and to achieve the final desired texture. Formability of shear rolled twin roll cast sheet will be evaluated once desired textures have been obtained through the process.

Progress

Initial progress has been achieved on developing computational models. The recovery model has been developed and incorporated within the framework of the Monte Carlo recrystallization model. Initial simulations of recovery and recrystallization have been carried out using the micromechanical deformation model. The deformation model has been used to study the influence of the compression to shear ratio during warm deformation of AZ31 on the deformation texture, without incorporating the effect of recrystallization. Results indicate that normal rolling leads to a spread of the initial basal texture along the rolling direction, while addition of shear causes a rotation of the basal peak about the transverse direction towards the rolling direction, as well as a reduction in the peak intensity. However, increasing the shear to compression ratio beyond a certain level leads to an increase in the peak intensity and introduces a spread in the basal texture along the transverse direction, as shown in Fig. 1. Results will be used to estimate initial processing conditions for shear rolling.

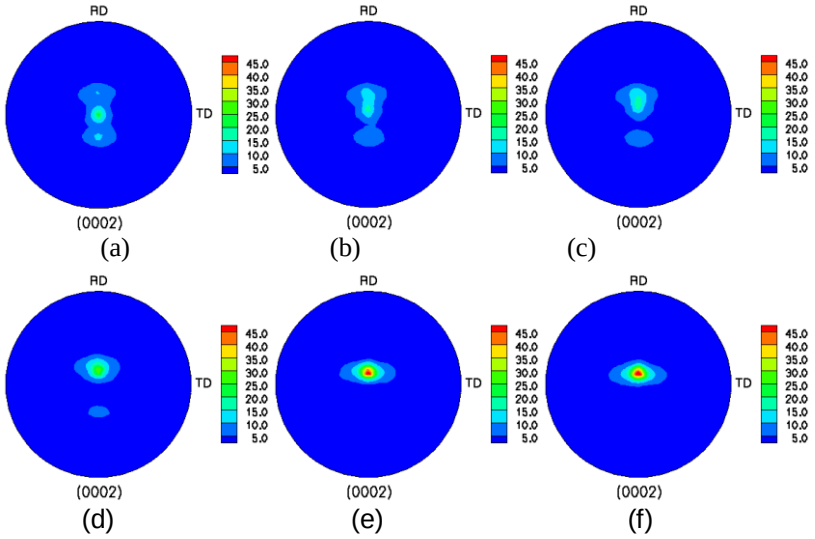

Fig. 1. (0002) pole figures from deformation simulations for different shear rates: (a) 0.0, (b) 0.15, (c) 0.25, (d) 0.5, (e) 2.0, and (f) 3.0.

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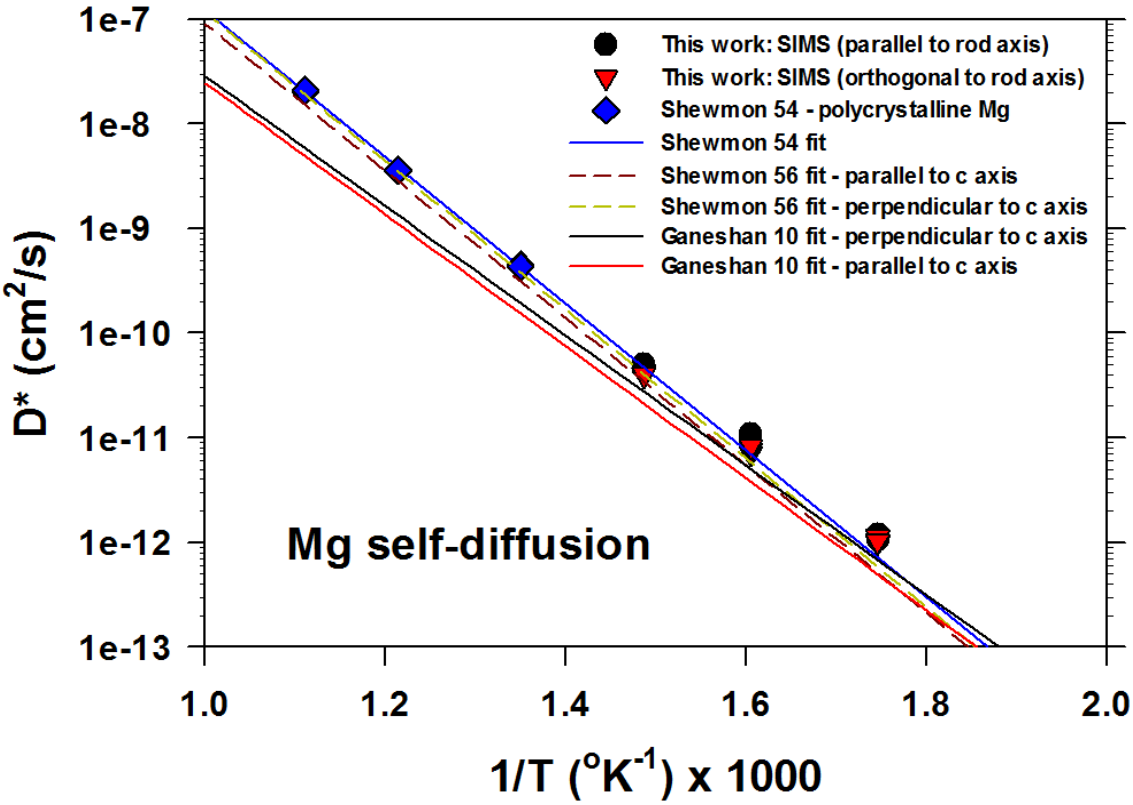
2011 Project Highlights
Metals Modeling & Computational Materials Science Research and Development



