1. INTRODUCTION

Automotive Lightweighting Materials R&D

As a major component of the U.S. Department of Energy's (DOE's) FreedomCAR and Vehicle Technolgies (FCVT) Program, Automotive Lightweighting Materials (ALM) focuses on the development and validation of advanced materials and manufacturing technologies to significantly reduce automotive passenger-vehicle body and chassis weight without compromising other attributes such as safety, performance, recyclability, and cost.

The specific goals of ALM are to develop material and manufacturing technologies by 2010 that, if implemented in high volume, could cost-effectively reduce the weight of passenger-vehicle body and chassis systems by 50% with safety, performance, and recyclability comparable to 2002 vehicles.

ALM is pursuing five areas of research: cost reduction, manufacturability, design data and test methodologies, joining, and recycling and repair. The current long-range plan for activities in these areas is found at www.eere.energy.gov. Because the single greatest barrier to the use of lightweight materials is cost, priority is given to activities aimed at reducing costs through development of new materials, forming technologies, and manufacturing processes. Priority lightweighting materials include advanced high-strength steels (AHSSs), aluminum, magnesium, titanium, and composites including metal-matrix materials and glass- and carbon-fiber-reinforced thermosets and thermoplastics. The inclusion of AHSSs is an example explaining the term "lightweighting" as opposed to "lightweight" in order not to imply focus on only lower density materials.

Collaboration and Cooperation

ALM coordinates, cooperates and even collaborates extensively to identify, select and conduct its research and development (R&D) activities with others. The primary interfaces have been and still are with entities of the "Big Three" domestic automotive manufacturers (DaimlerChrysler, Ford, and General Motors), namely, the FreedomCAR Materials Technical Team, the Automotive Composites Consortium (ACC), the United States Automotive Materials Partnership (USAMP) and the Vehicle Recycling Partnership (VRP). These are the main means for determining critical needs, identifying technical barriers, prioritizing, assessing and selecting projects. Other important U.S. partners include the Auto/Steel Partnership (A/SP) of the American Iron and Steel Institute (AISI), the Plastics Division (formerly the American Plastics Council - APC) of the American Chemistry Council, the American Foundry Society (AFS) and the North American Die casting Association (NADCA). ALM closely coordinates some of its R&D activities with those of Natural Resources Canada's (NRCan's) CANMET Materials Technology Laboratory due to common interests in automotive lightweighting in North America. Contacts with similar efforts in other countries are maintained. A major thrust in magnesium was planned in fiscal year (FY) 2006 with CANMET and the China Magnesium Center of the Chinese Ministry of Science and Technology (MOST) and will begin in FY 2007 (see 2.K and 2.L). Six projects at six universities are jointly funded with the U.S. National Science Foundation (NSF) (see 4.J to 4.O) and others are expected to be initiated in FY 2007 or 2008 in the AHSS area. Another project at a university (see 4.E) is jointly funded with DOE's Office of Science.

Projects Development and Selection

In cooperation with the USAMP and the FreedomCAR Materials Technical Team (MTT), a procedure has been established to help facilitate the development of projects. The ALM has only rarely done open solicitations of projects. Most projects are usually developed by informal contacts with OEM and/or national

Research areas and responsible organizations

Coordinated area	Organization
Production and fabrication of Al	Natural Resources of Canada (NRCan)
Production and fabrication of Mg	NRCan
Recycling, reuse, repair of automotive parts and materials	Vehicle Recycling Partnership, Plastics Division of the American Chemistry Council
Fabrication of steel	American Iron and Steel Institute, the Auto/Steel Partnership
Fundamental materials research	DOE Office of Science, National Science Foundation (NSF)
Production and fabrication of composites	Plastics Division of the American Chemistry Council

lab researchers and are brought forth for consideration, assessed and selected on the bases of recommendations of either the USAMP or the MTT. The ALM, however, retains final say as to what is funded. This flexibility allows the ALM to select the most appropriate partners to perform critical tasks that have optimal chances of migrating to original equipment manufacturers (OEMs) or suppliers as application-engineering projects and eventually being implemented in production vehicles.

