1. Introduction

As part of the U.S. Department of Energy's (DOE's) Vehicle Technologies Program (VTP), the Lightweight Materials (LM) activity focuses on the development and validation of advanced materials and manufacturing technologies to significantly reduce light and heavy duty vehicle weight without compromising other attributes such as safety, performance, recyclability, and cost. Because it takes less energy to accelerate a lighter object, replacing cast iron and traditional steel components with lightweight materials such as high-strength steel, magnesium (Mg), aluminum (Al), and polymer composites can directly reduce a vehicle's fuel consumption. For example, a 10% reduction in vehicle weight can result in a 6%–8% fuel economy improvement. Reducing vehicle weight has other benefits such as allowing cars to carry advanced emissions control equipment, safety devices, and integrated electronic systems without becoming heavier. LM are especially important for improving the efficiency and range of hybrid electric, plug-in hybrid electric, and electric vehicles because they offset the weight of power systems such as batteries and electric motors.

In the short term, vehicle weight reduction can be achieved by replacing heavy steel components with materials such as high-strength steel, Al, or glass fiber-reinforced polymer composites. The properties and manufacturing of these materials are well established; however, better and more cost effective technologies and processes are needed for joining, modeling, and recycling. In the longer term, even greater weight savings are possible (50%–75% weight reduction for some components) through use of advanced materials such as Mg and carbon fiber reinforced composites. However, more extensive research and development (R&D) is needed to better understand the properties of these materials and reduce their costs.

Research and development work conducted within the LM activity is broken down into three categories: Properties and Manufacturing, Modeling and Computational Materials Science (CMS), and Multi-material Enabling. Work within Properties and Manufacturing aims to improve properties (such as strength, stiffness, or ductility) and manufacturability (such as material cost, production rate, or yield) of a variety of metal and polymer composite materials. The focus of the Modeling and CMS work and the Multi-material Enabling work is to provide supporting technologies necessary for full system implementation such as joining methods, corrosion prevention techniques, predictive models, and other computational tools. This introduction summarizes the highlights of the program in all of these areas during the 2011 fiscal year. The remainder of the report discusses the specific technical accomplishments in the Lightweight Materials activity broken down into four areas: Automotive Metals, Polymer Composites, United States Automotive Materials Partnership (USAMP) Cooperative Research, and Crosscutting.

Carbon Fiber and Polymer Composites

Carbon fiber reinforced polymer composites have the potential to reduce component weight by more than 60%; however, there are significant technical and cost barriers to their widespread introduction onto vehicles. The cost of input material (precursor) and the carbonization process contribute significantly to the total cost of carbon fiber hence significant focus has been provided to these areas. Oak Ridge National Laboratory (ORNL) has been seeking to reduce the cost of carbon fiber by utilizing different low cost starting materials (including textile grade polyacrylonitrile, lignin, and polyolefins) and through advanced processing techniques for stabilization and oxidation as well as carbonization/graphitization that promise to improve the rate and cost of conversion to carbon fiber. The process improvements are enabling validation of successfully converting larger volumes (tows) of precursor to carbon. Reports in this document outline the specific progress made under each aspect of cost reduction towards achieving realized carbon fiber at $5 per pound.

In the area of lowering the cost of processing, ORNL and Pacific Northwest National Laboratory (PNNL) have developed initial capability for prediction of fiber length and orientation of long fiber injection molded thermoplastic composites. From this information, the mechanical properties can be predicted. The focus has shifted from model development to validation of prediction of stiffness and strength in progressively complex shaped parts. The detailed report for predictive engineering documents the advances made in developing and understanding this aspect so that industry may use this robust capability to accelerate product development of injection molded composites and lower the technical risk by optimizing tool design and injection molding conditions to optimize properties.

Magnesium Alloys

Figure 1. Mg extrusion exhibiting low ductility failure.

Magnesium alloys, with the lowest density of all structural metals, have the potential to reduce component weight by greater than 60%. However, significant technical barriers limit the use of Mg to approximately 1% of the average vehicle by weight. These barriers include high raw material cost and price volatility, relatively low specific stiffness, difficulty in forming sheet at low temperatures, low ductility of finished components (such as in Figure 1), and a limited alloy set, among others. In addition, using Mg in multi-material systems introduces joining, corrosion, repair, and recycling issues that must be addressed.

Ongoing work in the LM activity is supporting the wider application of Mg components by addressing some of these technical gaps. As reported in chapter 2, research at PNNL has achieved several interesting results including production of ultra-fine grain Mg sheet by a unique extrusion-machining process and initial development towards a non-rare earth containing Mg extrusion alloy with energy absorption performance comparable to Al. Together with PNNL, ORNL has demonstrated promising joint properties in friction stir welded Mg-steel joints, a challenging and very important joint type for enabling wider integration of Mg components. ORNL also provided important design data for the automotive community by developing a specially designed test method for characterizing the structural performance of Mg at automotive strain rates. Work conducted collaboratively with USAMP has yielded a variety of exciting improvements in Mg technology including development of Mg sheet warm forming techniques that may be suitable for high volume applications, production of demonstration structures for a Mg-intensive vehicle front end, and several advances in corrosion prevention in mixed-material systems. Combined, this work continues to improve the readiness of Mg processing, integration, and modeling towards wider application and significant vehicle weight reduction.

Aluminum Alloys

Aluminum alloys represent a middle-ground in the structural light metals spectrum. Years of development within the aerospace, construction, and automotive industries have led to a well-developed and reasonably well understood alloy and processing set. Applications of Al within automotive design include hoods and panels, power train components, and even entire vehicle body-in-white (BIW) structures. There are several barriers to the increased use of Al in vehicle weight reduction applications such as material cost, room temperature formability, and limitations within the existing manufacturing infrastructure. As with Mg, the addition of significant amounts of Al to the automotive manufacturing stream presents added multi-material challenges in joining, corrosion, paint and coatings, repair, and recycling.