Diffusion Database for Magnesium - ICME

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory
UT-BATTELLE

Background

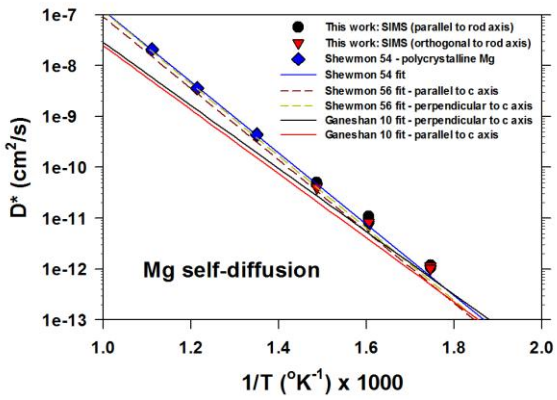
A key objective of the DOE Vehicle Technologies Program is to reduce the average weight of transportation vehicles by 50% over the course of the next 25 years. Achievement of this objective will improve vehicle efficiency and reduce greenhouse gas emissions by 40% by 2030 and 80% by 2050 compared to 2002 levels. Components based on advanced lightweight materials such as magnesium alloys offer by far the highest potential for achieving such weight reductions by replacing traditional materials based on steel and cast iron. Achievement of the desired weight reductions cannot occur through simple material substitution in existing designs but will require material specific designs using advanced materials design and manufacturing tools. For this purpose, the Mg-Integrated Computational Materials Engineering (ICME) program is developing an integrated suite of validated computational materials modeling tools that are linked to analysis systems used in manufacturing as well as engineering design. The Mg-ICME goal is to provide a quantitative linkage between the processing, microstructure, and properties of Mg-alloys used in automotive components. Knowledge of fundamental materials properties, thermodynamics, and kinetics in the form of reliable databases are in essence the foundations on which the ICME approach is based.

The objective of this project is to assist the Mg-ICME effort by developing a tracer diffusion database in the Mg-Al-Zn-Mn system, which is the base system for commercial Mg-alloy components. The safety issues that have hampered previous tracer diffusion measurements based on radioactive tracers are somewhat avoided in this project with the use of stable isotopes and secondary ion mass spectrometry (SIMS) for measurement of diffusion depth profiles. However, since two of the four elements in the desired Mg-Al-Zn-Mn system are monoisotopic (Al, Mn), other types of interdiffusion measurements involving diffusion couples are conducted to extract the Al and Mn tracer coefficients using relations from established diffusion theories, such as the Darken-Manning theories.

Approach

The procedure for obtaining tracer diffusion data requires the preparation of homogeneous single phase alloy samples in the desired Mg-Al-Zn-Mn system. This is followed by deposition of the enriched stable isotopes (tracers) of these elements in the form of thin films (100 nm thick) on the sample surfaces. After diffusion annealing at various temperatures and times, the isotopic diffusion depth profiles in these samples are measured using secondary ion mass spectrometry (SIMS). Analysis of these diffusion profiles using the thin-film error-function (Gaussian) solution provides the tracer diffusivity for the selected sample composition.