Once selected, R&D projects are pursued through a variety of funding mechanisms, including cooperative research and development agreements (CRADAs), cooperative agreements, university grants, R&D subcontracts, and directed research. Those developed through the USAMP are usually cost-shared equally (dollar-for-dollar) with the ALM funds by the USAMP or other non-Federal sources, either in cash or in-kind. No ALM funds are paid to the USAMP. Those projects developed through the MTT are usually performed at national laboratories and universities and not cost-shared. Laboratories currently involved include Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL). ANL oversees the ALM's recycling efforts (see 7) and ORNL provides overall technical support and coordination, including for the DOE cooperative agreement with USAMP. The National Energy Technology Laboratory (NETL) provides external projects management including the cooperative agreement with USAMP.

R&D projects are assigned to one of three phases as depicted in the figure and defined below: concept feasibility, technical feasibility, and demonstrated feasibility. Projects are guided to meet the requirements of each phase before they move on to the next phase. Not all projects must go through these phases under ALM funding; some may enter the technical or demonstrated feasibility stages from efforts funded elsewhere.

Typical phases/stages of projects

Concept Feasibility: Concept-feasibility projects focus on a specific idea to address a need or to create something new. Projects are usually exploratory and small in monetary requirements and time, typically less than $200,000 total over 1–2 years, to provide a yes/no answer to the value of the idea. All projects are required to have a detailed research plan, budget, and timing. They can be ended before proceeding to technical feasibility if there is a lack of technical progress or if the preliminary business case turns out to be unfavorable.

Technical Feasibility: Technical-feasibility projects typically continue R&D for ideas with proven concept-feasibility merit or potential. These projects should identify the key barriers to implementing the technology and focus on overcoming them. Technical-feasibility projects should have well-defined, industrial OEM and/or supplier participation and pull. They are usually larger and longer term than the concept feasibility projects with typical investment in the $1M to $2M (or more) range and length of 2–3 years (or more). Technical-feasibility projects can be ended before proceeding to demonstrated feasibility if there is a failure to overcome the key barriers to implementation or if the cost or business case does not develop as favorably as initially assessed.

Demonstrated Feasibility: Technology projects that need larger-scale validation may become demonstrated-feasibility projects. Not all technical-feasibility projects will need a demonstration or validation phase. These projects are few in number, much larger in scale, and may involve component or system fabrication and tests. Support and leverage from the industrial OEMs and/or suppliers is a key requirement.

FY 2006 Accomplishments

The Friction-Stir Spot-Welding of High-Strength Steels project (see 5.D) addresses the questions of whether the friction-stir spot-welding (FSSW) process can be accomplished in AHSSs and, if so, whether FSSW has advantages over conventional processes like resistance spot-welding (RSW); preliminary work suggests that it does. In addition, the process may be able to join lightweight materials that currently have joining problems using conventional joining techniques (e.g., DP1000, Martensitics, hot-stamp boron steels (HSBSs), etc). If this can be accomplished, the FSSW process could be an important enabler for more widespread use of these lightweight, advanced and ultra- high-strength materials.

Friction-stir spot-welds were made on two-high stack-ups of DP780 and HSBSs using polycrystalline cubic boron nitride tools. Initial mechanical testing demonstrates that FSSWs are capable of achieving failure stress levels that exceed the minimum required by industry standards for RSWs. See Figure 1. However, load-carrying capability still must be improved for FSSW to be competitive with RSW. This aspect of the process depends directly on stir-tool considerations and process parameters. Key technology barriers associated with stir tooling include design, material, durability, and cost. Recently-redesigned tools appear capable of improving load-carrying capability at welding times of 4 seconds.