Aluminum research and development supported by the LW activity focuses on addressing the manufacturing and integration technology gaps described above. PNNL reported several accomplishments in Al research this year including accurate measurement of improved room temperature formability during high rate deformation of Al sheet and significant increases in both strength and ductility of 6000-series Al sheet for heavy duty truck cab components using an optimized forming process. Collaborative research conducted with USAMP generated improvements to process design and simulation for warm forming of Al sheet and also demonstrated an ablation Al casting process to produce high integrity, high performance permanent mold castings for automotive structures.

Advanced High-Strength Steel (AHSS)

Conventional iron and steel alloys are prominent in existing vehicle architectures, making up over 70% of the weight of a vehicle. Despite the relatively high density of iron based materials, the exceptional strength and ductility of advanced steels offers the potential for efficient structural designs and reduced weight. Application of a new generation of AHSS has the potential to reduce component weight by up to 25%, particularly in strength limited designs. Steel components are also generally compatible with existing manufacturing infrastructure and vehicle materials, making them a likely candidate for near-term weight reduction. Steel development and research in the LM activity is focused on introducing the so-called "3rd generation advanced high strength steels." As shown in Figure 2, 3rd generation AHSS are targeted to properties in between 1st and 2nd generation AHSS with high strength, improved ductility, and low cost.

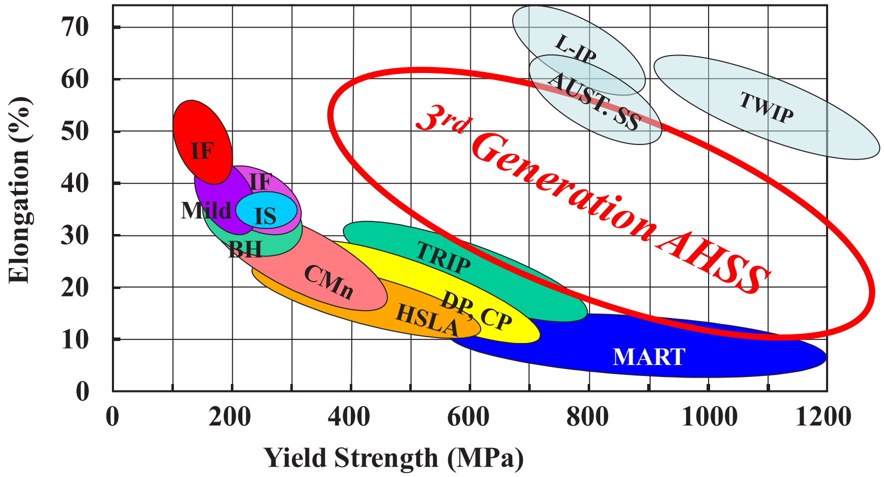

Figure 2. Yield strength versus uniform elongation for a variety of steel types.

The LW activity supports a variety of projects focusing on 3rd Generation AHSS. Examples include in-situ characterization of the austenite-ferrite transition during heating and deformation and several projects that are addressing joining challenges in AHSS. Collaborative work with USAMP and the Auto/Steel Partnership (A/SP) represents a significant effort towards realizing weight reduction through the application of AHSS; projects include mapping forming results to crash models in order to more efficiently use the true post-formed properties of AHSS, optimization and development of the AHSS stamping process, and assessing the use of AHSS for fuel tanks in hybrid vehicles.

Modeling and Computational Materials Science

Developing new, lightweight vehicle structures will require advances in areas such as structural design, processing, and alloy chemistry. Classical approaches to these advancements such as experimental, analytical, or Edisonian techniques can often yield the desired results but with limited efficiency. Computational approaches to materials engineering offer the potential to "short-circuit" the development cycle through predictive engineering and simulated experimentation. Advanced modeling techniques can also be used to optimize designs in well-established materials, further reducing component weight. By reducing the time and resources necessary to advance lightweight materials towards vehicle applications, it is possible to introduce relatively immature materials such as Mg without the decades (or centuries) of development applied towards conventional steel and Al. The National Research Council recently released a report on Integrated Computational Materials Engineering (ICME), identifying vehicle weight reduction as an area likely to benefit from ICME techniques . In addition, the Office of Science and Technology Policy (OSTP) recently released a white paper outlining the Materials Genome Initiative (MGI), an interagency effort to support the development of ICME which has also identified vehicle weight reduction as a promising area for application of ICME techniques.

Many of the projects supported by the LW activity include an element of computational materials science, while other projects focus almost exclusively on ICME techniques. ORNL combines exceptional experimental work with sound theory to generate diffusion and mobility data for Mg alloy simulations. PNNL has demonstrated the use of materials informatics techniques in support of a Mg cyberinfrastructure. A collaborative project with USAMP that focuses specifically on development of ICME tools for Mg automotive structures has yielded significant progress, as reported in this document. Yet, while ICME is a promising technique for solving vehicle weight reduction problems, continued focus on improving the tools and techniques is required to realize the potential of this approach.

Looking Forward

The following reports provide a detailed description of the activities and technical accomplishments of the Lightweight Materials activity during the 2011 Fiscal Year. The work shown here has produced technologies that make today's vehicles more efficient, safe, and affordable. In collaboration with industry, universities, and national laboratories, VTP continues to develop the next generation of lightweight components. These efforts are building the foundation of technologies—and technology manufacturers—that tomorrow's vehicles need to achieve ultra-high efficiency and resulting reductions in petroleum use and greenhouse gas emissions.