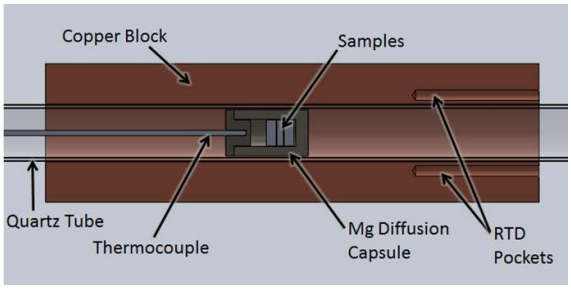
By repeating tracer diffusion measurements for different compositions and temperatures, a significant amount of tracer diffusion data for Mg and Zn in the single phase Mg-Al-Mn-Zn system will be obtained. Tracer data for Al and Mn are obtained by utilizing diffusion theory to connect interdiffusion and thermodynamic data with the tracer diffusivities. The tracer diffusion data for all the elements can then be fitted using suitable functions to generate the tracer diffusion database for the Mg-ICME program.



Mg self-diffusion coefficients using the SIMS-based stable-isotope thin-film technique (this work) in comparison with previous high-temperature radiotracer data (Shewmon 1954) and low- temperature first principles calculations (Ganeshan 2010).

Benefits

- ***Provides diffusion database input for computational modeling of manufacturing processes and properties, e.g., super-vacuum die casting (SVDC) in Mg alloys and high-temperature creep properties.***
- ***Enables understanding and replacement of expensive Mg rare-earth (RE) alloys with Mg RE-free alloys using ICME approach.***



ORNL diffusion annealing technique based on the Shewmon-Rhines (1954) design for protecting Mg samples during tracer diffusion experiments.

Progress

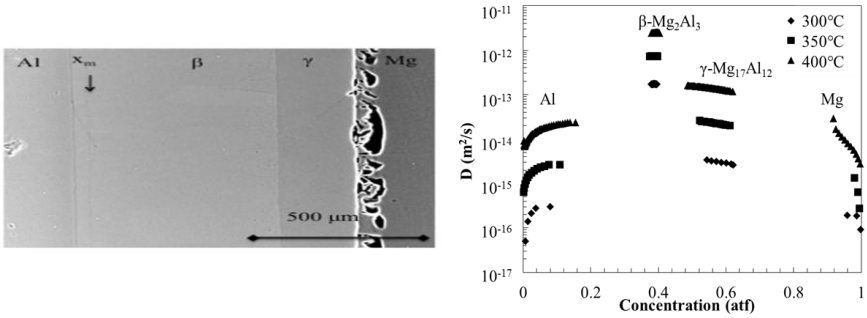
***Mg self-diffusion coefficients*:** Using the SIMS-based thin-film stable-isotope technique, we obtained Mg self-diffusivities in pure polycrystalline Mg samples, validating and extending historic radiotracer measurements to lower temperatures. Additionally, we were able to measure the anisotropy in the Mg self-diffusion coefficients along directions that were parallel and normal to the hexagonal C axis.

Diffusion annealing system: We developed an advanced annealing system and procedure based on the Shewmon-Rhines approach that (a) minimizes Mg and Zn vapor phase loss during diffusion annealing of Mg-alloy samples, (b) prevents oxidation and (c) allows measurement of precise sample temperatures to enable full numerical corrections associated with heat-up and cool-down times during diffusion annealing.

Mg-Al-Zn alloy studies: With the assistance of Magnesium Elektron, we synthesized a matrix of Mg-alloy compositions in the Mg-Al-Zn system for tracer diffusion and interdiffusion studies, and confirmed their composition uniformity across representative cross-sections. Mg and Zn tracer diffusion measurements for select compositions within this matrix along with diffusion couple experiments are in progress. An internal ORNL website (http://www.ornl.gov/sci/diffusion) was established to facilitate sharing of data among ORNL staff on this project and our external collaborators.

***Molecular Dynamics (MD) simulations of grain boundary diffusion*:** Using MD simulations in Mg bicrystals, we found that the grain boundary diffusion coefficients for asymmetric tilt grain boundaries were at least three orders of magnitude higher than the volume diffusion coefficients at 750 K, while along symmetric tilt boundaries there was no diffusion.

Interdiffusion studies in Mg-Al and Mg-Zn: Using binary full-range solid-to-solid diffusion couples, we conducted interdiffusion studies in the Mg-Al and Mg-Zn systems and obtained the interdiffusion coefficients.



Interdiffusion studies in the Mg-Al system. Left: Backscatter electron micrograph from a solid-to-solid diffusion couple annealed at 400°C for 10 days. Right: Interdiffusion coefficients for phases in the Mg-Al system that were obtained by analyzing concentration profiles in the diffusion couples.