The Future Generation Passenger Compartment project (see 2.X) demonstrated more than a 30 percent mass savings of the passenger compartment at cost parity relative to a typical 2005 baseline four-door, five-passenger sedan. This was accomplished by the intensive use of AHSSs combined with state-of-the-art design optimization and manufacturing approaches. The design solution improved performance for the new Insurance Institute for Highway Safety (IIHS) side-impact test and proposed Federal Motor Vehicle Safety Standard (FMVSS) side-pole impact and 2.5X roof-strength requirements while maintaining performance in static and dynamic stiffness, durability, and front and rear crash. The design solution was determined to be robust to both the IIHS side-impact bumper-height variations and vehicle-weight increases. Also, manufacturing-feasibility evaluations assessed the solution to be acceptable for high-volume manufacturing.

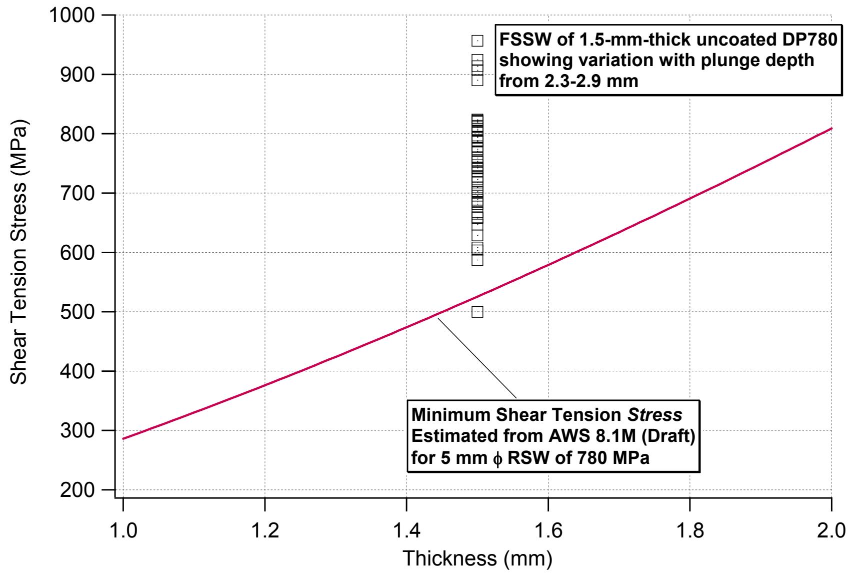

Figure 1. Data plot showing the variation of shear tension stress with DP780 sheet thickness. Data points indicate that intrinsic strength of FSSWs can exceed minimum specified for RSWs.

The project scope included additional objectives to expand learnings. The packaging study comprehended both conventional and fuel-cell powertrain requirements. See Figures 2 and 3. Crash analysis identified that the worst-case loading scenario for the IIHS side-impact test was controlled by the internal-combustion-engine variant and not the fuel-cell variant. Project results indicated that if steel grades with tensile strengths of 1600 MPa with capability of meeting the manufacturing forming requirements can be developed, mass savings could improve by an additional six to eight percent. When combined with mass compounding, results show that total mass reduction will approach the 50 percent mass reduction objective of the FreedomCAR program while also maintaining the desired affordability, durability, and recyclability.

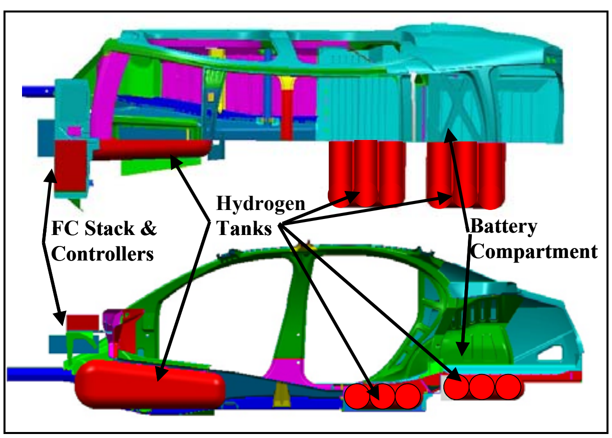

Figure 2. Optimized AHSS solution.

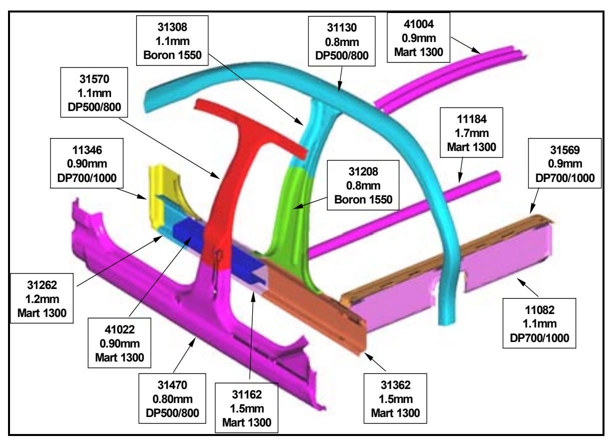

Figure 3. Fuel-cell powertrain components comprehended.

The need to improve fuel economy has led automakers to explore lightweight materials like Al for automobile body and closures. While attractive, there are challenges to the widespread use of Al owing to its limited formability and cost as compared to steel. A prior study into warm forming, concluded in 2001, focused on the development of special Al alloys to achieve formability. This approach increased material cost and widened the process cost differential. A technical cost model was developed and used to evaluate and optimize the warm-forming process as well as to demonstrate the cost advantages of the process. Results of the model indicated a significant cost advantage for the production of an Al door inner as compared to a multi-piece design fabricated with conventional steel.

In the follow-on Warm Forming Al II project (see 2.A), a warm-forming process was demonstrated on a production-grade, commercially-available Al alloy AA5182-O. A new cleanable lubricant suitable for use at warm-forming temperatures was developed and used in all of the forming trials. Two dies were utilized in the project: a production die for the stamping of steel door inners refitted with cartridge heaters and a purpose-built die for warm forming. The second was designed and built using finite-element (FE) simulation tools and the thermal and distortion behavior knowledge gained during trials with the door-inner die. The temperature distribution in this new warm-forming tool was shown to offer exceptional thermal control and minimal distortion as compared to the door-inner die. Post-forming analyses are underway, but depth of draw and formability control differences can be seen in the AA5182-O panels yielded by the two dies. Figure 4 shows the typical panel coming off the refitted die and Figure 5 shows two typical panels coming off the purpose-built warm forming die.

Specific accomplishments include: development and demonstration of key elements of warm-forming technology with the forming of a door inner panel from a commodity Al alloy; application of thermal and forming simulation tools for improved process control in warm forming; and design and construction of a new, optimized, warm-forming die for excellent forming and thermal control.

Figure 4. Inner door panel warm formed using refitted steel stamping die.

Figure 5. Deep-drawn panels warm formed using a purpose-built warm-forming die.

The Ultra Large Castings of Aluminum and Magnesium (ULC) project (see 2.I) successfully cast its first demonstration component, the thixomolded magnesium front-rail "shotgun" shown in Figure 6. This project seeks to describe and substantiate the rationale for using light-metal castings in place of conventional stamped-and-welded steel automotive body structures to significantly reduce vehicle weight. The ULC project is executed in two concurrent phases. *Phase I* focuses on process issues and emerging casting processes aimed at improving the quality of cast components vs. conventional high-pressure die-casting casting. Pha*se II* focuses on designing, analyzing, producing and testing a demonstration component for a "real-world" vehicle application. The demonstration component chosen by the ULC team replaces the conventional multi-piece steel structure that forms the inner front fender—known in the industry as a "shotgun"-- with a single thixomolded magnesium casting (Figure 6). Ultimately, this "shotgun" will become part of an integrated front-end structure for a large body-on-frame pickup or sport utility vehicle (SUV) made entirely of magnesium castings (Figure 7). Besides demonstrating a mass reduction of over 60% compared to conventional steel construction (Figure 8), the thixomolded shotgun is made with a first-of-its-kind, multiple-drop, direct-injection hot-runner system (Figure 9).