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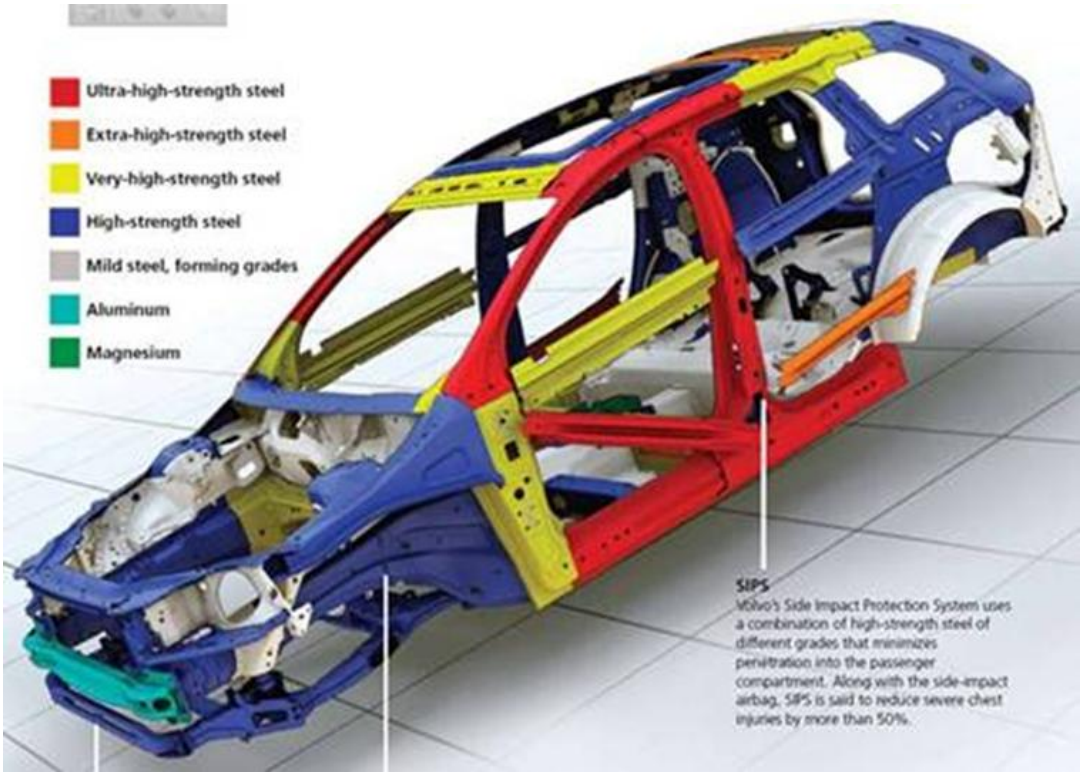
2011 PROJECT HIGHLIGHTS MATERIALS CROSS-CUTTING RESEARCH AND DEVELOPMENT



Cost Modeling

Lightweighting Materials Cost Modeling

U.S. Department of Energy

Energy Efficiency and Renewable Energy
Vehicle Technologies Program

Oak Ridge National Laboratory

UT-BATTELLE

Background

As a major component of the U.S. Department of Energy's (DOE's) Office of Vehicle Technologies, Lightweighting Materials (LM) focuses on the development and validation of advanced materials and manufacturing technologies to significantly reduce vehicle body and chassis weight without compromising other attributes such as safety, performance, recyclability, and cost. To achieve its long-term weight reduction goal, LM has prioritized its research areas in several lightweighting materials including advanced high-strength steel, aluminum, magnesium, and carbon-fiber composites. Several technical barriers prohibit most lightweight materials from being commercialized widely, cost being one significant barrier even after taking into account lightweighting and part consolidation as a few of the major benefits they offer. A system level life cycle assessment of competing materials and design options is essential to evaluate various whole vehicle design approaches that optimize the materials used according to system requirements and cost targets. Those assessments are then used by DOE management to aid in setting program priorities and evaluating potential impacts.

Approach

A systematic approach that facilitates consideration of various lightweight materials and technologies for automotive systems scenarios—and the interactions among them within a scenario—an automotive cost model for a baseline midsize passenger car has been developed to examine the cost effectiveness of LM's multi-year weight reduction goals. This approach facilitates the consideration of several lightweighting strategies such as lightweight metals, composites, and multi-materials, each of which can be optimized at the specific component level and the vehicle system level before its cost-effectiveness can be evaluated by comparison among scenarios for determining a lightweighting strategy. The analysis also considers the impacts of lightweighting a component beyond the component itself to the complete vehicle retail price and life cycle/ownership costs.

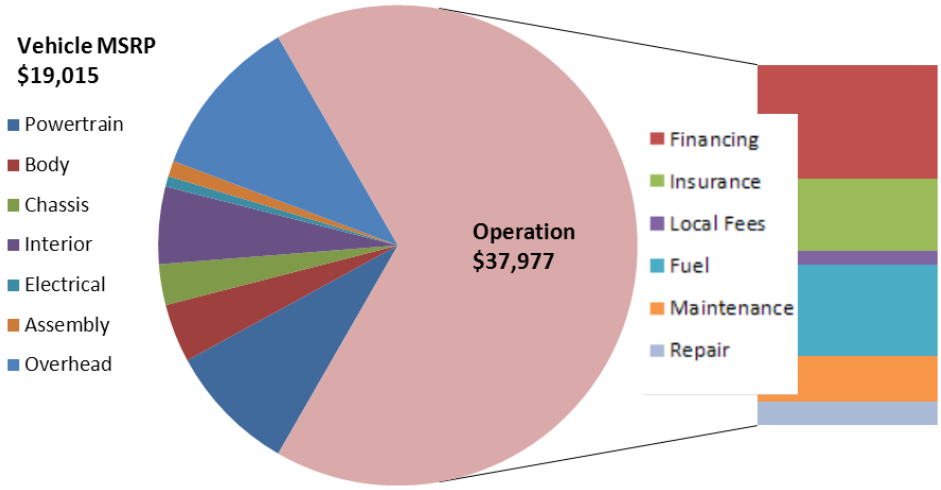
The baseline Automotive System Cost Model (ASCM) developed for a midsize passenger car is based at the level of 35+ major components, for which specific mass and technology data has been collected. Using the component data and specific alternative component technology data available from the industry representing a specific lightweighting (LW) scenario, lightweighting cost-effectiveness can be estimated. It is the sizing interrelationships among various vehicle components (i.e., mass decompounding/secondary mass savings impacts) considered in ASCM that allows the systems-level examination of cost-effectiveness impacts, an approach that goes beyond one-for-one component substitution. The mass decompounding effect also allows consideration of how the heavier and expensive alternative electric powertrains can impact the cost-effectiveness of non-powertrain lightweighting options. This effect is limited to the consideration of component-level mass and the associated cost for the hybrid and fuel cell advanced powertrain types currently included in the model. Component-manufacturing costs are estimated after components are sized after taking into account their interrelationships; to this,

Benefits

- Allows to examine cost-effectiveness of component lightweighting opportunity for 35+ major components at the complete vehicle system-level
- Cost-effectiveness is estimated in terms of part cost, vehicle retail price, and ownership/life cycle cost
- Cost-effectiveness of LM's multi-year weight reduction goals can be estimated using a systematic approach that facilitates consideration of various lightweight materials and technologies defined by several plausible automotive systems scenarios
- Consideration of the mass decompounding effect allows to examine the impacts between alternative advanced powertrain and lightweighting body and chassis options

vehicle assembly, OEM corporate overhead, and dealer costs are added for estimating vehicle retail price. Comparison of alternative LW scenarios is finally made at the level of vehicle life cycle/ownership cost, which is estimated by adding operation cost that consists of six major cost categories, including fuel—a category strongly influenced by vehicle lightweighting and powertrain type considered. As most lightweighting options have high initial costs, it is the vehicle life-cycle cost, rather than the vehicle retail price on which the automotive industry currently focuses, that needs to be considered to determine each option's economic viability. It is the systems approach that allows consideration of the impacts of a specific component-level lightweight substitution in the context of a plausible scenario of the vehicle mass and associated life cycle cost, that facilitates the for formulation of a cost-effective LW strategy.

A baseline midsize passenger car—a 2002 midsize vehicle with a curb weight of 3,249 lbs (as reported by EPA in its annual trend report), manufactured by a domestic OEM—was considered for the capability demonstration of the system-level cost model developed here. Mass data at the 35+ component level were obtained using the vehicle teardown data from the A2Mac1 database (an industry database). Intellicosting's benchmarking cost data, based similarly on teardown data, are developed at a more detailed level to estimate costs of major components within each of the 35+ component categories considered in our cost modeling framework, as shown in Table 1. For example, the engine has been disaggregated further into seven major components. Representation of cost components at a detailed level provides additional capability to examine lightweighting opportunities at a one-step-more-detailed level. Major subcomponent cost data represent OEM purchased cost at an annual production volume of 250,000. The model is dynamic in the sense that new component-level technology data can be added to the model database when data become available and needed for cost-effective LW strategy analyses. The total baseline manufacturing cost of a midsize passenger car is estimated to be $12,762 or $8.64/kg, with components such as engine, transmission, body-in-white, and seating and restraints form a major share of total cost.



Vehicle Ownership Cost Distribution of a 2002 Baseline Midsize Car

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