Figure 6. Thixomolded magnesium shotgun casting.

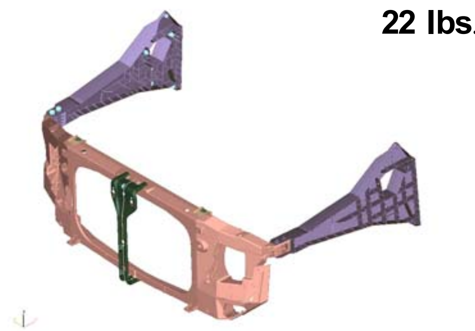

Figure 7. ULC Cast magnesium front-end proposal (68% lower weight).

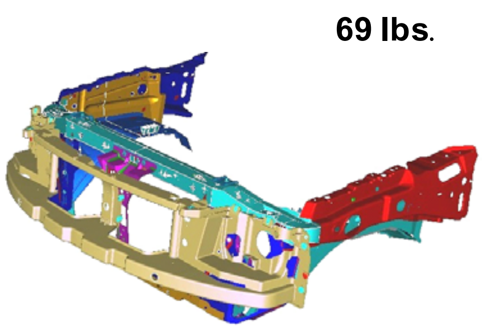

Figure 8. Conventional steel front end structure (2006 Ford Expedition).

Figure 9. Example of flow simulation and filling pattern for hot runners.

The Automotive Composites Consortium (ACC) Focal Project 3 (FP3) Composite-Intensive Body Structure project (see 4.D) team designed a carbon-fiber body-in-white with a 60% mass reduction compared to a comparable steel structure. Current carbon-fiber composite manufacturing processes use slow autoclave or liquid-molding processes. Successful automotive implementation requires the development of a rapid, low-cost fabrication technology, such as the liquid molding of dry fiber preforms. The ACC has successfully demonstrated a rapid-molding process for carbon- fiber composites.

The ACC developed the programmable powdered preform process (P4)--preforming process for carbon fiber. A robotically-controlled chopper gun directs fiber and binder into a forming tool to produce a preform in the shape of the part to be molded (Figure 10). This preform is then placed into the composite molding tool. The ACC optimized the structural reaction-injection molded (SRIM) process for molding these performs into the final composite panels, which are then bonded together (Figure 11) into the final structure.

Figure 10. Carbon-fiber preform for B-pillar outer panel.

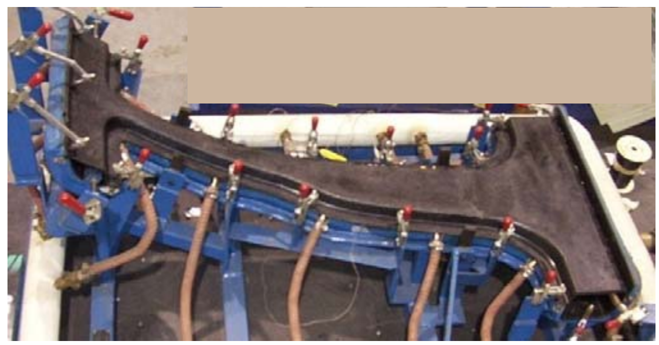

Figure 11. Carbon-fiber B-pillar inner and outer panel in bonding fixture.

The Structural Cast Magnesium Development (SCMD) project (see 2.G) work advanced far enough that General Motors decided to introduce the project's focal component, a front engine cradle (Figure 12), in its 2006 Chevrolet Corvette (Figure 13). The magnesium version is 34% lighter than the 2005 production Al engine cradle it replaces.

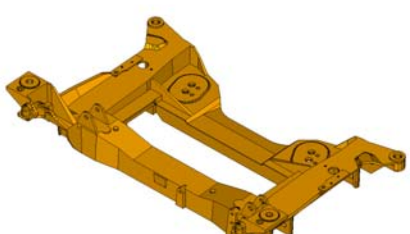

Figure 12. Image of magnesium front engine cradle.

Figure 13. 2006 Corvette.

Argonne has successfully produced recovered plastics, at least polyproylene/polyethylene (PP/PE) materials, with less than 2 parts per million (ppm) polychlorinated biphenyls (PCBs) in multiple tests. (See 7.C.) This is significant in that current Environmental Protection Agency (EPA) regulations require less than 2 ppm PCBs in recycled automotive plastics, the current limit of detectability with modern analytical technology, which could preclude the recycling of such plastics. Though banned for several decades from automotive applications, PCBs are apparently still ubiquitous and typically show up at 25-30 ppm levels in recycled automotive plastics, probably due to contamination in auto shredders and scrap yards and from contact with materials from non-automotive products. Previous attempts at cleaning the recycled automotive plastics were able to reduce the levels consistently to only around 5 ppm. The less-than-2-ppm level, however, has been shown only in small-scale experiments and it is not clear if the process could be cost-effective. In FY 2007, larger-scale experiments will be conducted to investigate the scalability of the process including required residence time and operating temperatures.

Bolstered by the successes in the SCMD and the Mg Powertrain Cast Components (see 2.H) projects and the positive indications of cost models, the USAMP completed a strategic vision study, outlining recommendations for North American automotive magnesium through the year 2020. The study was published in late 2006 and is available through USCAR (www.uscar.org).

Future Directions

In FY 2002 and FY 2003, the FreedomCAR and Fuels Initiative formed from the 1994–2001 Partnership for a New Generation of Vehicles (PNGV). Thinking and planning on what replaces the ALM efforts that began in the PNGV in roughly 1999–2002 has continued since. The MTT conducted a series of strategic reviews of various materials and manufacturing topics in FY 2004. The planning is now essentially complete. Based on those reviews, carbon-fiber-reinforced polymer-matrix composites and Mg will be emphasized in the next few years as they have the greatest weight-reduction potential, but there will be some efforts on AHSSs, titanium, and metal–matrix composites because these will contribute in niche roles to the overall FreedomCAR weight-reduction and cost-neutrality goals. Material-crosscutting work in general manufacturing will continue in joining, nondestructive evaluation (NDE), and recycling. Planning for the future NDE efforts will be concluded in 2006. Though technical-feasibility (see above) projects will dominate as before, concept-feasibility and demonstrated-feasibility projects will also be pursued as will some university base-technology projects.

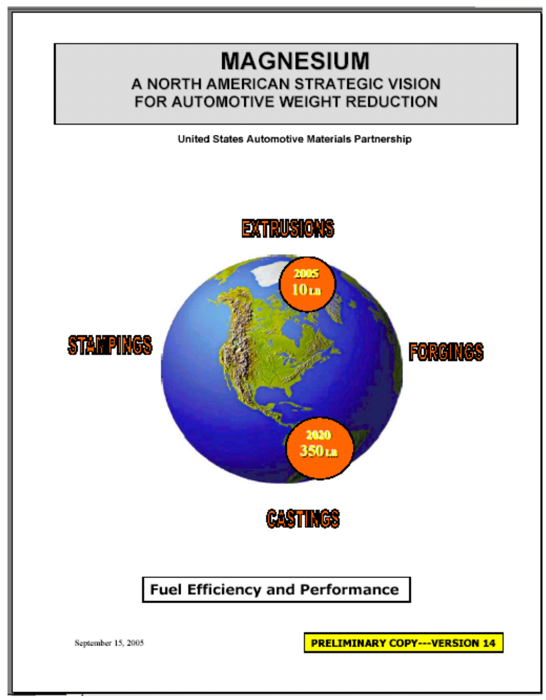

Figure 14. Cover of USAMP strategic vision for automotive Mg through 2020.